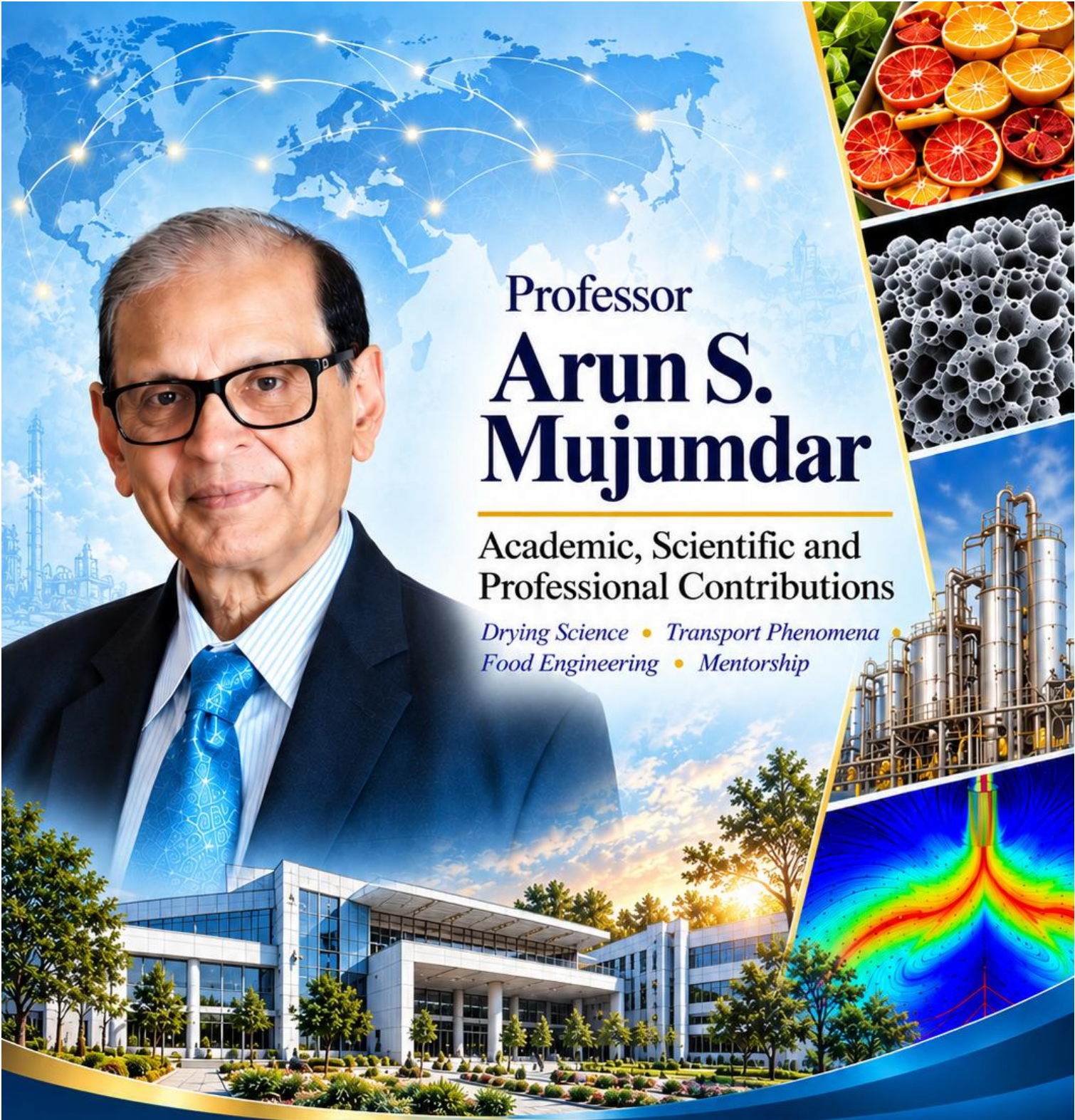




Professor **Arun S. Mujumdar**

Academic, Scientific and
Professional Contributions

*Drying Science • Transport Phenomena •
Food Engineering • Mentorship*

Transport Processes Research (TPR) Group
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Compiled by

Mr. Devendra Khade

Prof. M. M. Sharma Doctoral Research Fellow
Department of Chemical Engineering
Institute of Chemical Technology (ICT), Mumbai-19

PREFACE

This volume brings together, in one place, an overview of the academic, scientific, and professional contributions of Professor Arun S. Mujumdar across more than five decades of research, teaching, mentorship, and service to the international drying and transport-processes community.

The chapters survey his contributions to academic mentorship and the “virtual mentor” model; food and agricultural drying science; energy-efficient drying technologies; gas–particle flow, heat and mass transfer; fundamental and applied thermal sciences and transport phenomena; additive manufacturing of novel foods; and impinging-jet transport phenomena. Two appendices provide selected critical reviews in drying and process engineering, along with an overview of his academic publication record.

This volume is prepared for convenient academic and professional reference. While every effort has been made to compile and present the information accurately and systematically, some information may be dated, incomplete, or subject to further verification. The content may therefore be updated, corrected, and expanded in future editions.

The volume has been compiled by Mr. Devendra Khade, with the assistance of Gemini AI and ChatGPT AI models for literature organization, drafting, editing, language refinement, and compilation support. The use of these AI tools is intended to facilitate the preparation and presentation of the material, while the compilation remains subject to human review, verification, and further revision.



Transport Processes Research (TPR) Group

TABLE OF CONTENTS

Chapter 1: The Architecture of Academic Mentorship	1
Chapter 2: The Contributions and Global Impact of Professor Arun S. Mujumdar in Food and Agricultural Science and Technology	13
Chapter 3: The Evolution of Food Drying Science and Technology	26
Chapter 4: Pioneering Innovations in Energy-Efficient Drying Technologies	42
Chapter 5: Advances in Gas-Particle Flow, Heat, and Mass Transfer	57
Chapter 6: The Extensive Contributions of Professor Arun S. Mujumdar to Basic and Applied Thermal Sciences	71
Chapter 7: Quantitative Analysis of Fundamental and Applied Transport Phenomena Research	85
Chapter 8: Advanced Additive Manufacturing of Novel Food Products	96
Chapter 9: Transport Phenomena in Impinging Jets	110
Appendix A: Critical Reviews in Drying & Process Engineering	123
Appendix B: Academic Publication List	144

CHAPTER 1

The Architecture of Academic Mentorship: Professor Arun S. Mujumdar's Global Paradigm and the Role of Virtual Mentors in Researcher Development

Introduction to the Mentorship Imperative in Modern Scientific Research

In the highly specialized ecosystem of academic and industrial research, the trajectory of scientific advancement is inextricably linked to the quality of mentorship provided to emerging scholars. Over the past five decades, the discipline of chemical and process engineering—specifically the interdisciplinary field of thermal drying technology—has been profoundly shaped by Professor Arun S. Mujumdar. Widely acknowledged as the "Drying Guru," Professor Mujumdar's contributions extend far beyond his expansive bibliography of over 1,200 refereed publications, 60 edited books, and 64,000 citations¹. While his longevity in continuous research and education since 1975 is an awe-inspiring academic feat, his most enduring legacy lies in his revolutionary approach to academic mentorship¹. This approach has fundamentally altered how global research networks are formed, sustained, and leveraged for the professional development of successful researchers².

Professor Mujumdar has formally advised over 120 PhD students and 35 postdoctoral researchers across institutions such as McGill University and the National University of Singapore (NUS), while simultaneously offering guidance to countless other scholars across the globe¹. However, the sheer volume of his mentees is less significant than the philosophical and structural innovations he introduced to the mentoring process. Long before globalization and digital connectivity became standard in higher education, Professor Mujumdar championed a borderless, inclusive, and multi-disciplinary mentoring framework². He recognized early on that the traditional, localized apprenticeship model of doctoral education was insufficient to address complex, transnational industrial challenges. Consequently, he pioneered and formalized the concept of the "virtual mentor"—a paradigm that transcends geographical, financial, and institutional barriers to provide comprehensive psychosocial and career-related support to researchers worldwide⁵.

This report provides an exhaustive analysis of Professor Mujumdar's mentoring philosophy, the structural mechanisms he established to foster global collaboration, and his specific advocacy for virtual mentorship. By examining these elements, the analysis elucidates the critical importance of non-traditional mentoring models in the holistic professional development of successful researchers in the modern academic landscape.

The Philosophical Foundations of the Mujumdar Mentoring Model

To understand the efficacy of Professor Mujumdar's mentoring approach, one must first examine the core philosophies that dictate his interactions with emerging scholars. His methodology diverges sharply from purely transactional academic advising, emphasizing instead a holistic, deeply empathetic integration of the researcher into a global community of practice.

Vasudhaiva Kutumbakam: The World is One Family

A defining characteristic of Professor Mujumdar's mentorship is his commitment to the Sanskrit ideology of *Vasudhaiva Kutumbakam*, which translates to "the world is one family"³. This worldview fundamentally rejects the hyper-competitive, exclusionary practices that often characterize elite academic institutions. Instead of utilizing others to build up his own status, Professor Mujumdar leverages his extensive global network to elevate junior researchers, expanding his own reach to build up others³.

This philosophy directly informs his "restorative and empathetic personality" in academic relationships. Mentees frequently report that he possesses an exceptional ability to "read between the lines," understanding the emotional and personal challenges that scholars face behind their academic output³. He provides holistic support that encompasses intellectual guidance, emotional encouragement, and, when necessary, financial

assistance³. This empathetic posture mitigates the high attrition rates, isolation, and mental health crises frequently observed in high-pressure academic environments, fostering a sense of belonging that is critical for long-term professional resilience.

Intellectual Humility and Psychological Safety

A critical component of professional development for researchers is the cultivation of a psychologically safe environment where intellectual risk-taking is encouraged. Professor Mujumdar consistently imparts the value of humility to his mentees, frequently quoting the poet William Cowper: "Knowledge is proud that it knows so much and wisdom is humble that it knows no more"³. By modeling this humility, Professor Mujumdar dismantles the traditional hierarchy of the laboratory. He creates an environment where young researchers feel empowered to question established paradigms, propose novel methodologies, and admit knowledge gaps without fear of harsh judgment. This intellectual humility prevents academic arrogance and ensures that researchers remain lifelong learners, a necessity in rapidly evolving fields.

Breadth versus Depth in Creative Thinking

In traditional doctoral programs, researchers are often encouraged to adopt a hyper-specialized focus on a singular, narrow project. Professor Mujumdar vehemently opposes this restrictive approach, positing that creative thinking is the fundamental catalyst for all breakthrough research across the sciences, engineering, liberal arts, and business⁷. He advocates that the training of researchers should not be rigidly bound to a specific project. Instead, he insists that depth of expertise must be irrevocably paired with a breadth of knowledge⁷.

To stimulate this breadth, he frequently shares the wisdom of Mae Jemison with his research cohorts: "Never limit yourself because of others' limited imagination; never limit others because of your own limited imagination"⁸. By encouraging his mentees to read widely across disciplines, engage with diverse methodological frameworks, and participate in multidisciplinary discussions, he cultivates scholars who are capable of lateral thinking and interdisciplinary innovation⁹.

Furthermore, he recognizes the intense cognitive demands placed on researchers and advocates for holistic well-being to sustain creative output. As a testament to this, Professor Mujumdar himself engages in watercolors and acrylic painting as a stress relief technique—a practice he shares with his network to underscore the importance of taking one's mind off rigorous academic pressures to allow subconscious problem-solving to occur¹.

Philosophical Pillar	Implementation in Mentoring Practice	Impact on Researcher Professional Development
Vasudhaiva Kutumbakam	Borderless collaboration; connecting researchers across diverse nations and cultures without gatekeeping.	Expands global perspective, builds international social capital, and fosters cross-cultural competency.

Philosophical Pillar	Implementation in Mentoring Practice	Impact on Researcher Professional Development
Empathetic Support	Providing holistic emotional, intellectual, and financial backing; integrating families into the social circle.	Reduces burnout; builds resilience and strong psychosocial foundations necessary for academic longevity.
Intellectual Humility	Modeling lifelong learning; quoting literature to underscore the limits of current knowledge.	Creates a safe environment for inquiry; encourages intellectual risk-taking and prevents rigid dogma.
Interdisciplinary Breadth	Decoupling PhD training from singular projects; encouraging lateral exploration and creative thinking.	Fosters adaptability, allowing researchers to pivot to new technologies and drive breakthrough innovation.
Holistic Well-being	Promoting non-academic pursuits (e.g., painting, art)	Sustains long-term creative output and mitigates the
	for cognitive recovery.	psychological toll of intense academic pressure.

The Industry-Academia Nexus in Researcher Development

A central pillar of Professor Mujumdar's professional development strategy is the conviction that academic excellence must be intrinsically linked to real-world relevance¹. He has consistently argued that the ultimate impact of engineering research must be measured by its capacity to enhance industrial output, save energy, and address societal challenges, rather than merely by accumulating citation metrics¹¹.

When mentoring young faculty and doctoral candidates, he instills the belief that academic inquiry should not remain confined within isolated university laboratories. Industrial drying operations, for instance, consume vast quantities of global energy and directly influence product quality and environmental sustainability². Consequently, researchers must actively engage with industry to understand practical constraints, scale-up challenges, and commercial opportunities².

This philosophy has been highly operationalized in his collaborative work in China, where he was recognized as a High-End Foreign Expert at Tianjin University of Science and Technology and played a pivotal role in establishing the Jiangnan-Pepsico Institute at Jiangnan University¹¹. Through these initiatives, he mentored local researchers in developing innovative drying technologies (such as microwave freeze-

drying at cryogenic conditions) with direct financial backing and strategic input from multinational corporations¹². This approach significantly alters the professional development trajectory of his mentees. It equips them with the translational skills required to navigate both academic institutions and the commercial sector, bridging the critical gap between basic science and applied technology, and thereby maximizing their overall employability and socio-economic impact¹¹.

The Conceptualization and Evolution of the "Virtual Mentor"

At the core of Professor Mujumdar's enduring global influence is his profound understanding and practical application of the "virtual mentor" concept. This paradigm operates on two distinct theoretical and temporal levels: his own historical experience of being guided by distant luminaries, and his subsequent adoption of modern digital technologies to serve as a ubiquitous mentor to a global diaspora of researchers.

Historical Origins: Learning from Distant Masters

The concept of a "virtual mentor" does not strictly denote a relationship mediated by digital video conferencing; in its purest form, it is the proactive cognitive assimilation of knowledge and values from a distant expert. Professor Mujumdar frequently attributes his own foundational development to a cohort of "virtual mentors" scattered across the globe⁵. In the decades preceding the internet, geographic distance posed a formidable barrier to direct collaboration. Yet, Mujumdar recognized that profound mentorship does not strictly require physical proximity, frequent conversation, or formal institutional affiliation.

He actively sought intellectual guidance, methodological rigor, and moral inspiration from the writings and sporadic personal interactions with international pioneers in his field⁵. He specifically lists the late Professor Carslaw Strumiłło (Łódź University, Poland), late Professor Ryoze Toei (Kyoto University, Japan), Professor Michel Roques (University of Pau and Pays de l'Adour, France), late Professor Ernst-Ulrich Schlünder (University of Karlsruhe, Germany), Professor Roger Keey (University of Canterbury, New Zealand), late Professor Owen Potter (Monash University, Australia), late Professor Lazlow Imre (Budapest Technical University, Hungary), Professor Iva Filkova (Czech Technical University), and the late Professor Marcus Karel (MIT, USA) as his virtual mentors⁵.

By meticulously studying their publications, observing their professional ethos, and internalizing their approaches to scientific inquiry, Mujumdar absorbed invaluable lessons regarding research methodology, professional service, and human values⁵. This historical context establishes a crucial precedent for professional development: researchers must take agency in their own growth by actively seeking out and learning from global excellence, utilizing the published record as a medium for virtual apprenticeship.

The Modern Execution of Virtual Mentorship

Having benefited immensely from distant guidance, Professor Mujumdar leveraged the advent of digital communication to invert the model, becoming an omnipresent virtual mentor to thousands of researchers. Despite demanding administrative, teaching, and editorial duties, he utilized email, video conferencing, and messaging platforms (such as WhatsApp) to maintain continuous, high-frequency contact with mentees across the globe¹⁴.

His mentees recount how he transcends the limitations of geographic distance through rapid and meticulous engagement. As the Editor-in-Chief of *Drying Technology*, it is not uncommon for him to receive a manuscript, review it comprehensively within a single day, and return detailed, constructive feedback immediately to the authors⁹. This rapid iteration accelerates the learning curve for young authors, teaching them the nuances of high-impact academic writing and experimental design far faster than traditional, delayed peer-review cycles.

Furthermore, he proactively disseminates relevant articles, editorials, and strategic ideas to his network, sparking continuous intellectual dialogue¹⁴. His virtual mentorship extends beyond the technical aspects of fluid mechanics or thermodynamics; he prompts his mentees to analyze global macro-economic and political trends critically. For instance, he frequently engages his network in deep analytical discussions regarding the

divergent economic development paths and technological infrastructures of India and China, encouraging his mentees to view their specific research through the lens of global policy and international development¹⁴. This transforms the virtual mentoring relationship from a narrow academic transaction into a comprehensive masterclass in global intellectual leadership.

The Strategic Importance of Virtual Mentoring in Academic Professional Development

The model of virtual mentoring championed by Professor Mujumdar intersects powerfully with contemporary pedagogical research regarding the professional development of STEM researchers. Virtual Mentorship Programs (VMPs) are increasingly recognized as essential mechanisms for fostering equity, building research capacity, and providing comprehensive career support in an era often referred to as the Fifth Industrial Revolution¹⁵.

Overcoming Systemic and Geographic Barriers

Traditional, in-person mentorship relies heavily on physical proximity, which inherently disadvantages researchers located in developing nations, under-resourced institutions, or those facing personal mobility constraints. Virtual mentoring effectively democratizes access to elite guidance and social capital¹⁷. It circumvents physical travel constraints, financial limitations, and personal responsibilities (such as caregiving), thereby creating a more equitable scientific community¹⁷.

Professor Mujumdar's active mentoring of scholars in China, India, Malaysia, Thailand, and Sub-Saharan Africa demonstrates how virtual networks can uplift entire national industries by transferring high-level technological expertise across borders⁶. For researchers in these regions, the ability to collaborate virtually with a leading expert provides unprecedented access to cutting-edge methodologies and global publication standards that would otherwise be inaccessible, fundamentally altering their professional trajectories and the research output of their home institutions.

Enhancing Research Capacity and Technical Skill Acquisition

The professional development of a researcher hinges on the acquisition of complex technical and methodological skills. Virtual mentoring has proven highly effective in this domain. Recent qualitative studies and collaborative autoethnographies analyzing virtual mentorship in academia reveal that mentees successfully acquire critical competencies, such as advanced time management, experimental design, and manuscript preparation, through digital collaboration¹⁶.

For example, virtual mentors can guide early-career researchers through novel methodologies by sharing foundational literature, providing step-by-step frameworks, and offering real-time feedback¹⁶. In Professor Mujumdar's practice, this is evident in his remote co-supervision of doctoral and postdoctoral projects in distant universities. He assists junior faculty in drafting competitive grant proposals, securing external funding, and publishing in high-impact journals¹⁴. By lending his expertise, critical eye, and international credibility to these projects, he provides grant reviewers and journal editors with confidence in the rigor of the proposed work, thereby catalyzing the careers of his virtual mentees¹⁴.

Psychosocial Support and the Development of Self-Efficacy

While some contemporary research suggests that participants in formal virtual mentoring programs may expect less psychosocial support compared to career-related guidance¹⁸, the most effective virtual mentors actively bridge this gap. Mentorship is fundamentally a relational endeavor. The development of self-efficacy—a researcher's belief in their own capability to execute complex scientific tasks—is heavily reliant on the psychological safety and encouragement provided by the mentor¹⁹.

Professor Mujumdar exemplifies the integration of profound psychosocial support into virtual mentoring. His mentees frequently reflect on his "parental warmth," his intense interest in their personal lives, and his unwavering belief in their intellectual capabilities³. Even from a distance, he integrates his mentees into his broader social circle, inviting visiting scholars to family gatherings during holidays and maintaining lifelong friendships spanning decades¹⁴. This deep level of personal investment mitigates the isolation often felt by

early-career researchers, fostering a powerful sense of belonging and integration into a global learning community¹⁹.

Dimension of Development	Traditional Mentoring Paradigm	Virtual Mentoring Paradigm (The Mujumdar Model)
Accessibility & Equity	Strictly limited by institutional enrollment, funding, and geographic proximity.	Borderless; readily available to scholars in developing nations and remote institutions.
Methodological Training	Relies on hands-on laboratory training and localized academic writing support.	Rapid iteration via digital platforms; co-authorship; exposure to global peer-review standards.
Network Expansion	Highly localized to the primary mentor's immediate departmental and regional contacts.	Immediate integration into a massive, multi-national network spanning academia and industry.
Psychosocial Support	Occurs through scheduled in-person meetings; highly variable based on departmental culture.	Sustained digital communication; personalized, empathetic tracking of career and life milestones over decades.
Resource Allocation	Dependent on the home institution's grant funding and local library access.	Democratized through open-access resources, shared global datasets, and collaborative grant writing.

Professor Mujumdar did not merely preach the virtues of open collaboration; he architected enduring global structures designed explicitly to facilitate the socialization and professional development of young researchers at scale. A primary vehicle for this is the Transport Processes Research (TPR) Group.

Originally consisting of his direct research students and postdoctoral fellows at NUS and McGill University, the TPR Group has expanded organically over two decades into an informal, multidisciplinary global team spanning more than twenty countries⁸. The group functions as a massive virtual laboratory and mentorship hub, where early-career faculty and students collaborate on diverse topics ranging from novel industrial drying technologies to mathematical modeling, electronics cooling, and food processing⁸.

A revolutionary aspect of the TPR Group's mandate is its commitment to the democratization of knowledge through the production of free, peer-reviewed eBooks⁸. Recognizing that researchers and industry professionals in developing economies often face prohibitive financial barriers to accessing premium scientific literature, Professor Mujumdar mobilized his global network of mentees and collaborators to author and edit concise, self-contained texts covering critical subjects like the drying of foods, spray drying technology, and solar drying²³. By "donating" their professional time, these scholars ensure that high-quality knowledge is disseminated globally at no cost²³.

Crucially, this open-access initiative serves a dual purpose: it disseminates vital engineering knowledge, and it functions as an intensive mentoring tool for professional development. By entrusting junior researchers (such as Dr. Sachin V. Jangam and Dr. Shivanand S. Shirkole) with the responsibility of compiling, editing, and peer-reviewing these vast volumes, Professor Mujumdar provides them with a masterclass in editorial processing, project management, and academic publishing²³. This hands-on editorial experience accelerates their professional maturation, transitioning them from passive consumers of knowledge to active curators and thought leaders within the global academic community.

Global Socialization Platforms: The IDS and ADC Symposia

Professional development requires socialization—the process by which novice researchers learn the norms, behaviors, and communicative practices of their chosen field. To facilitate this on a global scale, Professor Mujumdar established massive international symposia that function as pedagogical tools as much as they do scientific conferences.

Established at McGill University in 1978, the International Drying Symposium (IDS) is widely recognized as the premier global platform for drying science². Long before inclusivity became a ubiquitous mandate in higher education, Professor Mujumdar designed the IDS to ensure that young scientists and researchers from developing nations were given prominent platforms². He deliberately dismantled hierarchical academic structures by encouraging novice researchers to present their findings alongside internationally recognized experts².

This exposure is a critical rite of passage in professional development. It forces early-career scholars to articulate their ideas to a high-level audience, defend their methodologies under scrutiny, and integrate themselves into a global community of practice. The relationships forged at IDS have consistently evolved into enduring international collaborations, student exchanges, co-authored publications, and technology transfer initiatives². By democratizing access to the global stage, Mujumdar ensured that merit and innovation, rather than geographic location or institutional prestige, dictated a researcher's trajectory.

Following the success of IDS, his global associates spearheaded the creation of the Asia-Pacific Drying Conference (ADC) series in 1999, effectively regionalizing his vision and creating additional, accessible platforms for novice researchers in the Asia-Pacific region to socialize professionally²⁴.

Case Studies in Transformative Mentorship and Career Trajectory Shifting

The ultimate measure of any professional development initiative is its ability to positively alter the career trajectory of its participants. Mentoring, particularly in the virtual space, has the power to shift a researcher's

trajectory from regional obscurity to international prominence. An examination of specific mentees illustrates the profound impact of Professor Mujumdar's methodology.

The Trajectory of Dr. Guohua Chen

The transition from a doctoral student to an independent academic leader is fraught with challenges. Early-career researchers face immense pressure to secure funding, establish an independent research agenda, and navigate institutional politics. Virtual mentors play a critical role during this vulnerable phase. Because the virtual mentor is often outside the mentee's home institution, they can offer objective, unbiased advice and strategic support.

Dr. Guohua Chen first met Professor Mujumdar in 1986 as a postgraduate student at McGill University, where Mujumdar was one of the faculty members mentoring the research group¹⁴. After completing his PhD, Dr. Chen faced critical career junctures. Mujumdar utilized his international network to identify an industrial postdoctoral opportunity in Japan and introduced him to key academic figures in Hong Kong¹⁴. When Dr. Chen applied for an assistant professor position at the Hong Kong University of Science and Technology (HKUST) in 1996—a time when rapid communication was difficult—Mujumdar provided immediate, critical support via fax to ensure the application's success¹⁴.

Following the appointment, the virtual mentoring relationship intensified. Recognizing the importance of external funding for a junior faculty member, Mujumdar agreed to serve as a co-investigator on Dr. Chen's early grant proposals to the Research Grant Council¹⁴. His guidance and collaboration not only secured the funding but provided peer reviewers with confidence in the project's rigor, leading to high-impact publications¹⁴. Furthermore, Mujumdar appointed Dr. Chen to the Editorial Board of *Drying Technology*, deeply integrating him into the professional society¹⁴. Today, Dr. Chen serves in major leadership roles, including Deputy Director of the Chemical and Industry Engineering Society of China (CIESC) and Chairman of the World Chemical Engineering Council¹⁴. This trajectory underscores how virtual mentoring serves as a continuous, adaptable scaffolding system throughout a researcher's career evolution.

The Trajectory of Dr. Hee Joo Poh

Dr. Hee Joo Poh's experience provides another powerful testament to the longevity and psychosocial depth of Mujumdar's mentoring. Having known Professor Mujumdar for 25 years since they first met in 2001, Dr. Poh highlights the seamless blend of personal warmth and rigorous academic direction³. Following a short-term secondment under Mujumdar's mentorship at NUS in 2004, Mujumdar guided Dr. Poh closely through a Co-Principal Investigator role for a mine ventilation project³.

Mujumdar systematically integrated Dr. Poh into the global community by facilitating visits to the Institute of Chemical Technology (Mumbai) and guiding his participation in ADC events across Hong Kong and Bangkok³. When Dr. Poh eventually took on the monumental task of organizing the 10th and 11th Asia Pacific Drying Conferences in India, he did so under the continuous virtual leadership and strategic vision of Professor Mujumdar³. Dr. Poh explicitly credits Mujumdar's "parental warmth" and empathetic understanding of human emotion as the foundational support that shaped his life and career, demonstrating that premier scientific mentorship must be deeply anchored in profound human connection³.

Elevating Mentorship to a Core Scientific Metric: The Arun S. Mujumdar Medal

The academic community has historically struggled to properly incentivize and reward the labor of mentoring, often prioritizing research output, patent generation, and grant acquisition over the cultivation of human capital. However, the immense multiplier effect of Professor Mujumdar's mentoring has necessitated institutional recognition, thereby shifting the paradigm of how academic excellence is defined and rewarded within his field.

In recognition of his unparalleled contributions, the global drying community, spearheaded by his former students and research associates, established the **Arun S. Mujumdar Medal**²⁵. First awarded at the 5th Asia-Pacific Drying Conference in Hong Kong (2007) to Professor Czeslaw Strumillo (notably, one of Mujumdar's original virtual mentors), this prestigious award is entirely unique in its criteria²⁵. It explicitly

recognizes individuals who demonstrate an outstanding combination of excellence in drying R&D, community service, and, crucially, the *mentoring of younger generations of researchers*²⁵.

Subsequent recipients, such as Professor Timothy G. Langrish of the University of Sydney, Australia, have similarly demonstrated this commitment to cultivating global talent²⁴. By institutionalizing mentoring as a core criterion for one of the field's highest honors, Professor Mujumdar's network has successfully elevated the status of professional development within the discipline. It establishes a permanent legacy that sends a clear mandate to the scientific community: true leadership and scientific excellence are not achieved solely through data generation in the laboratory, but through the dedicated, selfless cultivation of other scholars²⁵.

Conclusion

The professional development of a successful researcher is a complex, multifaceted journey that extends far beyond the mastery of laboratory techniques and statistical analysis. It requires the cultivation of creative thinking, interdisciplinary breadth, strategic career planning, robust psychosocial resilience, and deep integration into a global community of practice. Professor Arun S. Mujumdar's illustrious career provides a definitive blueprint for how these outcomes can be achieved at scale through a paradigm of mentorship characterized by empathy, intellectual humility, and absolute inclusivity.

By actively deconstructing geographical and institutional barriers through the strategic pioneering of virtual mentoring, Professor Mujumdar democratized access to elite academic guidance. He recognized that "virtual mentors"—whether accessed through published literature in the pre-internet era or through real-time digital communication today—are indispensable tools for overcoming systemic inequities in higher education and accelerating technical skill acquisition. His creation of enduring structural mechanisms, such as the International Drying Symposium (IDS) and the open-access publishing initiatives of the Transport Processes Research (TPR) Group, ensures that the democratization of knowledge and the professional socialization of novice researchers remain permanent, structural fixtures in the engineering discipline.

Ultimately, the Mujumdar mentoring model proves that the highest calling of a leading academic is not merely the generation of new scientific knowledge, but the generation of new, capable, and confident scholars. By internalizing and propagating the ideology of *Vasudhaiva Kutumbakam*, Professor Mujumdar has engineered a self-replicating, interconnected global family of researchers whose collaborative innovations and dedication to mentorship will continue to address the world's most pressing industrial and societal challenges for generations to come.

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CHAPTER 2

The Contributions and Global Impact of Professor Arun S. Mujumdar in Food and Agricultural Science and Technology

Introduction

The global agricultural and food manufacturing sectors are currently navigating unprecedented challenges at the intersection of energy scarcity, climate change, and global food security. A significant nexus of these challenges is the process of thermal dehydration. Industrial drying is an inherently energy-intensive unit operation, estimated to consume between ten and twenty percent of the total industrial energy generated globally¹. In the context of food and agricultural sciences, drying is the critical step that determines the post-harvest preservation, shelf-life, structural integrity, and nutritional retention of perishable biological commodities. Over the past five decades, the scientific transition of drying from an empirical, heuristic art into a highly optimized, physics-driven engineering discipline has been spearheaded by Professor Arun S. Mujumdar, an academic widely recognized by his international peers as the global "Drying Guru"².

The integration of advanced transport phenomena, computational fluid dynamics, and thermodynamic modeling into food dehydration technology represents a monumental leap in agricultural processing. Professor Mujumdar's comprehensive research portfolio spans the fundamental physics of moisture migration in biopolymers, the development of novel hybrid drying technologies, and the frontier applications of additive manufacturing in food systems. His impact is not confined to the laboratory; it extends deeply into industrial applications, global scientific publishing, and the pedagogical frameworks that govern chemical and food engineering curricula worldwide.

This comprehensive report meticulously evaluates the academic lineage, scientific innovations, bibliometric standing, and profound global impact of Professor Mujumdar. By dissecting his foundational contributions to superheated steam drying, his advancement of smart and hybrid dehydration techniques, his foray into 3D and 4D food printing, and his unparalleled democratization of engineering knowledge, this analysis articulates the sweeping global scale of his contributions to both academic research and industrial manufacturing.

Academic Lineage and the Philosophy of Applied Engineering

The trajectory of Professor Mujumdar's career reflects a deliberate convergence of rigorous fundamental science and pragmatic industrial application. He earned his Bachelor of Chemical Engineering degree with distinction in 1965 from the University Department of Chemical Technology (UDCT)—an institution now known as the Institute of Chemical Technology (ICT) in

Mumbai, India⁴. This foundational education instilled a deep understanding of process engineering, which he subsequently refined in North America. Relocating to Canada, he earned his Master of Engineering in 1968 and his Ph.D. in 1971, both in chemical engineering from McGill University in Montreal⁴.

A critical differentiator in Professor Mujumdar's academic philosophy is his early and sustained exposure to industrial environments. Following his doctoral studies, he did not immediately retreat into an academic silo; rather, he worked as a Research Engineer at the Carrier Technical Centre in Syracuse, New York, and subsequently as a research associate at the Pulp & Paper Research Institute of Canada³. This dual exposure to corporate research and development and applied industrial processing shaped his long-term pedagogical and research philosophies. It instilled a perspective that engineering research must not merely satisfy intellectual curiosity but must actively resolve pressing industrial bottlenecks, particularly those concerning energy efficiency and product quality⁵.

In 1975, Professor Mujumdar joined the faculty of the Department of Chemical Engineering at McGill University, where he served with distinction for a quarter of a century until 2000⁴. During this tenure, he established a formidable research group focused on transport phenomena, impinging jets, and dehydration

technologies. Recognizing the rapid economic and scientific ascent of the Asia-Pacific region, he relocated in 2000 to the National University of Singapore (NUS)⁴. At NUS, he assumed a professorship in the Department of Mechanical Engineering and subsequently served as the Founding Director of the Mineral, Metal & Materials Technology Centre (M3TC) from 2006 to 2013, fostering deep ties with regional industries⁴.

Although he formally retired from his full-time position at NUS, his academic engagement has only accelerated. He continues to hold prestigious positions, including Adjunct Professorships at McGill University and Western University in Canada, an Emeritus Professorship at the National Institute of Food Technology Entrepreneurship and Management (NIFTEM) in India, and Honorary Professorships at Jiangnan University in China and the University of Queensland in Australia³. This ongoing global engagement allows him to actively mentor a diverse, international cohort of researchers and maintain a commanding presence in the evolution of food and agricultural engineering.

Bibliometric Performance, Global Rankings, and Scientific Eminence

Quantifying the impact of a researcher whose expertise bridges chemical engineering, mechanical engineering, and food science requires a nuanced evaluation of diverse bibliometric indicators. Professor Mujumdar's publication record is both exceptionally prolific and highly influential across multiple engineering disciplines. His ability to synthesize fundamental transport phenomena with agricultural applications has resulted in a citation record that places him in the elite echelons of global scientists.

Publication Output and Citation Metrics

Professor Mujumdar is universally recognized as the world's most prolific contributor to the peer-reviewed archival literature in the field of drying science⁵. As of recent bibliometric assessments, he has authored or co-authored over 870 peer-reviewed journal articles, predominantly distributed across the fields of agricultural and biological sciences, food science, thermal fluid engineering, and materials science⁸.

The impact of this vast body of work is reflected in his staggering citation metrics. According to the scientific ranking platform Research.com (which relies on rigorous discipline-specific curation), his publications in core engineering and mechanical/aerospace domains have amassed over 40,694 citations, yielding a highly selective D-index of 104⁸. Conversely, broader databases such as Google Scholar—which aggregate citations from books, edited volumes, technical reports, and a wider array of interdisciplinary journals—record his total citations at over 78,600, corresponding to a phenomenal h-index of 135 and an i10-index of 980⁹. These figures underscore not merely productivity, but a sustained, multi-decadal relevance to active research in the field.

Global and Canadian Rankings in Engineering and Food Science

Because Professor Mujumdar's foundational degrees are in chemical engineering and his longest faculty appointments were in chemical and mechanical engineering departments, ranking platforms frequently categorize his primary discipline as Mechanical and Aerospace Engineering or Engineering and Technology. However, a massive subset of his work—specifically addressing food dehydration, phytochemical retention, and additive manufacturing of edibles—directly dictates his standing in food and agricultural sciences.

Based on the 2026 data compiled by Research.com, Professor Mujumdar's standing within the Canadian and global academic landscapes is formidable. Furthermore, his inclusion in the Stanford University and Elsevier composite database of the "World's Top 2% Scientists" validates his cross-disciplinary impact, neutralizing citation density variations between mechanical engineering and food science¹⁰.

Bibliometric Indicator / Ranking Category	Value / Rank	Source Platform
Total Peer-Reviewed Publications	874+	Research.com (2026) ⁸
Total Citations (Broad Aggregation)	78,622	Google Scholar ⁹
Total Citations (Discipline-Specific)	40,694	Research.com ⁸
H-Index / D-Index	135 / 104	Google Scholar / Research.com ⁸
Global Rank (Mechanical / Aerospace)	48th Worldwide	Research.com (2026)⁸
National Rank (Canada)	4th Nationwide	Research.com (2026) ⁸

Analysis of Highly Cited Works

A detailed examination of his most highly cited publications reveals a persistent focus on optimizing the thermal management of complex systems. While his most cited individual papers investigate the theoretical and experimental behaviors of nanofluids and phase-change materials for thermal management (e.g., "Heat transfer characteristics of nanofluids: a review," amassing over 2,800 citations), his foundational texts in food and agricultural engineering form the backbone of modern processing literature⁸.

His co-authored review on the physical and chemical pretreatments of fruits and vegetables (and their subsequent effects on drying kinetics and quality attributes) represents a seminal text in post-harvest processing⁹. Furthermore, his extensive publications analyzing the models for sorption isotherms for foods, as well as the application of artificial neural networks (ANNs) in drying technology, have accumulated hundreds of citations, proving instrumental for food scientists attempting to digitize and automate agricultural processing facilities⁸.

Foundational Contributions to Food Physics and Thermodynamics

The transition of food dehydration from a heuristic, trial-and-error procedure to a predictive engineering science requires a profound understanding of how water interacts with the biological matrices of food. Professor Mujumdar has dedicated significant research bandwidth to elucidating these thermodynamic relationships, particularly through the study of moisture sorption isotherms.

An isotherm defines the equilibrium relationship between the moisture content of an agricultural product and the water activity of its surrounding environment at a specific, constant temperature¹³. This metric is the absolute foundation for designing any dehydration process, determining shelf-life stability, and engineering

appropriate packaging. Through extensive empirical modeling of products ranging from root vegetables (carrots, potatoes) to fruits (apples, apricots), Mujumdar and his frequent collaborators (such as S. Basu and U.S. Shivhare) have critically evaluated and refined models that predict these equilibrium states⁸.

His research has demonstrated how biological materials generally exhibit Type II (sigmoidal) sorption behaviors¹³. By applying rigorous thermodynamic principles—specifically the Clausius-Clapeyron equation—his group successfully determined the isosteric heat of desorption¹³. This value represents the precise quantum of thermal energy required to break the intermolecular binding forces between water molecules and the food's biopolymer matrix. This calculation is indispensable for food engineers; it dictates the energy load required for industrial dryers and helps predict physical transitions in the food structure¹³.

Furthermore, his documentation of glass transition and stickiness kinetics has revolutionized powder design in the dairy, pharmaceutical, and nutraceutical sectors¹. When spray-drying complex food solutions into powders, an improper understanding of the glass transition temperature leads to caking, stickiness, and ultimately, the failure of the entire production run¹. Mujumdar's thermodynamic models allow manufacturers to precisely tune the inlet and outlet temperatures of spray dryers to ensure that the resulting food powders maintain their structural integrity and instantized solubility.

Advancements in Superheated Steam Drying (SSD)

Among the myriad of drying technologies advanced by Professor Mujumdar, Superheated Steam Drying (SSD) stands as one of his most transformative contributions to the industrial processing of biological materials. Traditional convective drying relies on passing heated air over a wet product; the air supplies the sensible and latent heat for evaporation, and the resulting warm, moisture-laden air is subsequently exhausted into the atmosphere¹⁶. This open-loop process is notorious for its massive thermal energy losses.

Professor Mujumdar extensively championed a radical alternative: utilizing superheated steam as the primary drying medium. In an SSD system, steam is heated above its saturation point (for instance, to 110°C or 150°C at atmospheric pressure) and directed over the wet agricultural product. As the superheated steam transfers heat to the product, it cools toward its saturation temperature, while simultaneously evaporating the intrinsic moisture of the food¹⁷. The newly evaporated moisture simply becomes additional steam, joining the circulating flow.

The physical, chemical, and operational advantages of this technology, as elucidated through Mujumdar's extensive mathematical modeling and pilot-scale testing, are profound for the food industry:

1. **Unprecedented Energy Recovery:** Because the exhaust stream consists entirely of steam (devoid of non-condensable air), the latent heat of vaporization can be recovered almost in its entirety. By utilizing mechanical vapor recompression or integrating the exhaust into a multi-effect evaporator, the net energy consumption of the drying plant drops precipitously, fundamentally altering the economics of industrial dehydration¹⁶.
2. **Oxidation Prevention and Quality Enhancement:** In an SSD environment, oxygen is completely displaced. Consequently, oxidative degradation reactions—which typically destroy heat-sensitive vitamins, lipids, and pigments in hot air drying—are entirely arrested¹⁷. This ensures the retention of vibrant colors and the preservation of sensitive phytochemicals in high-value agricultural crops.
3. **The Inversion Temperature Phenomenon:** One of the most counterintuitive aspects of SSD, which Mujumdar's group successfully modeled, is the concept of the "inversion temperature." Below a certain temperature threshold, evaporation is faster in dry air. However, once the temperature exceeds the inversion point (typically between 170°C and 250°C, depending on the specific fluid dynamics), the evaporation rate in superheated steam actually surpasses that of air due to favorable shifts in the specific heat, viscosity, and thermal conductivity of the steam¹⁶.
4. **Microbial Decontamination and Food Safety:** The high-temperature steam environment inherently acts as a sterilization mechanism. Mujumdar's research highlighted that SSD drastically reduces microbial loads, including heat-resistant *Geobacillus* spores. Critically, it has been shown to effectively reduce the concentration of

Fusarium mycotoxins, such as deoxynivalenol (DON), in contaminated grains, directly enhancing global food safety protocols¹⁸.

5. **Enhanced Porosity:** The rapid heat transfer in SSD can cause internal moisture to flash into steam, effectively "puffing" the product. This creates a highly porous microstructure, lowering bulk density and significantly improving the rehydration kinetics of the dried food, which is highly desirable for instant soups and ready-to-eat meals¹⁷.

Professor Mujumdar's work extended to the rigorous techno-economic evaluation of these systems, designing rotary, fluidized bed, and flash dryers adapted for SSD, and pushing their application beyond food into the realm of the circular bioeconomy, such as the safe, vitrified drying of municipal sludges (e.g., the Carver-Greenfield process) for use as biofuel¹⁶.

Hybrid, Smart, and Emerging Dehydration Technologies

Recognizing that the vast biological diversity of agricultural products prevents a "one-size-fits-all" approach to processing, Professor Mujumdar has been a pioneering advocate for hybrid drying technologies. Biological tissues are highly sensitive to thermal stress; prolonged exposure to convective heat leads to detrimental case-hardening (where the exterior surface forms an impermeable barrier), severe volumetric shrinkage, and the destruction of delicate cellular architectures¹⁶. To mitigate these mass transfer limitations, his research group systematically investigated the superimposition of physical and electromagnetic fields onto traditional drying mechanisms.

Electromagnetic and Field-Assisted Drying

Conventional drying relies on conduction or convection, meaning heat must slowly penetrate from the surface to the core of the food, while moisture must navigate the reverse path. By applying electromagnetic fields—specifically microwave (MW) and radio frequency (RF) energy—heat is generated volumetrically within the food²⁰. This is due to the rapid dipolar rotation and ionic conduction of the water molecules embedded within the biological tissue. Mujumdar's extensive research into microwave-assisted hybrid drying demonstrated that when electromagnetic fields are coupled with vacuum systems (e.g., microwave-vacuum freeze-drying) or spouted beds, the total processing time can be reduced by up to 50%²². This rapid, internal heat generation prevents the collapse of the cellular structure. Studies conducted with his collaborators on products like bitter melon, apples, and ginseng roots demonstrated that these hybrid methods yield products with significantly lower color differences, reduced shrinkage ratios, and superior retention of chlorophyll, flavonoids, and total phenolic contents compared to traditional hot-air drying²².

Furthermore, he explored non-thermal and targeted thermal interventions, such as electrohydrodynamic (EHD) drying and infrared (IR) radiation²⁶. EHD utilizes high-voltage electric fields to generate an "ionic wind" that effectively disrupts the saturated boundary layer of air surrounding the food surface, accelerating moisture removal at ambient temperatures²⁶. His work also proved the efficacy of combining ultrasound-assisted osmotic dehydration as a pretreatment before infrared drying (e.g., for Pakchoi stems), demonstrating that acoustic cavitation creates micro-channels in the tissue that drastically accelerate subsequent mass transfer²⁴.

Process Intensification in Particulate Drying

For granular agricultural products, grains, and food powders, Mujumdar concentrated on process intensification techniques such as impinging stream drying and pulse combustion drying¹. These technologies utilize high-velocity, highly turbulent, and sometimes pulsating gas flows to maximize the convective heat and mass transfer coefficients. By maximizing the relative velocity between the drying medium and the food particles, these dryers achieve massive evaporation rates in a fraction of the time, thereby shrinking the physical footprint of the industrial dryer and minimizing the thermal degradation of the food powder¹.

Additive Manufacturing: The Intersection of Drying and 3D/4D Food Printing

In an exceptional demonstration of scientific agility, Professor Mujumdar seamlessly integrated his decades of dehydration expertise with the nascent field of additive manufacturing, specifically the 3D and 4D printing of foods⁸. As consumer demand pivots toward personalized nutrition and sustainable protein

sources, extrusion-based 3D food printing has emerged as a disruptive manufacturing paradigm²⁸. This technology allows for the precise, layer-by-layer construction of customized foods utilizing plant-based proteins (such as soy or pea isolates), starches, and upcycled agricultural byproducts¹¹.

However, the primary engineering hurdle in 3D food printing is structural fidelity. A freshly extruded hydrogel or protein paste is inherently mechanically unstable; it must be carefully dehydrated to maintain its shape, arrest microbial growth, and achieve the desired organoleptic texture. Professor Mujumdar's recent research dissects the critical role of drying dynamics within these 3D-printed matrices. Differential drying rates across complex geometries can induce severe internal stresses, leading to warping, layer delamination, and structural collapse²³. His application of digital twins and artificial intelligence (AI) to simulate coupled heat and mass transfer allows manufacturers to fine-tune drying protocols dynamically, correcting defects in real-time based on the rheological properties of the printing ink²³.

More revolutionary is his foray into **4D food printing**²³. In 4D printing, a 3D-printed food construct is explicitly designed to undergo a programmed, spontaneous transformation in shape, color, flavor, or texture over time, triggered by an external stimulus such as pH, heat, light, or moisture²³. For instance, Mujumdar and his collaborators investigated the extrusion printing of sago starch blended with curcumin (turmeric powder)²⁹. When this printed construct was exposed to varying concentrations of sodium bicarbonate (a pH trigger), it exhibited a time-dependent, spontaneous color shift from yellow to orange-red²⁹.

By deliberately manipulating the internal moisture gradients and utilizing stimuli-responsive biopolymers, researchers can print flat, space-saving structures that spontaneously fold, curl, or transform into complex 3D shapes upon rehydration or boiling²³. Mujumdar's work dictates that the synergistic integration of drying science with advanced AI monitoring (such as near-infrared spectroscopy and infrared thermography) is the key to unlocking the commercial viability of these "super reconstructed foods" (SRFs)²³.

Pedagogical Legacy: Democratizing Dehydration Science

Professor Mujumdar's legacy is equally defined by his relentless dedication to pedagogy, knowledge dissemination, and the cultivation of an inclusive global scientific community. He identified early in his career that drying technology was a fragmented discipline, with valuable insights siloed disparately across the chemical, agricultural, pharmaceutical, and pulp and paper industries.

The Handbook of Industrial Drying

To unify this fragmented knowledge base, Professor Mujumdar conceptualized, authored, and edited the *Handbook of Industrial Drying*³². Initially published in 1987, and now in its extensively revised fourth edition (2014), this monumental compilation is universally acknowledged as the definitive "bible" of drying technology³³. Spanning over 1,300 pages and synthesizing the expertise of dozens of international contributors, the handbook offers an exhaustive treatment of process calculations, dryer typologies, and specific agricultural applications³³. It serves as the standard reference text utilized by academic faculties and industrial design firms globally, directly influencing the engineering of modern agricultural processing facilities.

Leadership of Drying Technology – An International Journal

In 1982, Professor Mujumdar co-founded *Drying Technology – An International Journal* alongside Dr. Carl W. Hall, officially assuming the mantle of Editor-in-Chief in 1988¹. Under his continuous leadership spanning over three decades, the journal evolved from a niche archival outlet into a multidisciplinary powerhouse¹. Today, it boasts an Impact Factor of 2.7, a Scopus CiteScore of 7.1, and has published over 5,500 articles accumulating more than 150,000 citations¹.

Mujumdar utilized the journal strategically to direct global research toward critical societal needs. He championed special issues focusing on energy-efficient drying, nano-scale droplet kinetics, and the stabilization of functional foods and probiotics¹. Crucially, he used the platform to democratize scientific publishing. By establishing a rigorous yet constructive peer-review ecosystem, he provided a highly visible platform for researchers from emerging scientific hubs in Asia, Eastern Europe, and Latin America, actively shaping the careers of thousands of early-stage agricultural engineers in the developing world¹.

The Global Symposia: IDS and ADC

Recognizing that scientific advancement requires physical networking and cross-pollination of ideas, Professor Mujumdar founded the biennial *International Drying Symposium (IDS)* series in 1978 at McGill University⁴. The IDS quickly became the premier global forum for dehydration science, bridging the historical divide between academic theoreticians and industrial practitioners⁴⁰. In 1997, acknowledging the explosive economic and scientific growth of the Asian continent, he co-founded the *Asia Pacific Drying Conference (ADC)* series alongside Professor A. Kamaruddin⁴. Through these symposia, Mujumdar effectively architected a cohesive, interactive global community of researchers where none had previously existed.

The Transport Processes Research (TPR) Group and the Free E-Books Initiative

Professor Mujumdar's altruistic philosophy of academic service culminates in the Transport Processes Research (TPR) Group, a virtual network of researchers spanning over twenty countries⁵. Acknowledging the severe financial barriers that prevent researchers, students, and practitioners in developing economies from accessing state-of-the-art technical literature, Mujumdar initiated a revolutionary open-access publishing project through the TPR network³⁹. He coordinated the authoring, rigorous peer-review, and editing of numerous specialized e-books and made them freely available for download on his personal website³⁹. The catalog includes highly relevant titles such as the three-volume *Drying of Foods, Vegetables and Fruits*, *Spray Drying Technology*, *Solar Drying: Fundamentals, Applications, and Innovations*, and *Processing and Drying of Tropical Fruits*³⁹. This initiative bypasses the restrictive paywalls of commercial publishers, ensuring that agricultural engineers, local farmers, and food entrepreneurs in the Global South possess unrestricted access to the knowledge required to reduce post-harvest losses and optimize their local food processing operations⁴⁰.

Industrial Impact and the Circular Bioeconomy

The translation of academic theory into industrial practice is the ultimate metric of engineering success. Because drying operations are responsible for 10% to 20% of global industrial energy consumption, the implementation of Mujumdar's optimized protocols—such as SSD, microwave-vacuum drying, and smart step-down relative humidity control—has allowed processing plants to slash their energy consumption by 15% to 40%¹. This massive reduction in thermal energy reliance translates directly to millions of tons of averted greenhouse gas emissions, aligning agricultural manufacturing with global sustainability and climate change mitigation targets¹.

His influence is deeply embedded in the commercial sector through decades of industrial consultations and joint academic-industry initiatives. A prime example is his extensive collaboration with Jiangnan University (via Professor Min Zhang) and the Haitong Food Group Co., Ltd. in China, a partnership that has flourished for over twenty years⁷. By leading National Key Projects, Mujumdar and his Chinese counterparts developed smart, precise drying equipment for fruits and vegetables²². These advanced technologies, protected by over 230 invention patents, have been integrated into commercial production lines, resulting in

higher retention of antioxidants in dried produce and significant cost savings²². His advisory footprint extends globally, encompassing senior technology consultations for multinational conglomerates such as PepsiCo (USA), as well as numerous specialized technology firms including Landscape Food Co. and The Wild Food Co.⁷.

Furthermore, his expertise in moisture removal has been pivotal in advancing the circular bioeconomy. He applied his drying principles to the dewatering and vitrification of municipal and industrial sludges, evaluating technologies like the Carver-Greenfield process⁸. By converting highly aqueous waste sludges into dried, combustible pellets without the leaching of toxic chemicals, his work provides a scalable pathway for generating sustainable biofuels while resolving critical waste management bottlenecks in rapidly expanding urban centers¹⁶.

Global Mentorship, Strategic Cooperation, and State Honors

Professor Mujumdar is revered by his colleagues as an exceptional mentor, possessing a rare capacity to identify, cultivate, and elevate young scientific talent. Over his long career at McGill, NUS, and various adjunct institutions, he has personally supervised over 75 Ph.D. students and mentored more than 35 postdoctoral fellows⁴. His academic progeny, including prominent figures such as Min Zhang (Jiangnan University), Guohua Chen (City University of Hong Kong), Sakamon Devahastin (King Mongkut's University of Technology Thonburi), and Bhesh Bhandari (University of Queensland), now populate the leadership ranks of academic institutions and corporate boardrooms worldwide⁸.

To formalize the recognition of his unparalleled impact on human capital development, the international drying community instituted the "**Professor Arun S. Mujumdar Medal for Excellence in Drying and Outstanding Mentorship**" in 2007⁴. Awarded annually at the IDS and ADC conferences, this medal represents the highest honor within the discipline, perpetually linking his legacy to the pursuit of scientific excellence and academic generosity.

Strategic International Cooperation and Chinese State Recognitions

Professor Mujumdar's ability to transcend geopolitical boundaries to foster collaborative, impactful science is most profoundly demonstrated by his relationship with the People's Republic of China. Recognizing China's latent potential and its pressing need for advanced agricultural processing technologies during the nation's rapid economic ascent in the 1980s, Mujumdar engaged deeply with Chinese academia and industry².

Over three decades, he served as a crucial bridge, bringing Chinese domestic research to the global stage via the IDS and *Drying Technology* journal, while simultaneously infusing Chinese engineering with advanced, energy-efficient methodologies⁴⁷. He held honorary professorships at six Chinese universities and co-supervised numerous Chinese doctoral students who subsequently drove the modernization of China's food drying industry⁵.

In recognition of these transformative, decade-spanning contributions, the Chinese state bestowed upon him its absolute highest honors. In January 2014, in a grand ceremony at the Great Hall of the People in Beijing attended by the Premier and the cabinet, he was awarded the **National Award for International Cooperation in Science and Technology**⁴⁷. Later that same year, in September 2014, he received the **Friendship Award**, the most prestigious honor granted by the Chinese government to foreign nationals for outstanding contributions to China's economic and social progress⁴⁷. He also received the Jiangsu Province International Science and Technology Cooperation Award in 2013, an honor for which he was the sole academic selected by a committee of government and industry leaders⁶.

His recognitions span the globe. In his native India, his alma mater, the Institute of Chemical Technology (ICT), awarded him the prestigious Platinum Award in 2009 for lifetime achievement and instituted a Distinguished Visiting Fellowship in his name⁷. He has been awarded Doctor *Honoris Causa* degrees by Lodz Technical University in Poland and the University of Lyon 1 in France⁴. Furthermore, he is a Life Fellow of the American Society of Mechanical Engineers (ASME) and the Chemical Institute of Canada (CIC), solidifying his permanent standing in the pantheon of global engineering elites³.

Conclusion

The evolution of food and agricultural processing over the last half-century is inextricably linked to the intellectual output, strategic vision, and tireless global engagement of Professor Arun S. Mujumdar. By systematically applying the rigorous laws of fluid mechanics, thermodynamics, and transport phenomena to the biological complexities of food, he successfully decoupled dehydration from its empirical, energy-wasting past. His pioneering innovations—ranging from the energy recovery paradigms of superheated steam drying to the volumetric heating of hybrid electromagnetic systems, and extending to the futuristic architectures of 4D food printing—have provided the food industry with the technical blueprints required to navigate an era defined by resource scarcity and climate change.

Beyond his staggering bibliometric achievements, his true legacy is defined by an unwavering commitment to the democratization of scientific knowledge. Through his visionary leadership of the *Drying Technology* journal, the establishment of the International Drying Symposium series, and his unprecedented initiative to distribute high-level engineering texts freely to the developing world, Professor Mujumdar has ensured that the science of food preservation is accessible across all economic and geographic divides.

He stands as the undisputed architect of the modern global drying community. His synthesis of theoretical brilliance, industrial pragmatism, and selfless mentorship will continue to secure the global food supply chain, reduce industrial carbon footprints, and inspire generations of agricultural, chemical, and food engineers for decades to come.

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CHAPTER 3

The Evolution of Food Drying Science and Technology: A Comprehensive Analysis of Professor Arun S. Mujumdar's Four-Decade Research Legacy

Introduction to the Industrial Drying Paradigm

Drying is arguably the oldest, most ubiquitous, and most diverse chemical engineering unit operation, fundamental to the preservation, transport, and stabilization of products across the agricultural, pharmaceutical, ceramic, and chemical sectors. Despite its fundamental necessity, the process of thermal dehydration is notoriously energy-intensive, accounting for 10% to 25% of national industrial energy consumption in developed economies such as the United States, Canada, the United Kingdom, and Germany¹. For much of industrial history, the design, selection, and operation of drying equipment were relegated to empirical trial-and-error, driven largely by vendor experience and rudimentary heuristics rather than fundamental transport phenomena. Over the past four decades, however, the discipline has undergone a profound paradigm shift, evolving into a rigorous, predictive, and highly interdisciplinary science capable of addressing the complex demands of the modern global economy.

At the vanguard of this scientific and engineering transformation is Professor Arun S. Mujumdar. Widely recognized in the global academic and industrial communities as the "Drying Guru," Professor Mujumdar has single-handedly shaped the theoretical and applied frameworks of thermal dehydration, particularly in the realm of food science and technology⁴. Graduating with a degree in chemical engineering from the University Department of Chemical Technology (UDCT, now the Institute of Chemical Technology) in Mumbai in 1965, and subsequently earning his Ph.D. from McGill University in Canada, his career spans over five decades of continuous, prolific research and innovation⁵. His extensive body of work encompasses the fundamental thermodynamics of moisture removal, the development of advanced hybrid drying technologies, the preservation of heat-sensitive bioactives in foods, and the modern integration of artificial intelligence (AI), machine learning (ML), and additive manufacturing into food engineering⁸.

This comprehensive report synthesizes Professor Mujumdar's monumental contributions to food science and technology. By systematically analyzing his research across thermal dehydration mechanisms, fruit and vegetable preservation, food quality optimization, emerging smart materials (3D/4D printing), and intelligent process control, this analysis highlights the second and third-order impacts of his work. Furthermore, it details how his global leadership—most notably through the *Handbook of Industrial Drying*, his tenure as Editor-in-Chief of the *Drying Technology* journal, and the founding of the International Drying Symposium (IDS) series—has permanently reconfigured the global food processing industry¹².

Fundamental Principles of Thermal Dehydration and Transport Phenomena

To fully appreciate the depth of recent advancements in food drying, one must first examine the complex transient heat, mass, and momentum transfer mechanisms that govern the process.

The conversion of a solid, semi-solid, or liquid feedstock into a stable solid product via evaporation or sublimation is an extraordinarily complex multiphysics phenomenon³. Drying times can range from 0.25 seconds for thin materials like tissue paper to over five months for certain hardwood species, while product porosities can range from near zero to 99.9%³.

Transport Phenomena in Heterogeneous Porous Food Media

Food materials are highly heterogeneous, anisotropic, and hygroscopic porous media. During the initial constant-rate drying period, unbound surface moisture is evaporated, and the drying rate is predominantly controlled by external convective heat transfer from the drying medium (usually hot air) to the material surface, with virtually no internal mass transfer resistance¹⁵.

However, as the surface moisture is depleted, the process enters the falling-rate period, where the rate-limiting step transitions entirely to the internal mass transfer of moisture migrating from the core to the surface. Professor Mujumdar's foundational research has emphasized the application of Fick's second law of diffusion to accurately model this effective moisture diffusivity, highlighting that this parameter is not static but highly dependent on localized structural changes, such as macroscopic shrinkage, pore formation, and localized temperature gradients¹⁶.

Furthermore, the thermodynamic properties of air-water mixtures and the moisture sorption isotherms of food products strictly dictate the theoretical limits of dehydration. The non-linear relationship between equilibrium moisture content and water activity (a_w) is critical for food engineers because lowering a_w effectively halts microbial proliferation and exponentially slows moisture-mediated deteriorative chemical reactions¹⁸. Early computational modeling efforts by Professor Mujumdar and his global collaborators demonstrated that understanding the binding energy of water within the food polymer matrix is essential for optimizing variable drying schedules and preventing case-hardening—a detrimental phenomenon where a dry, impermeable, and glassy outer shell traps internal moisture, thereby halting further dehydration and leading to internal spoilage¹⁵.

Glass Transition and the Physical State of Food Polymers

A critical component of Professor Mujumdar's work involves the integration of polymer science into food engineering, specifically regarding the glass transition temperature (T_g) of amorphous food components. The removal of water from cellular tissues inherently leads to a loss of turgor pressure, resulting in macroscopic volume reduction, or shrinkage. The extent and nature of this shrinkage are heavily dependent on the material's thermodynamic state in relation to its T_g .

When a food polymer is dried at temperatures significantly above its T_g , it exists in a rubbery, highly mobile state. In this rubbery state, the solid matrix lacks the structural rigidity to support its own pore network against the capillary forces exerted by evaporating liquid water, which facilitates severe structural collapse, loss of porosity, and poor ultimate rehydration capacity²⁰. Conversely, deploying rapid drying techniques that drop the moisture content quickly—thereby elevating the local a_w above the product temperature—forces the material into a brittle, glassy state. Once in the glassy state, molecular mobility is kinetically arrested, which helps preserve the porous architecture and prevents catastrophic shrinkage²⁰. Understanding these phase transitions has guided the powder design and particle formation kinetics in the dairy, nutraceutical, and pharmaceutical sectors, enabling the engineering of spray-dried and freeze-dried products that resist caking and stickiness during storage²³.

Innovations in Fruit and Vegetable Preservation and Pretreatment

Fruits and vegetables pose a unique and formidable challenge in commercial dehydration operations due to their high initial moisture content (often exceeding 80%), the presence of highly heat-sensitive nutrients (e.g., ascorbic acid, carotenoids, flavonoids), and their intense susceptibility to both enzymatic and non-enzymatic browning¹⁸. Traditional continuous hot-air drying necessitates prolonged exposure to elevated temperatures and oxygen, which universally results in the severe degradation of vitamins, catastrophic structural collapse, and the development of off-flavors and undesirable dark pigmentation¹⁸. To overcome these inherent limitations, a vast segment of Professor Mujumdar's research trajectory has concentrated on developing advanced pretreatments and highly optimized hybrid drying technologies.

The Evolution of Thermal Blanching

Blanching is an essential preparatory step designed primarily to inactivate quality-deteriorating bio-enzymes, specifically polyphenol oxidase (PPO) and peroxidase (POD), which rapidly catalyze oxidative browning reactions upon tissue injury¹⁸. Conventional hot-water blanching, while highly effective at

enzyme inactivation and destroying surface microorganisms, suffers from severe technological drawbacks: it induces intense nutrient leaching, leads to the loss of water-soluble pigments and aromas, and causes excessive texture softening²⁶.

In response to these deficiencies, Professor Mujumdar and his frequent collaborators (notably Professor Min Zhang at Jiangnan University and Professor Hong-Wei Xiao at China Agricultural University) spearheaded the investigation and industrial scale-up of advanced impingement blanching technologies, namely High-Humidity Hot Air Impingement Blanching (HHAIB) and Superheated Steam Impingement Blanching (SSIB)¹⁷.

SSIB utilizes high-velocity jets of superheated steam to rapidly and uniformly raise the surface temperature of the agricultural produce. In landmark studies on line peppers and sweet potatoes, researchers demonstrated that a brief SSIB pretreatment (e.g., 3 minutes at 110°C) effectively damages the hydrophobic waxy epidermal cuticle of the fruit. This targeted structural disruption drastically reduces the resistance to moisture transfer, accelerating the subsequent drying process by over 30%¹⁷. Moreover, because the superheated steam creates a localized low-oxygen environment around the produce, the oxidative degradation of red pigments, vitamin E, and carotenoids is massively suppressed compared to untreated or conventionally blanched samples¹⁷. The thermal activation energy of drying for SSIB-pretreated samples is measurably lowered, proving that diffusion remains the dominant physical mechanism governing moisture movement, but with significantly less anatomical resistance¹⁷.

Acoustic Cavitation and Non-Thermal Pretreatments

Simultaneously, the quest to preserve the thermodynamic integrity of delicate cellular structures has driven heavy investigation into non-thermal physical pretreatments. High-intensity ultrasound (operating typically between 20 kHz and 100 kHz) generates acoustic cavitation—the rapid formation, expansion, and violent implosive collapse of micro-bubbles within the liquid phase of the plant tissue²⁸.

This repeated mechanical stress induces the "sponge effect," creating micro-channels and causing cellular disruption that massively enhances effective moisture diffusivity during subsequent osmotic dehydration or convective drying²⁸. Professor Mujumdar's collaborative analyses have demonstrated that multi-frequency ultrasound treatments (such as tri-frequency ultrasound) are vastly superior to mono-frequency modes. Multi-frequency ultrasound creates an optimal, highly interconnected porous matrix that resists excessive macroscopic shrinkage, ensuring significantly better textural qualities and rehydration ratios in dried pineapples, sea cucumbers, and other biomaterials²⁹. While ultrasound significantly reduces drying times (frequently by 20% to 50%), researchers carefully balance the intensity to prevent the excessive generation of free radicals that could degrade phenolic compounds²⁸.

Furthermore, emerging non-thermal technologies like cold plasma pretreatment, pulsed electric fields, and high hydrostatic pressure have been extensively reviewed and mathematically modeled by the Mujumdar network to increase cell membrane permeability and enhance microbial decontamination prior to thermal drying, thereby bridging the gap between food safety and energy-efficient processing²¹.

Pretreatment Method	Primary Mechanism of Action	Effects on Dehydration Kinetics and Quality	Key Advantages
Hot Water Blanching	Thermal denaturation of PPO and POD enzymes.	Moderate increase in drying rate; severe loss of soluble nutrients.	Simple, low cost, effective enzyme inactivation.
SSIB / HHAIB	High-velocity steam impingement; disrupts waxy	30%+ reduction in drying time; high retention of	Low oxygen environment prevents oxidation;
	epidermis.	pigments and vitamins.	minimal nutrient leaching.
High-Intensity Ultrasound	Acoustic cavitation; creates microchannels (sponge effect).	20%–50% reduction in drying time; increases effective moisture diffusivity.	Non-thermal; prevents thermal degradation of antioxidants; improves rehydration.
Cold Plasma	Generation of reactive species; modifies cellular surface energy.	Enhances surface hydrophilicity; increases drying rate.	Highly effective microbial decontamination; zero thermal damage.

Osmotic Dehydration and Hybrid Integration

Osmotic dehydration remains a cornerstone of energy-efficient food processing. The technique involves immersing the biomaterial in a hypertonic solution (e.g., concentrated sucrose, sodium chloride, or maltodextrin), utilizing the inherent osmotic pressure gradient to extract 10% to 70% of the tissue's initial water content at ambient or slightly elevated temperatures, crucially without triggering a phase change¹⁸. By removing a substantial portion of the moisture load prior to initiating thermal drying, the total latent heat energy requirement is drastically reduced, and the thermal damage to bioactive compounds is heavily mitigated¹⁸.

To further optimize the entire dehydration supply chain, hybrid technologies have been developed that combine differing, complementary modes of heat and mass transfer. Microwave-assisted freeze-drying (MFD) is a prominent example of this synergistic approach. While conventional freeze-drying

(lyophilization) yields exceptional product quality by sublimating ice directly to vapor under high vacuum, it is severely hindered by extremely slow drying rates and exorbitant capital and operating costs, largely due to poor conductive heat transfer through the progressively thickening, highly insulative dry porous layer³³.

The application of microwave energy directly addresses this bottleneck by providing volumetric heating. Microwaves penetrate the dry layer and couple directly with the dipole moments of the ice core, sublimating the moisture internally and bypassing the conductive resistance. This hybrid approach has been shown to reduce total freeze-drying times by up to 50% while maintaining the pristine structural fidelity required for high-value biologicals and premium foods⁸. Similarly, radio frequency (RF) heating has been coupled with hot air drying (RFHAD). Because RF energy generates volumetric heat via molecular friction, it forces internal moisture to migrate rapidly to the surface, where the convective hot air easily sweeps it away. RFHAD significantly reduces drying times for products like restructured bitter melon and apple chips, simultaneously maximizing antioxidant capacity, chlorophyll retention, and total flavonoid content by minimizing the duration of thermal exposure³⁴.

Engineering the Quality of Dried Foods: Microstructure and Bioactives

The overarching objective of modern food drying has irrevocably transitioned from mere moisture removal to the precise, intentional engineering of product quality. Quality in this context is a multifaceted parameter encompassing sensory attributes (color, flavor, texture), nutritional density (retention of heat-labile vitamins, antioxidants, polyphenols), and physical functionality (rehydration capacity, bulk density, flowability, and dissolution kinetics)³⁵.

Intermittent Drying: A Thermodynamic Balancing Act

Continuous convective drying frequently subjects the exterior of a food product to harsh, elevated temperatures long after the surface moisture has evaporated, leading to severe thermal degradation and non-enzymatic browning (the Maillard reaction). Recognizing the inherent inefficiency of this approach, Professor Mujumdar has extensively championed the theory and industrial application of intermittent drying¹⁹.

Intermittent drying involves applying heat input—whether convective, microwave, or infrared—in cyclical pulses, separated by intentional resting or "tempering" periods³⁸. During the active heating phase, moisture is evaporated from the surface, creating steep internal moisture and temperature gradients. If heating were continuous, the surface would rapidly dry out, cross its glass transition temperature, and case-harden. However, during the tempering period (where heat is removed or significantly reduced), the internal moisture is allowed time to diffuse from the wet core to the dry surface via capillary action and diffusion, effectively re-wetting the exterior³⁸.

This redistribution ensures that when the next heating cycle commences, evaporation occurs at the surface once again, maximizing the mass transfer potential while keeping the overall product temperature uniformly low. Research has definitively demonstrated that optimized intermittent microwave convective drying (IMCD) achieves superior ascorbic acid and total polyphenol retention compared to continuous drying¹⁹. For instance, in kiwifruit samples, specific microwave power ratios (e.g., 20 seconds on, 80 seconds off) provided ideal conditions that resulted in the highest ascorbic acid retention (3.944 mg/g dry matter), the lowest color degradation, and a highly desirable porous microstructure, entirely circumventing the localized overheating (hot spots) that typically plague continuous microwave processing¹⁹. By matching the energy input directly to the instantaneous drying kinetics and internal moisture diffusivity of the material, intermittent drying represents a monumental leap in both product quality and thermodynamic energy efficiency³⁸.

Superheated Steam Drying (SSD): A Paradigm of Process Sustainability

One of the most consequential technological advancements heavily researched, modeled, and championed by Professor Mujumdar is the industrial maturation of Superheated Steam Drying (SSD). Although the foundational concept originated in Germany over a century ago, its widespread technical deployment was historically hindered by severe engineering challenges related to system leak-proofing, continuous feeding and discharge mechanisms under pressure, and the management of initial condensation¹⁰. Through

decades of rigorous computational modeling and pilot-scale empirical research, the Mujumdar network has positioned SSD as a pinnacle of sustainable chemical engineering.

The Physics and Advantages of Superheated Steam

In SSD, superheated steam replaces conventional hot air or combustion flue gases as the convective drying medium¹⁵. The substitution of air with steam fundamentally alters the physics and chemistry of the dehydration process. Most importantly, because the drying environment is entirely devoid of oxygen, oxidative degradation reactions are completely eliminated. This leads to the unparalleled preservation of color, prevention of lipid oxidation in high-fat foods, and the elimination of oxidative browning¹⁰. Furthermore, the lack of oxygen completely nullifies the risk of fire and catastrophic dust explosions, which is a critical safety and regulatory advantage when drying highly combustible fine powders, organic municipal sludges, or biomass biofuels¹⁰. Thermodynamically, SSD exhibits a highly counterintuitive and unique phenomenon known as the *inversion temperature*. While one might assume that dry air would always evaporate water faster than pure steam, above a specific temperature threshold (the inversion temperature), the evaporation rate of water into superheated steam actually surpasses the evaporation rate into dry air under identical mass flow conditions¹⁵. This occurs because the resistance to mass transfer in a pure vapor environment is fundamentally different from diffusion through a binary air-vapor boundary layer; in pure steam, there is no diffusional resistance of vapor through a stagnant air film.

Furthermore, the continuous evolution of steam from within the interior of the food product causes internal boiling. This internal pressure generation physically expands the elastic wet solid during the early stages of drying, preventing macroscopic shrinkage and creating a highly porous, open microstructure. Consequently, the bulk density of SSD products is lower, and their rehydration behavior is vastly superior to hot-air-dried equivalents¹⁵. The high heat transfer coefficient of superheated steam also ensures simultaneous pasteurization, sterilization, and deodorization of the foodstuff, yielding a microbiologically pristine final product¹⁰.

Perhaps the most significant industrial and environmental advantage of SSD is its immense energy recovery potential. In conventional hot air drying, the latent heat of vaporization supplied to the product is lost as hot, humid air is exhausted into the atmosphere. In SSD, the exhaust gas is pure steam. The latent heat contained in this exhausted vapor can be almost entirely recovered via condensation in a heat exchanger or upgraded through mechanical vapor recompression (MVR) for use elsewhere in the processing plant, rendering the net energy consumption of the actual drying process remarkably low¹⁵.

Low-Pressure Superheated Steam Drying (LPSSD)

A notable limitation of atmospheric SSD is that, at 1 bar of pressure, the product temperature inevitably reaches and sustains 100°C during the entire constant-rate drying period¹⁵. While acceptable for robust materials like coal, wood, or certain meats, maintaining 100°C can cause irreversible melting, severe starch gelatinization, or massive thermal damage in highly heat-sensitive biomaterials, pharmaceutical precursors, and delicate fruits¹⁵.

To brilliantly circumvent this thermodynamic limitation, Low-Pressure Superheated Steam

Drying (LPSSD) was developed to operate under vacuum conditions. By systematically lowering the operating pressure inside the drying chamber, the saturation temperature (boiling point) of the steam is depressed. This allows the system to leverage all the benefits of oxygen-free, pure-vapor drying at much lower, non-destructive temperatures (e.g., 60°C–70°C). This LPSSD innovation has proven highly effective and economically viable for drying premium agricultural products, exotic tropical fruits, and medicinal herbs where the absolute maximum retention of volatile aromatic flavor profiles, sensitive bioactives, and complex secondary metabolites is mandatory for market viability¹⁹.

Additive Manufacturing and the Frontier of 3D/4D Food Printing

As the global food industry continuously gravitates toward customized personalized nutrition, decentralized manufacturing, and zero-waste sustainability, the convergence of additive manufacturing (3D

printing) and traditional food engineering has opened explosive new research frontiers. Professor Mujumdar, alongside leading global research teams, has made seminal, highly cited contributions to understanding the post-processing thermodynamics and formulation rheology required for 3D and 4D printed foods⁸.

Super Reconstructed Foods (SRFs) and the Role of Drying

3D food printing, or food additive manufacturing, generally utilizes Extrusion-Based 3D Printing (DIW - Direct Ink Writing). This involves the highly precise, layer-by-layer robotic deposition of viscoelastic food inks—composed of hydrogels, modified starches, cellulose nanocrystals, and protein isolates—to create complex, digitally designed geometries. This technology enables the fabrication of Super Reconstructed Foods (SRFs)—products meticulously engineered to possess specific nutritional profiles, controlled chewiness/texture, and aesthetic appeal that go far beyond their natural macroscopic state⁴³.

A primary and deeply impactful application of SRFs is the development of visually appetizing, pureed-texture meals for elderly patients or individuals suffering from dysphagia (clinical swallowing difficulties)⁴⁵. Traditionally, dysphagia diets consist of unappealing, amorphous purees that lead to appetite loss and malnutrition. By precisely 3D printing pureed tuna (protein), pumpkin (fruit), and beetroot (vegetable) into the exact visual shape of a fish, nutritional intake and psychological satisfaction are drastically improved⁴⁵.

However, the thermodynamic stabilization of these extruded 3D structures requires precise post-printing processing. The drying step is absolutely paramount in determining the mechanical integrity, shape fidelity, and final water activity of the printed construct⁸. Traditional convective drying causes massive, anisotropic shrinkage due to uneven moisture gradients, leading to severe warping, layer delamination, and the total collapse of the 3D-printed geometry.

Consequently, Professor Mujumdar's analyses indicate that freeze-drying and refractance window drying are currently heavily favored for delicate, protein- or polysaccharide-based printed constructs, as they perfectly preserve shape fidelity. Microwave-assisted drying has also shown immense promise in accelerating moisture removal while maintaining internal structural homogeneity, reducing total drying times for 3D printed objects by up to 50%⁸.

The Transition to 4D Food Printing and Smart Materials

4D printing elevates additive manufacturing by introducing time as the fourth dimension. In 4D printing, 3D-printed constructs are programmed with "smart," stimuli-responsive materials that autonomously transform in shape, color, flavor release, or texture over time in direct response to specific external environmental triggers (e.g., shifts in pH, temperature variations, moisture absorption, or microwave electromagnetic fields)⁴⁶.

Professor Mujumdar's collaborative research network has pioneered the application of 4D printing within the food sector. For instance, landmark studies have successfully utilized sago starch blended with turmeric powder (rich in curcumin) as a functional 3D-printable ink. When this precisely printed construct is subsequently exposed to varying pH levels (via immersion in sodium bicarbonate solutions), it undergoes a spontaneous, programmed, and concentration-dependent color transformation from a pale yellow to a vibrant orange-red⁴⁹. This capability to program spontaneous aesthetic changes holds massive potential for interactive, customized food products and molecular gastronomy.

Furthermore, moving beyond direct consumption, 4D printing is revolutionizing food packaging and supply chain logistics. Researchers have developed 4D-printed deformation labels designed to autonomously monitor the freshness and quality of respiring climacteric fruits during storage and transit. These smart labels are formulated using methacrylic anhydride grafted konjac glucomannan (MAKGM) and essential oil emulsions. Crucially, they simultaneously change both shape (microstructural morphing) and color in direct response to shifting humidity and carbon dioxide levels emitted by the ripening fruit inside the packaging⁴⁷. By introducing this dual-response mechanism, these 4D labels act as highly accurate, dynamic, and visual non-destructive quality sensors. When integrated with machine learning image recognition models (such as MobileNet, which achieved 97% recognition accuracy), these labels outperform traditional

cast or 3D-printed versions, enabling automated, intelligent warnings regarding food spoilage across the global supply chain⁴⁷.

Printing Dimension	Material Characteristics	Processing Challenge	Primary Application in Food Science
3D Printing	Viscoelastic inks (hydrogels, starches, purees); static geometry.	Anisotropic shrinkage and layer delamination during post-print drying.	Super Reconstructed Foods (SRFs); dysphagia diets; personalized nutrition.
4D Printing	Smart, stimuli-responsive polymers (e.g., curcumin,	Programming the precise rate and trigger threshold of the transformation.	pH-triggered color shifting foods; programmable texture release
	MAKGM).		during cooking.
4D Active Packaging	Moisture/CO ₂ responsive biopolymers with embedded bioactives.	Ensuring stable, controlled release of bioactives without premature deformation.	Dual-response (shape/color) intelligent deformation labels for spoilage tracking.

Artificial Intelligence, Machine Learning, and Process Sustainability

The inherent non-linearity and thermodynamic complexity of industrial drying processes—characterized by simultaneously coupled transient heat, mass, and momentum transfer, intimately accompanied by dynamic structural and phase changes—make traditional mechanistic mathematical modeling computationally exorbitant and often highly inaccurate outside of strict, ideal laboratory conditions⁵⁰. The integration of Artificial Intelligence (AI) and Machine Learning (ML) represents a paradigm shift from rigid, empirical heuristics to predictive, adaptive, and autonomous smart drying systems⁹.

Artificial Neural Networks (ANN) in Non-Linear Drying Control

Artificial Neural Networks (ANN), particularly multilayer perceptrons utilizing back-propagation updating algorithms, have been extensively and successfully applied to map the highly complex input-output dynamics of thermal drying systems²⁴. ANNs possess the profound ability to recognize hidden patterns, clustering, and noise within high-dimensional data without requiring an explicit, first-principles mathematical understanding of the underlying physical mechanisms. Professor Mujumdar's comprehensive reviews and direct experimental applications have definitively demonstrated that well-trained ANNs can

accurately predict real-time internal moisture content, final product quality parameters, and cumulative energy consumption based on fluctuating input vectors like inlet air temperature, bed temperature, and absolute humidity¹¹. For example, in the notoriously difficult drying of high-moisture olive oil extraction byproducts (alperujo) in continuous fluidized bed dryers, researchers utilized a simple three-layer perceptron (3 inputs, 4 hidden nodes, 1 output). The resulting ANN model seamlessly predicted the output solid moisture with a prediction error of just 4.5%, vastly outperforming computationally heavy traditional two-phase or three-phase mechanistic fluid dynamics models⁵².

Computer Vision, Bionic Sensors, and Digital Twins

Modern smart drying systems now flawlessly integrate AI models with advanced, high-resolution sensor arrays—such as computer vision cameras, electronic noses (e-noses), and near/mid-infrared (NIR/MIR) hyperspectral imaging. These biomimetic technologies facilitate the continuous, non-destructive, real-time monitoring of critical quality parameters, such as surface color degradation, microscopic shrinkage, moisture distribution, and aromatic volatile loss during the active drying process⁹. Instead of relying on static, fixed-time drying schedules that routinely result in overdrying and severe nutrient destruction, AI algorithms dynamically process this high-volume sensor data to autonomously adjust the drying parameters in real-time (e.g., rapidly modulating microwave power density or altering the hot air velocity)⁹.

Furthermore, the recent emergence of hybrid AI-CFD (Computational Fluid Dynamics) models has led to the creation of robust *digital twins* for industrial drying equipment. A digital twin is a virtual replica of a physical dryer that simulates the coupled multiphysics of the system while continually updating itself via real-time operational sensor feedback. Generative AI and deep reinforcement learning algorithms utilize these digital twins to autonomously explore incredibly complex design spaces, optimizing dryer internal geometries, nozzle placements, and operating parameters to achieve optimal trade-offs between energy use, drying time, and product quality far more rapidly than conventional trial-and-error engineering methodologies⁸.

Legacy, Mentorship, and Global Industrial Impact

The dissemination of complex scientific knowledge and the fostering of a highly connected, global academic community is the ultimate cornerstone of Professor Mujumdar's legacy. He has authored over 600 peer-reviewed journal papers—garnering over 55,000 citations and an extraordinary h-index—authored 3 definitive books, and edited more than 70 specialized volumes⁷. His lifelong effort to consolidate the historically fragmented and highly scattered literature on drying (previously isolated within Russian, German, Polish, and Japanese linguistic silos) into a unified, accessible, and rigorous engineering science is universally recognized as unparalleled¹³.

The *Handbook of Industrial Drying* (published by CRC Press), meticulously edited by Professor Mujumdar across four continuously expanding editions (1987, 1996, 2006, 2014), is universally acknowledged by process engineers as the definitive "Bible of Drying"⁴. Spanning over 1,500 pages across oversized volumes, the compendium covers theoretical modeling, computational fluid dynamic simulations, specific dryer designs, and specialized applications across the food, pharmaceutical, textile, pulp and paper, and mineral processing industries¹². Furthermore, as the Editor-in-Chief of *Drying Technology – An International Journal* since 1988, he guided the publication from a nascent state into becoming the premier, high-impact archival forum for dehydration sciences, expanding its output to 16 issues per year to properly accommodate the massive global surge in high-quality research output¹.

Professor Mujumdar's impact transcends the printed page; it is deeply and permanently embedded in the institutional infrastructure and human capital of the global engineering community. In 1978, responding to the extreme fragmentation of drying literature and the urgent industrial pressures of the global energy crisis, he founded the International Drying Symposium (IDS) series on the campus of McGill University¹³. Over 20 biennial symposia spanning more than four decades, the IDS has facilitated the exchange of over 4,000 peer-

reviewed papers from researchers across 80 countries, directly spawning major regional research networks such as the Asia-Pacific Drying Conference (ADC) and the Euro-Drying events⁶.

His pedagogical legacy is equally profound. Mentoring over 100 Ph.D. students and postdoctoral fellows across institutions globally, he established the virtual Transport Processes Research (TPR) group, a highly active, collaborative research network operating seamlessly across 18 nations⁵. His academic philosophy of "excellence with relevance" has ensured that highly theoretical academic research is continually and directly translated into tangible industrial efficiency, safety, and economic growth⁶.

This globally integrated approach is most distinctly visible in his monumental impact on rapidly developing economies, particularly the People's Republic of China. Recognizing early that China's massive, rapidly expanding agricultural output required advanced, highly efficient preservation technologies to ensure national food security and minimize catastrophic postharvest losses, he actively collaborated with major institutions like Jiangnan University and Tianjin University of Science & Technology beginning in 1984⁵⁹. By deeply integrating Chinese researchers into the upper echelons of the global drying community, co-supervising dozens of doctoral candidates, and promoting highly efficient, energy-saving technologies, he fundamentally upgraded and modernized China's entire food drying industrial base. In recognition of this monumental, decades-long contribution, the Government of China awarded him the prestigious Friendship Award (the absolute highest honor bestowed upon foreign nationals) and the National Award for International Cooperation in Science and Technology in 2014, presented at the Great Hall of the People in Beijing⁵. Additionally, he has been honored with Doctor Honoris Causa degrees from Lodz Technical University (Poland), the University of Lyon (France), and Western University (Canada), further underscoring his universal academic reverence⁷. In his home country of India, his alma mater (ICT Mumbai) bestowed upon him its highest honor, the Platinum Award, to commemorate his globally recognized achievements⁵.

Conclusions

The dramatic scientific and technological trajectory of the food processing industry over the past four decades is inextricably linked to the rigorous evolution of thermal dehydration. What was once treated as a black-box, highly empirical, and vastly energy-wasting industrial necessity has been successfully elevated to a highly predictive precision science, driven heavily by the visionary foresight, relentless productivity, and unparalleled global leadership of Professor Arun

S. Mujumdar. Through the rigorous, multidisciplinary application of transport phenomena, physical thermodynamics, and advanced material science, his expansive body of work illuminated the exact, complex mechanisms by which cellular foods lose moisture, undergo phase transitions, and biologically degrade.

By pioneering the industrial maturation of superheated steam drying, defining the efficacy of advanced non-thermal acoustic pretreatments, and optimizing hybrid microwave-assisted intermittent systems, his research provided the global food industry with the exact theoretical frameworks and practical tools necessary to massively slash carbon footprints while simultaneously retaining critical nutritional bioactives and ensuring food safety. Today, as the global food supply chain faces unprecedented new challenges regarding energy sustainability, zero-waste manufacturing, and the demand for customized, personalized nutrition, Professor Mujumdar's early, prescient integration of artificial intelligence, digital twins, and 4D stimuli-responsive food printing continues to provide the foundational roadmap for the next generation of smart manufacturing. His legacy—permanently cemented in tens of thousands of pages of archival literature, a thriving, deeply interconnected global network of researchers, and highly efficient industrial food dryers operating worldwide—will continue to ensure global food security, engineering innovation, and process sustainability for decades to come.

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CHAPTER 4

Pioneering Innovations in Energy-Efficient Drying Technologies: A Comprehensive Analysis of Professor Arun S. Mujumdar's Contributions

1. Introduction and Historical Context of Industrial Drying

Thermal dehydration, or drying, is universally recognized as one of the most energy-intensive unit operations across the global manufacturing landscape. Historically, industrial drying processes have accounted for an estimated 10% to 15% of total industrial energy consumption in developed nations, and often up to 25% in specific sectors¹. Because the process fundamentally requires the continuous supply of the latent heat of vaporization to remove water or organic solvents from solid matrices, it is bound by rigid thermodynamic barriers³. Globally, approximately 27 million tons of water are removed annually in drying processes, consuming nearly 4.5 million tons of oil equivalent (TOE) and resulting in staggering fossil fuel combustion and greenhouse gas emissions⁴. Current efficiency levels in classical dryers frequently stagnate between 15% and 35%, signifying that vast quantities of thermal energy are lost to the environment⁴.

For much of the twentieth century, industrial drying was treated predominantly as an empirical, highly fragmented engineering art rather than a rigorous, multi-disciplinary scientific domain¹. The trajectory of this field was fundamentally altered over the past five decades through the pioneering research, technological innovation, and global scientific leadership of Professor Arun

S. Mujumdar. Beginning his research at McGill University and continuing through his tenure at the National University of Singapore (NUS) and beyond, Professor Mujumdar transformed drying science into a highly coupled, mathematically rigorous discipline involving heat, mass, and momentum transfer¹.

Recognizing early that drying operations exerted profound impacts on global energy consumption, product quality, process economics, and environmental sustainability, his research evolved to focus heavily on process intensification, energy conservation, and carbon footprint reduction¹. It has been quantitatively estimated that a mere 5% improvement in the energy efficiency of industrial drying could decrease global CO₂ emissions by 3 to 4 million tons per year, a statistic that underscores the profound environmental imperative of this research⁴. This report provides an exhaustive, quantitative, and theoretical analysis of Professor Mujumdar's contributions to energy utilization and efficiency in drying technologies, investigating fundamental thermodynamic metrics, heat pump and chemical heat pump systems, superheated steam drying, intermittent energy application, renewable solar energy integration, and the development of digital simulation tools.

2. Thermodynamic Fundamentals and Performance Metrics in Drying

The quantitative evaluation of drying efficiency requires moving beyond elementary heat balances to encompass specific metrics that capture the coupling of thermal energy input and mass transfer output. In conventional convective drying, the evaporation load represents the minimum thermodynamic energy demand, given by the latent heat of evaporation. For water, this requires approximately 2400 kJ/kg at ambient conditions (around 20°C), whereas at 100°C the latent heat is 2256 kJ/kg ³. For a continuous process, the theoretical minimum volumetric heat Q_{min} (in kW) is expressed as:

contents (dry basis), and ΔH_v is the latent heat of vaporization³. For batch operations, this relationship is defined instantaneously by the rate of moisture change dX/dt ³. However, actual energy consumption in industrial settings is often more than double the theoretical minimum. The divergence between theoretical

and actual energy usage is attributed to sensible heat losses in exhaust gases, the supplementary energy required to break the molecular binding forces of bound moisture, structural heat losses through the dryer body, and thermodynamic inefficiencies in ancillary equipment such as steam ejectors and mechanical drives³.

To quantify the practical efficiency of innovative dryer designs and clearly evaluate energy utilization, Professor Mujumdar's research extensively utilizes standard and advanced metrics, notably the Coefficient of Performance (COP) and the Specific Moisture Extraction Rate (SMER).

The SMER defines the mass of moisture removed per unit of energy consumed, typically expressed in kg/kWh. It serves as the definitive benchmark for the energetic viability of a drying system⁵.

To model drying kinetics quantitatively, Mujumdar's collaborative research often relies on the Moisture

$$SMER = \frac{\text{Mass of water evaporated (kg)}}{\text{Total energy input (kWh)}}$$

Rate (MR) and Drying Rate (DR). Based on Newton's Law of cooling and heating for solids, MR is defined as:

equilibrium moisture content⁷. Under high-temperature convective drying, M_e becomes negligible⁷. The drying rate (DR) characterizing dehydration velocity is formulated as:

where Δt is the time interval⁷. Optimizing these kinetic rates while minimizing the energy input defines the core challenge of modern drying technology. Through mathematical optimization and fluid dynamic enhancements, Mujumdar's studies have demonstrated substantial improvements in basic heat transfer parameters. For instance, in convective tray configurations, altering the corrugation height and pitch of internal structures enriched the Nusselt number ratio between 1.81 and 3.126, thereby increasing heat transfer efficiency by up to 3.126 times and elevating the thermohydraulic performance parameter to a maximum of 1.748⁸.

3. Heat Pump-Assisted Drying (HPD) and Process Intensification

Heat pump drying (HPD) represents a major paradigm shift in industrial dehydration, championed extensively in Professor Mujumdar's literature as a highly energy-efficient and environmentally friendly alternative to open-cycle convective dryers⁸. By operating as a closed or semi-closed loop, an HPD utilizes a refrigeration cycle to dehumidify the exhaust air while simultaneously rejecting the condenser heat back into the drying air stream⁵.

3.1. Standard Vapor-Compression Heat Pump Dryers

In conventional HPD systems, the heat delivered by the condenser (Q_{cd}) is mathematically defined as: where $\dot{m}_a$ is the mass flow rate of air, C_p is the specific heat of the air, and $(t_1 - t_2)$ represents the temperature differential across the condenser⁶. HPD systems typically operate with a highly favorable COP ranging between 4 and 6, meaning they deliver four to six units of thermal energy for every unit of electrical energy consumed by the compressor⁶.

The primary advantage of HPDs lies in their ability to dry heat-sensitive biological materials, such as foods, leaves, and pharmaceuticals, at lower, medium-range temperatures (e.g., 40 °C to 60 °C) and low relative humidity (12% to 20%) without sacrificing drying kinetics⁶. This controlled low-contact-time process prevents thermal degradation, preserves vital nutrients and volatile aromatic compounds, and reduces the risk of case-hardening⁶. When drying fresh amaranth leaves in a heat-pump assisted batch dryer utilizing

optimized airflow configurations, researchers achieved a COP of 4.60 and a drying efficiency of 76.23%, alongside a highly competitive specific energy consumption of 1.16 kW/kg at a moderate drying velocity of

6.

The superiority of closed-loop heat pump systems over traditional solar or open-air methods has been quantitatively established in comparative studies. For example, during the drying of bananas (evaporating 3.2 kg of moisture from an 8 kg initial batch), researchers compared a Direct Solar Dryer System (DSDS) against a Closed Loop Heat Pump Dryer (CLHPD).

Drying System Configuration	Drying Time (Minutes)	Specific Moisture Extraction Rate (SMER)
Direct Solar Dryer System (DSDS)	720	0.35 kg/kWh
CLHPD (Without Preheating)	305	1.18 kg/kWh
CLHPD (With 30-min Preheating)	255	1.29 kg/kWh

As evidenced by the data, the CLHPD with preheating achieved nearly a fourfold increase in SMER compared to the DSDS, alongside a 64% reduction in drying time⁵. In broader applications, heat pump systems have demonstrated energy savings of up to 56%, accompanied by proportional reductions in CO₂ emissions¹¹.

3.2. Chemical Heat Pump (CHP) Drying Systems

Extending beyond traditional mechanical vapor-compression cycles, Professor Mujumdar's group pioneered the integration of Chemical Heat Pumps (CHP) with convective dryers. CHPs function not merely as heat recovery devices, but as thermal energy storage (TES) systems that utilize reversible endothermic and exothermic thermochemical reactions to upgrade low-grade waste heat without releasing contaminant gases⁴.

A prominent architecture developed and validated in these studies utilizes the calcium oxide/water/calcium hydroxide reaction system:

This zero-emission system operates sequentially in two distinct steps:

1. **Heat Storing Step:** Low-grade waste heat is used to drive the endothermic dehydration of Ca(OH)_2 into CaO and water vapor. The water vapor is transported to a condenser, storing the original heat as chemical potential energy within the unreacted CaO

12.

2. **Heat Releasing Step:** During heat demand periods, water vapor from an evaporator is introduced to the CaO reactor. The resulting exothermic hydration reaction releases high-grade thermal energy, which is subsequently transferred to the drying medium in the drying chamber¹².

Simulation and experimental studies on the $\text{CaO}/\text{H}_2\text{O}/\text{Ca}(\text{OH})_2$ CHPD demonstrated that the output air temperature from the CHP varies temporally with the progression of the chemical reaction¹³. By theoretically and experimentally mapping the coupled heat and mass transfer within the reactor and the drying chamber, Mujumdar's collaborative work successfully proved that CHPs can upgrade thermal energy efficiently to meet time-varying heat inputs characteristic of batch convective drying⁴.

Furthermore, investigations into alternative chemical architectures, such as the isopropanol-acetone-hydrogen chemical heat pump (IAH-CHP), revealed specific thermodynamic bottlenecks. Exergy loss analyses applied to the IAH-CHP pinpointed the distillation column as the primary source of irreversibility within the system on a global basis⁸. By identifying these thermodynamic irreversibilities, Mujumdar's work provided a quantitative pathway for structural optimization to maximize the coefficient of performance of thermochemical energy upgrading⁸.

4. Superheated Steam Drying (SSD): Thermodynamics of Airless Environments

One of the most radical departures from conventional convective architectures championed by Professor Mujumdar is Superheated Steam Drying (SSD). A significant portion of his fundamental and applied research over the decades has been dedicated to validating and commercializing this technology, which utilizes superheated steam rather than hot air as the convective drying medium⁸.

4.1. The Phenomenon of the Inversion Temperature

The physical mechanism of SSD relies on the absolute absence of non-condensable gases, specifically oxygen and nitrogen. In classical hot-air drying, evaporated moisture must diffuse through a stagnant boundary layer of air surrounding the wet product. This mass transfer resistance is a primary limiting factor in traditional drying kinetics. In SSD, because the drying medium is entirely composed of water vapor, there is zero diffusional resistance to mass transfer at the product surface¹⁵. The liquid moisture simply flashes into the continuous vapor phase once the product temperature reaches the boiling point corresponding to the operational pressure.

A critical thermodynamic concept extensively explored in Mujumdar's work is the *inversion temperature*. At relatively low drying temperatures, standard convective air drying is faster than SSD because the specific heat capacity and transport properties of air facilitate superior sensible heat transfer¹⁴. However, as the temperature of the drying medium increases, the specific heat and thermal conductivity of superheated steam evolve favorably relative to air. At a specific threshold known as the inversion temperature, the evaporation flux of SSD surpasses that of hot-air drying¹⁴.

Above this inversion temperature, SSD exhibits significantly higher drying rates, particularly during the falling rate period. This occurs because the product core temperature in SSD is elevated to the boiling point (exceeding 100°C at 1 bar), generating an internal pressure gradient that drives moisture outward, while the lack of air eliminates the external mass transfer resistance¹⁵. Furthermore, because moisture is driven out so rapidly, many products that traditionally form a "case-hardened" skin in rapid air drying do not exhibit this defect under SSD¹⁵.

4.2. Energetic, Environmental, and Safety Implications

From an energy conservation standpoint, SSD represents a closed-loop thermodynamic ideal. The evaporated water from the wet product simply adds to the mass and volume of the superheated steam medium. The excess steam generated during the process can be bled off, compressed, or condensed, allowing for the recovery of nearly 100% of the latent heat of vaporization¹⁴. This recovered heat can subsequently be repurposed for co-generation, evaporation, or pre-heating elsewhere in the industrial plant, drastically slashing the net specific energy consumption of the drying operation¹⁴.

Because SSD operates in a strictly oxygen-free environment, it completely eliminates the risk of fire and explosion¹⁴. This is a critical safety parameter when drying highly combustible materials such as low-rank coal, biomass, and paper¹⁵. Furthermore, the lack of oxygen prevents the oxidative degradation of biological products, preserving color, nutritional profiles, and structural integrity¹².

Mujumdar has heavily investigated SSD for highly energy-intensive and carbon-heavy industrial applications. For instance, in the pulp and paper industry, the application of superheated steam can drastically enhance the properties of diverse grades of paper while allowing massive energy recovery in the paper machine¹⁸. In agricultural applications, such as the dehydration of black tea leaves, experimental investigations between and demonstrated that SSD provided substantially higher drying rates and significantly shortened drying times compared to conventional techniques⁸.

Perhaps most critically for urban sustainability, Mujumdar has proposed SSD for the dewatering and drying of wastewater treatment sludge¹⁹. Sludge drying is notoriously difficult due to bound moisture, but applying SSD not only stabilizes the biological waste but recovers the latent heat, effectively converting hazardous urban sludge into high-calorific biofuels with a minimized carbon footprint¹⁸.

5. Intermittent and Non-Stationary Drying: Exploiting the Falling Rate Period

A profound second-order insight derived from Professor Mujumdar's extensive work is the recognition that the steady-state application of thermal energy is inherently wasteful when applied to a non-linear, transient mass transfer process. Traditional industrial drying operations supply a continuous influx of heat to the wet solid. However, drying kinetics strictly obey two distinct phases: the constant rate period and the falling rate period⁶.

5.1. The Physics of the Falling Rate Period

During the constant rate period, free unbound moisture at the surface of the material is evaporated. Here, the drying rate is limited only by the external boundary layer conditions of the drying medium (velocity, temperature, humidity). However, once the surface moisture is depleted, the process inevitably enters the falling rate period. In this phase, the drying rate is governed entirely by the internal diffusion of moisture from the core of the solid matrix to the surface⁶.

When a solid exhibits a high internal resistance to moisture movement, the moisture cannot diffuse to the surface as fast as the thermal energy can evaporate it. Applying continuous convective heat during the falling rate period results in two severe thermodynamic penalties:

1. Massive wastage of thermal energy, as the supplied heat simply raises the exhaust gas temperature and the product temperature rather than causing evaporation. This causes a stark drop in energy efficiency².
2. Severe thermal degradation, shrinkage, and case-hardening of the product's outer crust, which permanently traps the remaining internal moisture and ruins product quality².

5.2. Energy Savings via Intermittency and Hybridization

To circumvent this mass transfer bottleneck, Professor Mujumdar championed Intermittent Drying (ID) and non-stationary technologies. In ID, thermal energy is applied periodically rather than continuously².

When the heat source is turned off (the "resting" or "tempering" phase), the internal moisture continues to diffuse toward the surface due to the established concentration and thermal gradients, a phenomenon known as moisture relaxation². When the heat is subsequently reapplied, the solid surface is once again wet, allowing for highly efficient evaporation that mimics the rapid kinetics of the constant-rate period². This time-varying boundary condition yields profound advantages: it dramatically reduces the total specific energy consumption, lowers the total required airflow, and preserves the quality of the dried product by preventing thermal stress and case-hardening².

Intermittency can be achieved not only by cycling convective hot air but by alternating the modes of heat input entirely. Mujumdar has extensively researched multi-stage and hybrid drying systems that combine traditional convection with Microwave (MW) or Radio Frequency (RF) heating². Because biological

materials exhibit poor thermal conductivity, surface heating requires large temperature gradients. Conversely, electromagnetic waves penetrate the dielectric material and interact with the dipole moments of water molecules to generate heat volumetrically¹².

When applied intermittently, MW or RF energy creates a positive internal pressure gradient that drives moisture to the surface rapidly, conquering the internal mass transfer resistance that plagues the falling rate period²¹. For instance, comparative studies on edamame dehydration demonstrated that an optimized hybrid process—applying 70 °C hot air for 20 minutes followed by intermittent microwave drying—maximized drying rates and enhanced overall product quality¹². Similarly, a two-stage hybrid method utilizing vacuum freeze-drying (FD) followed by hot air finish drying (FAD) was successfully applied to strawberries, optimizing the balance between the flawless structural preservation of FD and the low energy cost of FAD¹².

6. Renewable Energy Integration: Advanced Solar

Drying and Phase Change Materials (PCMs)

Recognizing the urgent global mandate to decarbonize agricultural post-harvest processing, particularly in developing, off-grid, and rural regions, a substantial branch of Professor Mujumdar's research addresses the optimization and industrialization of solar drying technologies¹.

While open sun drying (OSD) is the oldest and most cost-effective dehydration method, it suffers from severe operational drawbacks, including diurnal intermittency, lack of temperature control, vulnerability to dust and insect contamination, and crop spoilage due to ultraviolet radiation exposure²⁷. To stabilize energy input, improve product hygiene, and accelerate drying kinetics, advanced active (forced convection) and passive (natural convection) greenhouse solar dryers were conceptualized, modeled, and analyzed²⁷.

6.1. Thermal Energy Storage via PCMs

The central limitation of solar energy is its transient and intermittent nature, driven by the day-night cycle and unpredictable cloud cover. To decouple solar energy collection from the drying operation, Mujumdar and his collaborators have strongly advocated for the integration of Phase Change Materials (PCMs) as Thermal Energy Storage (TES) systems within solar dryers²⁷.

PCMs, such as organic paraffin waxes or inorganic solid-phase materials, undergo a solid-liquid phase transition at specific temperatures, absorbing vast quantities of latent heat during periods of peak solar irradiation (the charging phase)²⁸. After sunset, or during periods of low insolation, the PCM solidifies, releasing the stored latent heat into the drying chamber (the discharging phase) with minimal temperature variation²⁸.

This continuous supply of thermal energy fundamentally alters the economics and efficacy of solar drying. For example, experimental evaluations of a novel passive solar dryer integrated with a natural soapstone TES system demonstrated remarkable performance improvements compared to traditional Open Sun Drying (OSD).

Product Dried	Drying Time in OSD	Drying Time in Solar Dryer (No TES)	Drying Time in Solar Dryer (With TES)
Pineapples	52 hours	24 hours	13 hours
Carrots	50 hours	23 hours	12 hours

As demonstrated, integrating the soapstone TES material reduced the total drying time of pineapples by 75% compared to OSD, and permitted the dryer to supply heat effectively for 3 to 4 hours post-sunset²⁹. The comprehensive thermal efficiency of the TES-integrated dryer was recorded at 45%, with a collector efficiency of 43% and a remarkable storage efficiency of 74.5%²⁹.

6.2. Hybridization and Intelligent Control of Solar Systems

To guarantee continuous industrial-scale production regardless of seasonal weather fluctuations, solar energy must be hybridized. Extensive reviews co-authored by Mujumdar have evaluated solar-biomass hybrid systems, solar-electric systems, and solar-assisted heat pump dryers (SAHPD)⁷. By combining the high coefficient of performance of heat pumps with the zero-carbon energy input of solar collectors, SAHPDs achieve unprecedented overall system exergy efficiencies⁷.

Furthermore, optimizing these non-linear, environmentally dependent systems requires advanced digital interventions. The application of Artificial Neural Networks (ANN), Computational Fluid Dynamics (CFD), and fuzzy logic control systems are increasingly utilized to dynamically predict and optimize airflow and

temperature distributions within hybrid solar dryers²⁷. A multivariable fuzzy logic control system responding to real-time variations in solar radiation and ambient air temperature ensures the optimal charging of the PCM accumulator, regulating panel valves to perfectly balance instantaneous drying loads against energy storage requirements²⁸.

7. Advanced Electrohydrodynamic (EHD) Drying

As industrial demands for rapid, energy-efficient drying of highly heat-sensitive biological materials escalated, Mujumdar's investigative scope expanded into advanced electric field-assisted technologies, most notably Electrohydrodynamic (EHD) drying¹⁸.

EHD drying represents a radical leap in energy efficiency. It utilizes high-voltage direct current (HVDC) electric fields applied between a specialized emitting electrode (such as a needle or thin wire) and a grounded plate. This high electric field strips electrons from surrounding gas molecules, generating an "ionic wind" or corona discharge that travels toward the wet product¹⁸. When this ionic wind impacts the surface of the wet material, it violently disrupts the stagnant boundary layer of air, creating localized micro-convective vortices that drastically accelerate moisture evaporation at purely ambient temperatures. Because EHD drying relies on electrical momentum transfer rather than the sensible heating of massive volumes of air, it consumes a fraction of the electrical energy compared to thermal convective methods. This non-thermal approach prevents any structural or nutritional degradation, making it a highly innovative, low-carbon solution for the dehydration of exceptionally sensitive biomaterials, enzymes, and specialized foods¹⁸.

8. Digitalization and System-Level Optimization: Simprosys Software

Theoretical advancements in the mathematics of mass and heat transfer are only industrially valuable if they can be easily and accurately implemented by practicing chemical and process engineers. Identifying a critical gap in commercial chemical engineering simulation software—which historically neglected the complex multiphase, solid-gas coupled mechanics inherent in drying operations—Professor Mujumdar co-developed the comprehensive drying software suite *Simprosys*³⁵.

8.1. Architectural Framework of Simprosys

Simprosys provides an integrated, user-friendly computational environment specifically tailored for the flowsheet design, simulation, and economic analysis of drying systems³⁷. Rather than relying on expensive, energy-intensive, and time-consuming trial-and-error pilot testing, engineers utilize Simprosys to perform rigorous heat and mass balance calculations across an entire drying plant³⁷.

The software includes detailed mathematical models for a vast array of associated unit operations. For standard air-water systems, Simprosys supports 19 distinct unit operations, and for non-aqueous systems, it supports 15, including solid dryers, cyclones, air filters, bag filters, electrostatic precipitators, scrubbers, condensers, fans/blowers, compressors, valves, heaters, coolers, heat exchangers, mixers, tees, pumps, and logical recycle loops³⁸.

A major breakthrough in the development of Simprosys version 2.1 was the expansion of its sophisticated thermodynamic databases. Moving beyond the standard air-water system—which calculates properties based on the 1967 ASME Steam Tables—the software was updated to handle 11 distinct non-aqueous organic solvent systems³⁸.

Solvent System	Carrier Gas	Primary Industrial Application
Ethanol	Air / Nitrogen	Pharmaceuticals, Fine Chemicals
Carbon Tetrachloride	Air	Industrial Solvents
Benzene / Toluene	Air	Chemical Synthesis
Acetone / Methanol	Nitrogen	Heat-sensitive organic extraction
Isopropanol / N-Butanol	Nitrogen	Specialized bio-product drying

The psychrometric properties for these organic liquids are derived from authoritative sources like Perry's Chemical Engineers' Handbook and Yaws' data, allowing the software to precisely model absolute humidity, wet-bulb temperatures, and humid enthalpies for complex gas-liquid mixtures³⁸.

8.2. Enhancing Industrial Sustainability and Safety

By simulating an entire plant flowsheet simultaneously, Simprosys enables engineers to pinpoint thermodynamic bottlenecks, calculate precise air handling power requirements, and design optimal exhaust gas recirculation loops that recycle latent heat³⁷.

Furthermore, the software is paramount for industrial safety. In the pharmaceutical and fine chemical industries, materials are often laden with organic solvents that possess low flash or burning points³⁸. Using air as a drying medium poses severe explosion risks. Simprosys allows engineers to model closed-loop systems utilizing inert carrier gases, such as an ethanol-nitrogen flowsheet. The software flawlessly balances the condenser loads required to strip the ethanol out of the nitrogen against the heater duties required for the dryer, ensuring absolute safety while minimizing total energy expenditure³⁸. Ultimately, Simprosys lowers the barrier to entry for performing complex life-cycle assessments (LCA) and system-wide carbon footprint analyses on industrial drying operations³⁹.

9. Sector-Specific Impacts: Decarbonizing Carbon-Intensive Industries

While drying high-value foods and pharmaceuticals requires meticulous attention to sensory and nutritional quality, the drying of massive bulk commodities dictates global energy economics.

Professor Mujumdar's work has aggressively targeted the most challenging, high-volume, and carbon-intensive materials: Low Rank Coal (LRC) and wastewater treatment sludge.

9.1. Upgrading Low Rank Coal (LRC)

Despite stringent environmental pressures, coal remains a cornerstone of global power generation, particularly in developing economies. The world possesses abundant reserves of Low Rank Coals (LRCs), which unfortunately suffer from exceptionally high inherent moisture contents²¹. This water acts as a massive thermal sink during combustion, drastically lowering the coal's calorific value and sharply increasing greenhouse gas and noxious emissions per megawatt-hour of electricity generated²¹. Furthermore, transporting water-logged coal incurs massive logistical carbon footprints²¹.

Recognizing that drying is an essential intermediate stage regardless of whether the coal is destined for direct combustion, gasification, or liquefaction, Mujumdar's group at the Minerals, Metals and Materials Technology Centre (M3TC) comprehensively evaluated various clean coal technologies²¹. The objective was to identify dehydration technologies that were energy- efficient, safe, cost-effective, and possessed minimal carbon footprints²¹.

A primary technology evaluated for LRC upgrading is the Screw Conveyor Dryer (SCD). The SCD utilizes a jacketed conveyor containing hollow flights and shafts through which high-temperature thermal transfer media (such as hot water, steam, pot oil, or Dowtherm fluid) flow²¹. This design offers a massive heat transfer area within a minimal spatial footprint and handles solids gently. Critically, because the SCD is an indirect contact dryer, the highly reactive, dust-prone dried LRC is not exposed to massive volumes of oxidizing hot air, significantly mitigating the risk of spontaneous combustion and catastrophic dust explosions inherent in direct coal drying¹⁰.

9.2. Sludge Dewatering and Stabilization

The environmental mandate to process wastewater treatment sludge is a rapidly escalating global challenge. Sludge acts as a complex biological and colloidal matrix containing large quantities of intracellular bound water, making purely mechanical dewatering highly inefficient beyond a certain threshold¹².

Mujumdar's extensive reviews on the physicochemical aspects of sludge dictate that thermal drying must inevitably follow mechanical dewatering to achieve genuine volume reduction and biological stabilization¹².

By employing technologies such as Superheated Steam Drying or Chemical Heat Pumps to recover high-grade waste heat from the downstream sludge incineration process, the massive carbon footprint of municipal waste management is substantially curtailed. This circular thermodynamic approach effectively converts hazardous biological sludge into a stable, high-calorific biofuel capable of offsetting its own processing energy¹⁸.

10. Institutional Legacy and the Global Dissemination of Drying Science

The technical, quantitative, and mathematical innovations detailed above form only one pillar of Professor Mujumdar's legacy; the second, equally important pillar is his profound sociological and institutional impact on the global engineering community.

Prior to 1978, despite industrial drying accounting for up to 15% of global industrial energy use, research activities were highly fragmented, dispersed across disparate mechanical, agricultural, chemical, and food engineering disciplines¹. Recognizing the critical need for a unified, cross-disciplinary platform to tackle these thermodynamic challenges, Professor Mujumdar founded the International Drying Symposium (IDS) series in 1978 at McGill University¹. For nearly five decades, IDS has served as the preeminent global forum for the cross-pollination of academic research, industrial application, and policymaking, actively driving the commercialization of sustainable drying technologies and decarbonization strategies globally¹.

Furthermore, realizing the absence of a dedicated peer-reviewed platform for this discipline, he founded *Drying Technology - An International Journal* in 1982¹. Serving as the founding Editor-in-Chief, he established the academic legitimacy and visibility of drying science, fostering thousands of publications focusing on transport phenomena, energy efficiency, and mathematical modeling¹. His pedagogical contributions culminated in the editing of the *Handbook of Industrial Drying* (currently in its Fourth Edition), universally regarded by peers as the authoritative 'bible' for dryer design, selection, and optimization³⁹. Through his establishment and mentorship of the Transport Processes Research (TPR) Group, which spans dedicated researchers and academic mentees across over twenty nations, Professor Mujumdar has ensured the continuity of rigorous, sustainable innovation in thermal engineering for generations to come⁴².

11. Conclusion

The comprehensive analysis of Professor Arun S. Mujumdar's five-decade career reveals a transformative and quantifiable impact on the science and application of industrial drying. By elevating the discipline from empirical guesswork to a highly complex, multi-scale transport phenomenon governed by rigorous mathematical principles, his work has laid the theoretical and practical foundations for immense global energy conservation.

From fundamentally altering the thermodynamic constraints of continuous heating through Intermittent Drying and electromagnetic hybridization, to totally eliminating the mass-transfer resistance of air via Superheated Steam Drying, his technological propositions strictly address the root inefficiencies of moisture removal. The championing of Heat Pump Dryers and the conceptualization of zero-emission Chemical Heat Pumps have proven that latent heat recovery and thermal energy storage can yield massive increases in the Specific Moisture Extraction Rate (SMER). Simultaneously, the integration of Phase Change Materials in passive solar drying architectures and the harnessing of Electrohydrodynamic fields provide viable, low-cost roadmaps for the complete decarbonization of agricultural post-harvest processing.

Through the co-creation of the Simprosys software suite, the theoretical thermodynamic gains achieved in academia have been successfully translated into actionable, system-level flowsheets for practicing engineers across the chemical, food, pulp and paper, and energy sectors. Ultimately, Professor Mujumdar's enduring legacy—cemented by the International Drying Symposium, the *Drying Technology* journal, and his prolific global mentorship—is an industrialized world vastly better equipped to decouple economic production from catastrophic energy consumption. As international climate change imperatives enforce ever-stricter energy regulations, the theoretical frameworks, optimization tools, and innovative drying

architectures established by Professor Mujumdar will remain indispensable to the future of sustainable, low-carbon industrial manufacturing.

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CHAPTER 5

Advances in Gas-Particle Flow, Heat, and Mass Transfer: A Half-Century Retrospective on the Contributions of Professor Arun S. Mujumdar

1. Introduction to the Paradigm Shift in Thermal Dehydration

Over the past five decades, the disciplines of chemical, mechanical, and agricultural engineering have witnessed a fundamental paradigm shift in the understanding, modeling, and industrial application of thermal dehydration and multiphase gas-particle flows. Historically, the design and scale-up of industrial drying equipment relied almost entirely on empiricism, vendor heuristics, and costly trial-and-error methodologies. This empirical approach posed significant economic and ecological challenges, as thermal drying is arguably one of the most energy-intensive unit operations in existence, accounting for between ten and twenty percent of the national industrial energy consumption in developed economies. The transition from an empirical art to a highly predictive, science-based engineering discipline has been largely catalyzed by pioneering research in transport phenomena and applied computational fluid dynamics.

At the vanguard of this transformation is Professor Arun S. Mujumdar, whose exhaustive investigations into the hydrodynamics, heat transfer, and mass transfer of complex gas-particle systems have redefined the global landscape of thermal processing. Beginning his academic tenure at McGill University (Canada) and continuing at the National University of Singapore (NUS), Professor Mujumdar recognized early that the chronic limitations of conventional dryers—particularly concerning scale-up bottlenecks, high energy consumption, and the thermal degradation of heat-sensitive materials—could only be resolved through a rigorous, first-principles understanding of multiphase flow dynamics.

His research portfolio spans an incredibly diverse array of novel gas-solid contactors, notably conventional and modified spouted beds, spout-fluid beds, pulsed fluidized beds, vibrated beds, spray dryers, and gas-particle impinging jets. By introducing transformative geometric and operational innovations—such as the two-dimensional spouted bed (2DSB) equipped with draft plates and the impinging stream dryer (ISD)—this body of work has facilitated the successful industrial scaling of highly efficient thermal fluid systems while circumventing traditional hydrodynamic limitations. This report provides a comprehensive, research-grade analysis of Professor Mujumdar's contributions, quantitatively and qualitatively evaluating the impact of his innovations, detailing the mathematical and fluid dynamic mechanisms of specialized gas-particle flows, and assessing the practical industrial applicability of these technologies.

2. Quantitative Impact, Interdisciplinary Reach, and Global Collaborative Networks

The magnitude of an academic's impact is traditionally measured through bibliometric indices, editorial leadership, the commercialization of novel technologies, and the propagation of collaborative research networks. In all these vectors, the quantitative and qualitative footprint of Professor Mujumdar is unprecedented in the field of thermal dehydration and transport phenomena.

2.1 Unprecedented Bibliometric and Academic Milestones

Professor Mujumdar's scholarly output is vast, encompassing over 600 peer-reviewed journal publications that have yielded an exceptional citation record. Depending on the indexing database and chronological measurement, his work has accrued between 55,000 and 101,625 citations across various platforms, reflecting an h-index ranging from 135 to 143 on Google Scholar, alongside an i10-index of 986. This

exceptional citation density underscores the foundational nature of his research, which serves as the theoretical bedrock for subsequent global investigations in thermal fluid engineering, nanotechnology, and energy systems.

Beyond primary research articles, the dissemination of his transport phenomena paradigms has been achieved through monumental editorial and pedagogical contributions. He has authored three foundational textbooks, edited over seventy books, and contributed more than 120 book chapters. Chief among these is the *Handbook of Industrial Drying* (CRC Press), currently in its fourth expanded edition. Widely regarded in the chemical and process industries as the definitive "Bible of Industrial Drying," this comprehensive resource integrates multiphase flow theory with practical dryer design, successfully bridging the historical gap between theoretical transport phenomena and industrial scale-up practice.

Bibliometric / Academic Metric	Record / Contribution Parameter	Source Reference
Total Citations (Google Scholar)	> 78,850 to 101,625	
h-index / i10-index (Google Scholar)	135 - 143 / 986	
Peer-Reviewed Journal Publications	575 to > 650	
Authored / Edited Books	3 Authored, > 70 Edited	
Doctoral Candidates Mentored	66+	
Post-Doctoral Fellows Supervised	40+	
Keynote / Plenary Lectures	93+	

2.2 Institutional Leadership and the Internationalization of Drying Research

Recognizing that the challenges of thermal dehydration intersect with mechanical, chemical, food, and environmental engineering, Professor Mujumdar sought to institutionalize a centralized platform for interdisciplinary knowledge exchange. In 1978, he founded the International Drying Symposium (IDS) series, which has operated continuously for decades, catalyzing global research and development networks and spawning numerous regional symposium series worldwide. Furthermore, he has served as the Editor-in-Chief of *Drying Technology: An International Journal* for over two decades, single-handedly elevating the publication into the premier archival journal for thermal processing and managing a high manuscript flow that frequently exceeds thousands of submissions annually.

His establishment of the Transport Processes Research (TPR) Group explicitly exemplifies his commitment to international collaboration. Operating as a decentralized, multi-disciplinary global team, the TPR network spans over eighteen countries, facilitating cross-border research initiatives in mathematical modeling, nanofluids, and advanced industrial drying technologies.

The objective of this global effort has always been the democratization of knowledge, evident in his initiative to publish a series of freely available e-books on mathematical modeling and food drying, ensuring that researchers in developing economies have unobstructed access to state-of-the-art literature.

Through his mentorship of over sixty-six PhD candidates and forty post-doctoral fellows across institutions such as McGill University and the National University of Singapore, Professor Mujumdar has populated the global academic and industrial sectors with leading experts.

Formal recognition of these global contributions is extensive, including China's highest award for International Cooperation in Science and Technology (2014), the Platinum Award of the Institute of Chemical Technology (Mumbai), and Doctor Honoris Causa degrees from Lodz Technical University in Poland and the University of Lyon 1 in France.

3. Fundamental Hydrodynamics and Turbulence Modeling in Gas-Solid Flows

At the core of Professor Mujumdar's industrial innovations is the rigorous mathematical and computational modeling of fluid dynamics, heat transfer, and mass transfer. The complex, chaotic nature of multiphase interactions in spouted beds, opposed impinging jets, and fluidized suspensions requires highly sophisticated numerical frameworks to accurately predict scale-up behavior.

3.1 Advanced Computational Fluid Dynamics (CFD) and Turbulence Corrections

Prior to the widespread availability of high-performance computing, the prediction of flow behavior in complex reactor geometries relied entirely on bulk empirical correlations, which frequently failed when scaling up dimensions. Mujumdar and his collaborators pioneered the application of Computational Fluid Dynamics (CFD) coupled with the Discrete Element Method (DEM) and Eulerian-Eulerian two-fluid models (TFM) to mathematically map gas-solid interactions at the particle level.

A highly specific and notorious challenge in simulating impinging gas-particle flows is the accurate prediction of the stagnation zone heat transfer. In this region, standard high-Reynolds number k - ϵ turbulence models drastically overestimate the turbulent kinetic energy, thereby grossly overpredicting the stagnation Nusselt number (Nu_0). To address this, extensive research was conducted evaluating various low-Reynolds number k - ϵ models and Reynolds Stress Models (RSM). Professor Mujumdar's team demonstrated that standard formulations miscalculate the near-wall length scales of turbulence. By incorporating the "Yap correction" into low-Reynolds number models (forming the LBY model), the numerical overestimation of the stagnation Nusselt number was substantially mitigated. This composite modeling approach successfully captured the steep radial gradients of the local Nusselt number across

the impingement surface, aligning numerical CFD predictions tightly with experimental aerodynamic data.

3.2 Granular Kinetic Theory and Frictional Stresses in Dense Beds

In dense gas-particle flows, particularly within the slow-moving annulus of a spouted bed, particle-particle collisions and sustained frictional contacts dominate the momentum transfer. Fluid models that assume dilute phase behavior fail entirely in these zones. Mujumdar's computational investigations solved this by utilizing the Kinetic Theory of Granular Flow (KTGF) coupled with frictional stress models—such as the Johnson et al. model—to simulate the continuous kinetic-friction stresses.

These sophisticated models accurately delineated the solid volume fractions across the reactor, revealing the sharp transition from dilute, high-velocity pneumatic transport in the central spout to the dense, slow-moving plug flow in the annulus. The inclusion of precise mathematical constants, such as setting the restitution coefficient to 0.9 and utilizing the Gidaspow inter-phase momentum exchange model, proved critical. These refinements allowed the CFD models to match predicted mean vertical particle velocities with high-fidelity Particle Image Velocimetry (PIV) experimental measurements, generating errors as low as 9% in the draft tube zone and 19% in the annulus.

Flow Zone / Mechanism	Dominant Physics	Recommended Modeling Approach
Stagnation Region (Impinging Jets)	Rapid deceleration, thin boundary layers	Low-Re k - ϵ model with Yap Correction, RSM
Spout Region (Spouted Beds)	Dilute pneumatic transport, high velocity	Eulerian-Eulerian Two-Fluid Model (TFM)
Annulus Region (Spouted Beds)	Dense plug flow, sustained particle contact	KTGF combined with Johnson frictional stress model

4. Spouted and Spout-Fluid Beds: Deconstructing Conventional Limitations

The conventional spouted bed (CSB), characterized by a cylindrical vessel with a conical base and a single central gas inlet, was originally developed for handling coarse, Geldart D particles (e.g., agricultural grains, wood chips, and large polymers) that are too massive or irregularly shaped to be fluidized uniformly. While CSBs offer excellent macro-mixing, vigorous gas-solid contact, and rapid removal of surface moisture, they suffer from fundamental hydrodynamic limitations that historically restricted their widespread industrial scale-up.

4.1 The Hydrodynamics of Spouting and the Maximum Spoutable Height (H_m)

In a classic CSB operation, a high-velocity gas jet penetrates the particle bed, forming a central, highly dilute spout. The particles are pneumatically transported upward, form a fountain above the bed surface, and subsequently rain back onto the peripheral annulus, slowly migrating downward and radially inward to be re-entrained into the spout. Two critical hydrodynamic parameters govern this entire operation: the minimum spouting velocity (U_{ms}) required to initiate and sustain the spout, and the maximum spoutable bed height (H_m).

The existence of H_m is the primary physical constraint on spouted beds. If the static bed height exceeds H_m , the gas pressure drop required to maintain the vertical spout exceeds the pressure drop required for the gas to simply percolate radially into the annulus. Consequently, the spouting gas is entirely diverted into the annulus, causing the spout to collapse and resulting in severe slugging, channeling, or total bed defluidization. Early empirical correlations for predicting H_m and U_{ms} —such as the classic Mathur-

Gishler equation or the McNab equation—were highly limited, performing adequately only for specific geometric configurations and perfectly spherical particles.

Collaborative research spearheaded by Passos, Raghavan, and Mujumdar fundamentally advanced this understanding. They developed refined, robust mathematical correlations for predicting the maximum spoutable bed height, successfully incorporating the complex effects of particle sphericity, bed cohesion, and cross-flow fluid percolation. Their models quantitatively demonstrated the distinct transition mechanisms of spout termination—specifically differentiating between the fluidization of the annulus top and the physical choking of the spout neck. By establishing these predictive boundaries, their work provided chemical engineers with the critical design constraints necessary to prevent catastrophic defluidization during pilot-plant trials.

4.2 Spout-Fluid Beds: Eradicating Annular Dead Zones

A secondary deficiency of the conventional spouted bed is the presence of aerodynamic "dead zones" at the extreme lower periphery of the conical base, combined with severely limited gas-particle contact in the dense, downward-moving annulus. To remedy this, the spout-fluid bed was rigorously investigated.

By introducing a secondary, auxiliary fluidization gas through a porous distributor located in the annular region—operating independently of the central high-velocity spouting jet—the hydrodynamics of the bed are fundamentally and beneficially altered. Experimental and theoretical studies on spout-fluid beds quantified the pressure drop dynamics and the revised minimum spouting/spout-fluidizing velocities. The findings indicated a highly symbiotic relationship: increasing the auxiliary fluidization velocity actively reduces the minimum spouting velocity (U_{ms}) required at the central nozzle, while simultaneously expanding the maximum spoutable bed height by lubricating the annular flow. This dual-flow mechanism effectively eliminates all basal dead zones and massively enhances the overall volumetric heat and mass transfer coefficients, making spout-fluid beds exceptionally suitable for the thermal processing of sticky, cohesive, or highly heat-sensitive biological materials.

5. Innovation I: Two-Dimensional Spouted Beds (2DSB) and Draft Plates

The most critical barrier to the widespread industrial adoption of conventional cylindrical spouted beds is the non-linear scale-up challenge. In a CSB, stable spouting strictly requires the column diameter (D_c) to inlet nozzle diameter (D_i) ratio to remain below a specific threshold (typically between 20 and 30) to avoid spout deflection and bed instability. Simultaneously, the overall volume is strictly constrained by H_m . Consequently, attempting to scale up a CSB to process higher industrial capacities demands complex, multi-spout configurations that inevitably suffer from severe jet interference, alternating spout deflection, and chaotic flow patterns.

5.1 The Slot-Rectangular Paradigm for Linear Scale-Up

To circumvent the geometric D_c/D_i constraint entirely, Professor Mujumdar and his colleagues pioneered the extensive use of the two-dimensional spouted bed (2DSB), also referred to as the slot-rectangular spouted bed. Instead of a cylindrical vessel utilizing a single circular orifice, the 2DSB utilizes a rectangular cross-section equipped with a continuous longitudinal slot for gas entry.

This geometrical shift radically alters the fundamental scaling laws of the multiphase reactor. To increase volumetric processing capacity, an engineer no longer needs to widen the vessel or add multiple interfering nozzles; they simply increase the depth (length) of the longitudinal slot and the corresponding bed, thereby preserving the exact two-dimensional hydrodynamic profile established at the pilot scale.

Extensive studies by Kalwar, Raghavan, and Mujumdar utilizing diverse particulate materials—such as shelled corn, soybeans, and wheat—verified that the drying kinetics in a drafted 2DSB adhere strictly to predictive "thin layer" models. Furthermore, their empirical derivations proved that the spouting

pressure drop and minimum spouting velocity maintain perfect geometric similitude during horizontal scale-up, effectively solving the spouted bed scale-up problem.

5.2 The Role of Draft Plates and Tubes in Optimizing Hydrodynamics

To further alleviate the maximum spoutable height (H_m) limitation and exert precise control over the solids residence time, internal draft plates (in 2DSBs) or draft tubes (in cylindrical beds) were introduced and highly optimized. A draft plate is a vertical physical partition strategically placed inside the reactor that separates the upward central spout from the downward-flowing annulus.

The inclusion of draft plates optimizes the bed's hydrodynamics in three profound ways:

1. **Massive Pressure Drop Reduction:** Draft plates provide a smooth, low-resistance pneumatic transport channel. Experimental data demonstrates that the peak pressure drop required to initiate spouting, as well as the steady-state operating pressure drop, is reduced by 17% to 30% compared to equivalent spouted beds lacking draft internals.
2. **Elimination of the H_m Limit:** Because radial gas percolation from the spout into the annulus is physically blocked by the solid walls of the draft plate (or tightly controlled via porous plates), the spout cannot choke due to fluid loss. This fundamental mechanical alteration essentially eliminates the maximum spoutable bed height limitation, allowing for exceedingly deep beds that maximize thermal efficiency.
3. **Decoupled Solid Circulation Control:** The physical gap between the gas inlet nozzle and the bottom edge of the draft plate (termed the entrainment zone) strictly governs the solid circulation rate. Adjusting this specific entrainment height allows operators to decouple the particle residence time from the superficial gas velocity, offering unprecedented control over the drying kinetics.

CFD simulations utilizing the Eulerian-Eulerian approach have confirmed that the particle volume fraction in the spout and fountain regions of a 2DSB with draft plates is considerably lower than in non-drafted beds. This increased voidage massively enhances the gas-to-particle heat transfer coefficient.

The 2DSB with draft plates has been successfully scaled for the continuous drying of grains, the dehydration of agricultural pastes, and the coating of suspensions onto inert particles (such as xanthan gum solutions coated onto inert glass beads). By employing pseudo-two-dimensional configurations equipped with custom heat transfer probes, researchers have definitively mapped the thermal profiles of these beds, proving that the highly uniform cyclic movement directly results in uniform product moisture profiles, essential for high-value commodities like cardamom.

6. Innovation II: Impinging Streams and Gas-Particle Jets

For certain industrial materials presenting exceptionally high drying loads—such as highly concentrated biochemical suspensions, viscous sludges, and ultra-fine cohesive powders—even optimized fluidized and spouted beds may lack the necessary convective driving force to prevent agglomeration. To address these extreme operational demands, Mujumdar championed the theoretical development and practical optimization of the Impinging Stream Dryer (ISD).

6.1 The Hydrodynamics of Opposing Streams

The foundational concept of impinging streams involves two coaxial, opposed jets of gas-particle suspensions colliding head-on along the same longitudinal axis. In the immediate impingement zone, the axial velocity of the gas carrier decelerates rapidly to zero, converting kinetic energy into a zone of intense turbulent shear and high static pressure. However, due to their significantly higher inertia, the solid particles or droplets do not stop immediately at the impingement plane; they physically penetrate the opposing gas stream, gradually decelerate, and are subsequently accelerated back toward the center.

This violent, oscillatory motion of particles across the impingement zone yields two profound transport phenomena benefits:

1. **Extreme Relative Velocities:** The relative slip velocity between the gas phase and the solid particle reaches an absolute maximum, vastly thinning the thermal and concentration boundary layers surrounding the particle and accelerating mass transfer to theoretical limits.
2. **Extended Residence Time:** Despite the extremely high macroscopic gas velocities, the oscillatory trajectory of the particles effectively traps them in the impingement zone, significantly extending their residence time in the specific spatial region of maximum heat and mass transfer.

The volumetric heat transfer coefficients achieved in ISDs are orders of magnitude higher than those observed in traditional flash or rotary dryers, permitting the near-instantaneous removal of unbound surface moisture. This rapid transport mechanism makes the ISD highly effective for the flash drying of temperature-sensitive biochemicals, the recovery of aluminum sulfate, the dehydration of municipal sewage sludge, and the processing of microbiological materials without causing thermal degradation.

6.2 Solving Scale-Up through Parallel Modularity

Traditional pneumatic flash dryers face severe physical height constraints during scale-up, often requiring towers tens of meters high to allow sufficient residence time for large capacities.

Impinging stream dryers elegantly solve this scale-up dilemma through modularity. Because the active drying zone is highly localized exactly at the impingement plane, an ISD can be scaled up by "numbering up"—arranging multiple pairs of impinging jets in parallel or series within a single, highly compact vessel. This modular architecture allows for a massive increase in continuous throughput while maintaining a significantly smaller physical footprint, reducing capital expenditures, and eliminating internal moving parts.

6.3 Pulsed and Intermittent Impinging Jets for Boundary Layer Disruption

To further optimize the heat transfer characteristics of impinging jets, Professor Mujumdar directed extensive numerical and empirical investigations into the effects of imposing pulsation on the turbulent slot impinging jets. Simulations analyzing both cooling and heating scenarios with exceptionally large temperature differences demonstrated that imposing an intermittent (on-off) square-wave pulsation significantly enhances the time-averaged local Nusselt number. This enhancement, observed to range from 10% to 40% under specific Reynolds numbers and nozzle-to-target spacing ratios (e.g., $H/w = 5$, $Re = 11,000$), occurs because the rhythmic pulsation continuously disrupts the hydrodynamic and thermal boundary layers at the stagnation point. By preventing the development of a steady-state thermal resistance layer, the rate of convective heat transfer is structurally magnified. This discovery holds tremendous implications not only for particulate drying but also for the rapid thermal processing of continuous sheets, such as the high-speed drying of tissue paper, textiles, photographic films, and the thermal management of high-power density electronics.

7. Pulsed and Vibrated Fluidized Beds for Cohesive Solids

The drying of cohesive, Geldart Group C particles—such as food powders, fine chemicals, polyhydroxybutyrate (PHB), and biological materials—presents a unique and persistent challenge in fluidization engineering. In these systems, interparticle forces (van der Waals, capillary, and electrostatic bonds) vastly exceed the gravitational and drag forces. Consequently, the bed fails to fluidize uniformly; it fractures, forms stable rat-holes, channels heavily, or defluidizes entirely into a rigid plug. To disrupt these cohesive bonds and restore uniform fluid-solid contact, external mechanical or aerodynamic energy must be actively supplied to the bed.

7.1 Pulsed Fluidized and Spouted Beds

Professor Mujumdar extensively explored the application of low-frequency pneumatic pulsation (typically ranging from 0.2 to 2.0 Hz) to the inlet gas stream. The application of a pulsed, square-wave

airflow introduces a cyclic macroscopic kinetic energy that physically shatters agglomerates and disrupts stable channels.

In pulsed spouted beds, visual tracking and detailed hydrodynamic data indicate that at optimal Strouhal numbers and frequencies, the sharp physical division between the dilute spout and the dense annulus begins to blur, superimposing a macroscopic "jiggling" movement over the standard gulf-stream circulation pattern. Crucially, flow pulsation preserves the upward momentum of the gas jet while minimizing wasteful radial percolation into the lower annulus. This specific dynamic results in a higher maximum spoutable bed height and a significantly enhanced solid circulation rate compared to steady-flow operations using the exact same time-averaged gas volume. The technique has proven particularly effective for complex food particulates of varying geometries (e.g., soybeans, red beans, French beans) where uniform moisture distribution is paramount to final product quality and structural integrity.

7.2 Vibrated Beds: Mechanical Fluidization

Mechanical vibration represents another highly effective method for handling cohesive or highly fragile crystalline materials. In vibrated fluidized beds (VFB), the entire reactor vessel (or the distributor plate) is mounted on an electrodynamic or mechanical shaker. The introduction of specific vibrational amplitudes and frequencies essentially fluidizes the bed mechanically, allowing the convective gas velocity to be reduced well below the theoretical minimum fluidization velocity (U_{mf}).

Operating below U_{mf} provides cascading operational advantages. It drastically reduces the thermal energy required for gas heating, minimizes the entrainment of fine dust particles into the exhaust filtration systems, and critically prevents the attritional degradation of fragile crystals and agglomerated biological products. Furthermore, theoretical modeling demonstrated that tuning the dimensionless vibration number allows operators to deliberately reverse the natural circulation pattern of the bed (e.g., forcing particles to descend near the inclined walls and ascend in the center), thereby enforcing highly specific residence time distributions for exacting quality control in pharmaceutical and food applications.

8. Advances in Spray Drying and Superheated Steam Technologies

Beyond the macro-particulate domains of spouting and fluidization, Mujumdar's work encompasses critical improvements to droplet evaporation dynamics in spray drying and the industrial implementation of Superheated Steam Drying (SSD).

8.1 Spray Drying: Mitigating Glass Transition and Wall Stickiness

Spray drying is a ubiquitous unit operation in the dairy, pharmaceutical, and functional food industries, utilized to transform liquid solutions into dry, free-flowing powders. However, the process is chronically plagued by particle stickiness—a thermodynamic condition where the amorphous product reaches a temperature above its glass transition temperature (T_g) while still retaining a critical moisture content. This causes the particles to become rubbery, leading to severe fouling, product degradation, and eventual fire hazards on the dryer walls.

Leveraging sophisticated CFD models, Mujumdar and his co-researchers simulated the highly complex interactions between droplet evaporation kinetics, turbulent gas dispersion, and temperature-moisture dependent particle rheology. By predicting the exact spatial coordinates within the drying chamber where particles cross their glass transition threshold, engineers can mathematically optimize the atomizer configuration, the primary inlet air swirl, and the chamber geometry. This predictive capacity ensures that droplets dry to a stable, non-sticky state precisely before they physically impact the chamber walls, thereby maximizing yield and minimizing downtime for cleaning.

8.2 Superheated Steam Drying (SSD): A Leap in Thermodynamic Efficiency

Traditional convective dryers utilize heated ambient air or combustion flue gases, ultimately venting a massive amount of unrecoverable latent heat to the atmosphere, contributing to immense energy waste. Superheated Steam Drying fundamentally alters this by replacing air entirely with superheated steam as the convective drying medium.

The thermodynamic and product-quality benefits of SSD are profound and multifaceted:

1. **Total Energy Recovery:** Because the exhaust from the dryer is pure steam (the original drying medium plus the evaporated moisture), the latent heat of evaporation can be completely recovered via condensation in a heat exchanger and reused elsewhere in the plant architecture. If this recovered energy is utilized, the net thermal efficiency of the drying operation approaches theoretical limits.
2. **Absence of Oxidation and Hazard Reduction:** The entirely oxygen-free environment fundamentally prevents oxidation reactions. This preserves the volatile aromas, color, nutritional profile, and bioactive compounds of heat-sensitive materials (e.g., GABA-enhanced rice, exotic fruits, and medical plants). It also inherently eliminates the risk of fire or dust explosions, a chronic hazard in coal and biomass drying.
3. **Enhanced Product Morphology:** In an SSD system, the internal moisture of the particle boils out of the matrix rather than purely diffusing along a concentration gradient. This internal boiling creates a highly porous, less case-hardened structural matrix with vastly superior rehydration properties, which is highly desirable in instant foods and advanced materials.
4. **The Inversion Temperature:** Mujumdar's analyses detailed the phenomenon of the inversion temperature—the specific point above which evaporation in superheated steam actually occurs faster than in dry air, overturning classical assumptions regarding drying kinetics.

Professor Mujumdar has successfully championed the integration of SSD principles into various geometric configurations, including superheated steam fluidized beds, impinging jets, and flash dryers. These implementations target diverse and challenging applications ranging from paper manufacturing and wood processing to the sterilization of municipal waste sludge and the upgrading of low-rank coals.

9. Industrial Applicability and Sustainable Future Operations

The ultimate validation of any engineering research is its successful transition from theoretical modeling in the laboratory to practical, large-scale industrial realization. Professor Mujumdar's vast output has heavily influenced the modernization of industrial practices globally, directly addressing the modern imperatives of energy efficiency and carbon footprint reduction.

In the global energy sector, the pre-drying of low-rank coals, woody biomass, and biosolids prior to combustion or gasification increases boiler efficiency by 5% to 15%, substantially reducing greenhouse gas emissions and improving the viability of alternative energy systems. By implementing ISD and 2DSB technologies, the requisite massive throughputs can be processed with significantly lower capital footprints. In the environmental management sector, the rapid dewatering and drying of municipal sewage sludge utilizing opposed impinging jets resolves an urgent and growing ecological burden.

In the agricultural and food technology sectors, the application of draft-tube spouted beds and heat-pump assisted drying has maximized the retention of volatile aromas, antioxidants, and structural integrity in high-value, heat-sensitive commodities such as cardamom, medical plants, and exotic tropical fruits. The meticulous classification and selection criteria developed by Mujumdar now serve as the recognized industry standard, ensuring that chemical manufacturers correctly pair the physical and rheological properties of the feed material with the optimal thermodynamic and hydrodynamic reactor profile, thereby preventing the costly selection errors that historically plagued the process industries.

10. Conclusion

The extensive publications and research initiatives of Professor Arun S. Mujumdar over the past five decades represent a foundational pillar of modern thermal fluid science and chemical engineering. By aggressively transitioning the study of gas-particle flows from empirical approximation to rigorous, CFD-

validated transport phenomena, his work has solved critical industrial challenges, most notably the scale-up limitations that previously crippled the adoption of conventional spouted and flash dryers.

Groundbreaking geometric innovations such as the two-dimensional drafted spouted bed and modular impinging stream dryers have drastically improved the volumetric processing capacities and thermal efficiencies available to the chemical, food, and energy sectors. Furthermore, comprehensive advancements in pulsed flows, mechanically vibrated beds, and superheated steam technologies highlight a career deeply dedicated to enhancing product quality, maximizing energy conservation, and ensuring operational safety in hazardous environments.

Supported by a robust, multi-disciplinary international network of collaborators and an unwavering commitment to the global dissemination of knowledge, the theoretical frameworks and practical equipment designs established by Professor Mujumdar will undoubtedly dictate the trajectory of sustainable thermal processing for decades to come.

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CHAPTER 6

The Extensive Contributions of Professor Arun S. Mujumdar to Basic and Applied Thermal Sciences: A Five-Decade Retrospective

The evolution of basic and applied thermal sciences over the past half-century has been unequivocally shaped by the pioneering theoretical, computational, and experimental research of Professor Arun S. Mujumdar. Operating at the intricate intersection of fundamental fluid dynamics, thermodynamics, and applied chemical and mechanical engineering, his expansive body of work spans multiple premier institutions. Over the last five decades, he has held distinguished positions at McGill University (Canada), the National University of Singapore (NUS), and the Institute of Chemical Technology (Mumbai, India), while maintaining highly influential distinguished and honorary professorships at King Mongkut's University of Technology Thonburi (Thailand), Jiangnan University (China), Tianjin University of Science and Technology (China), and Jiangsu University (China).

His research has fundamentally advanced the physical understanding of transport phenomena across a wide array of highly specialized and industrially critical domains. This comprehensive report systematically evaluates the monumental academic footprint and underlying physical theories developed by Professor Mujumdar. The analysis focuses specifically on his foundational contributions to flow and convective heat transfer in complex geometric channels (such as coils and curved ducts), the mechanical behavior of Newtonian and non-Newtonian fluids, the emergence and thermo-hydraulic characterization of nanofluids, steady and unsteady transport phenomena in impinging and opposing jets, thermodynamic optimization of single and multiple phase change materials (PCMs), and the critical, often non-linear effects of variable fluid properties induced by massive temperature gradients.

Bibliometric Impact and Scholarly Footprint

Professor Mujumdar's quantitative impact on the scientific literature is exceptional, positioning him as one of the most cited and influential researchers in the global mechanical, chemical, and bioresource engineering communities. An analysis of modern academic databases reveals a staggering citation count exceeding 78,850, underscoring the foundational and highly translational nature of his work.

The durability, breadth, and sustained relevance of his scholarly output are reflected in an h-index of 135 (with some database iterations reporting up to 139) and an i10-index ranging from 986 to over 1,000. These metrics indicate that roughly a thousand of his individual publications have been cited at least ten times, while well over a hundred of his foundational papers have secured more than 135 citations each. This monumental output is the result of decades of rigorous computational fluid dynamics (CFD) modeling, meticulous experimental validation, and extensive collaboration with a global network of specialized researchers, including frequent co-authors such as Agus P. Sasmito, Jundika C. Kurnia, Sakamon Devahastin, Min Zhang, Z. X. Gong, and X. Q. Wang.

His theoretical contributions have been honored globally, culminating in prestigious accolades such as the Platinum Award from his alma mater, the Institute of Chemical Technology (formerly UDCT) in Mumbai, India; Doctor Honoris Causa degrees from Lodz Technical University in Poland and the University of Lyon in France; the China National Scientific and Technological Progress Award; and the establishment of the Arun S. Mujumdar Medal to recognize unparalleled excellence in the field of drying and thermal sciences.

Key Highly Cited Publications and Theoretical Anchors

To properly quantify this impact, a selection of his most influential papers in the domains of nanofluids, PCMs, impinging jets, and drying technology must be examined. These works highlight the trajectory of his

citation footprint and demonstrate how his computational findings have been adopted as baseline truths by subsequent generations of engineers. The following table summarizes key cornerstone publications derived from his extensive bibliography, mapping the sheer scale of his academic reach:

Topic Area	Publication Focus / Title	Publication Year	Approximate Citation Volume
Nanofluids	<i>Heat transfer characteristics of nanofluids: a review</i>	2007	> 3,500
Nanofluids	<i>A review on nanofluids - part I & II: theoretical and numerical investigations / experiments and applications</i>	2008	> 1,570 (combined)
Electronics Cooling	<i>Transient cooling of electronics using phase change material (PCM)-based heat sinks</i>	2008	> 700
Food & Bio-Processing	<i>Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics...</i>	2019	> 660
Phase Change Materials	<i>Application of phase change materials in thermal management of electronics</i>	2007	> 590
Thermal Drying	<i>Drying technology: Trends and applications in postharvest processing</i>	2010	> 510
Thermal Drying	<i>Superheated-steam drying: A bibliography / Superheated steam</i>	1990 / 2014	> 480
Topic Area	Publication Focus / Title	Publication Year	Approximate Citation Volume
	<i>drying of foods and biomaterials</i>		
Impinging Jets	<i>Numerical flow and heat transfer under impinging jets: a review</i>	1989	> 370

These publications serve as theoretical anchors for thousands of subsequent studies in thermal engineering, cementing his legacy in bridging fundamental continuum mechanics with macroscopic, highly efficient engineering systems.

Flow and Heat Transfer in Complex Geometry Channels

The optimization of heat exchangers, chemical reactors, and thermal management devices frequently demands maximizing the convective heat transfer coefficient within the smallest possible physical footprint. Professor Mujumdar's work on curved, wavy, and coiled channels has provided deep mathematical and physical characterizations of how geometry actively induces secondary flows that profoundly augment thermal and mass transport.

The Physics of Secondary Flow and Dean Vortices

When a viscous fluid flows through a standard straight duct, the velocity profile assumes a standard parabolic shape in the laminar regime, and heat transfer is fundamentally limited by radial conduction through the relatively stagnant boundary layer. However, in coiled or curved tubes, the fluid experiences a centrifugal force as it navigates the bend. Because the fluid velocity is highest at the core of the tube and lowest at the walls due to the no-slip boundary condition, the centrifugal force is distributed unevenly across the cross-section. This imbalance forces the higher-velocity, high-momentum core fluid outward toward the outer radius of the curve.

To satisfy the fundamental laws of mass conservation, the slower-moving fluid near the walls is subsequently driven inward along the perimeter of the tube toward the inner radius. This continuous, self-sustaining motion creates two counter-rotating vortices superimposed on the primary axial flow, universally known as Dean vortices. Professor Mujumdar's high-fidelity computational fluid dynamics studies systematically explored this phenomenon across varying finite curvature ratios and pitch parameters. His numerical simulations demonstrated exactly how these Dean vortices continually sweep the thermal boundary layer away from the wall, replacing it with bulk fluid from the core. This continuous boundary layer disruption and fluid renewal drastically reduces the thermal resistance between the wall and the fluid, elevating the Nusselt number significantly compared to equivalent straight channels.

Non-Circular Cross-Sections and Novel Coil Configurations

A major, highly innovative subset of his research involved moving beyond standard circular tubes to examine the thermo-hydraulic behavior of non-circular cross-sections. His models evaluated geometries including square, rectangular, half-circle, triangular, elliptical, and trapezoidal ducts. Each geometric alteration shifts the focal points of the secondary vortices, modifies the local wall shear stress, and changes the fluid residence time in the boundary layer. Through rigorous parametric studies utilizing a constant square-duct Reynolds number (e.g., Re

$= 1000$) and fixed fluid flow rates, his research team investigated the behavior of Newtonian fluids (like water and air) under both constant wall temperature and constant wall heat flux conditions. The findings were highly decisive. For in-plane spiral ducts subjected to constant wall heat flux, the trapezoidal cross-section yielded the superior heat transfer performance among all tested geometries. Furthermore, studies evaluating elliptical tubes demonstrated a 10% higher heat transfer coefficient than circular tubes while concurrently maintaining a lower pressure drop—a crucial metric for pumping economics.

He expanded these detailed investigations into three primary macroscopic coil configurations: in-plane (flat) spiral ducts, helical spiral ducts, and conical spiral ducts. In specialized applications such as microchannel T-junctions used for highly sensitive chemical mixing, the integration of these coiled base designs demonstrated vastly improved species mixing and chemical reaction conversion rates compared to standard straight T-junctions. Similarly, the use of helical strips and twisted tape inserts inside circular pipes was shown to induce extreme swirl motion, creating turbulent flow heat transfer enhancements ranging from 36% to 48% over plain tubes.

Entropy Generation Minimization and the Figure of Merit

The primary engineering penalty for augmenting heat transfer via geometric modification is the corresponding increase in frictional pressure drop, which directly translates to higher pumping power requirements. To holistically address this, Professor Mujumdar advanced the use of a unified thermodynamic metric to evaluate overall performance, relying heavily on the Second Law of Thermodynamics.

He championed the application of Exergy Analysis and Entropy Generation Minimization (EGM) to these complex geometries. By mathematically separating the entropy generated by irreversible heat transfer across a finite temperature difference from the entropy generated by viscous dissipation (fluid friction), his team mapped the exact inefficiencies within the ducts. The resulting simulations revealed a critical insight: entropy production stemming from heat transfer contributions is generally two orders of magnitude higher than the entropy contribution from viscous dissipation in laminar coiled flows. Furthermore, cooling scenarios were found to produce slightly higher total entropy than their heating counterparts.

To provide a practical design tool, he defined a highly effective "Figure of Merit" (FoM). This FoM is calculated as the ratio of the total heat transfer rate to the required pumping power. Through this analytical lens, a complex picture emerged: while a square cross-section was found to generate the highest absolute heat transfer, it paradoxically generated the highest entropy; in contrast, appropriately designed coiled tubes overall provided lower entropy generation and higher efficiency compared to equivalent straight tubes. This holistic thermo-hydraulic approach provides a definitive design guideline for modern compact heat exchangers.

Transport Phenomena in Newtonian and Non-Newtonian Fluids

While the bulk of classical fluid mechanics relies on the assumption of a Newtonian fluid—where shear stress is perfectly, linearly proportional to the shear strain rate—many industrial processes in polymer processing, slurry transport, food engineering, and biochemical synthesis involve complex non-Newtonian fluids. Professor Mujumdar's contributions in this arena address the highly non-linear, coupled differential equations governing such flows.

His continuous research over several decades has tackled the non-isothermal flow of viscous non-Newtonian fluids within both circular and non-circular ducts, collaborating with international institutions ranging from Czech Technical University in Prague to the University of Port Harcourt in Nigeria. For non-Newtonian fluids exhibiting pseudoplastic (shear-thinning) or dilatant

(shear-thickening) behaviors, the apparent viscosity becomes a localized function of the velocity gradient rather than a constant property. In channels with complex geometries—such as sharp corners in rectangular or triangular ducts—the shear rate varies immensely across the cross-section, meaning the fluid viscosity is highly heterogeneous throughout the flow field. Professor Mujumdar's computational models expertly accounted for these varying viscosities under combined thermal and hydrodynamic development. In non-isothermal flows, the temperature dependence of the non-Newtonian consistency index and flow behavior index couples the energy and momentum equations in a mathematically stiff manner. His investigations explored how this coupling induces thermal stratification and severely alters the expected velocity profiles. By integrating the effects of chemical reactions and convective boundary conditions with non-Newtonian behavior, his work has enabled the chemical and food industries to accurately predict residence time distributions, pressure drops, and heat transfer coefficients in continuous-flow extrusion and complex duct systems.

Nanofluid Heat Transfer: Theoretical Frameworks and Applications

In the early 2000s, the dispersion of nanometer-sized particles—such as metals, metal oxides, or carbon nanotubes—into conventional base fluids like water, oil, or ethylene glycol emerged as a revolutionary method to overcome the inherently low thermal conductivity of liquid coolants. Professor Mujumdar was a critical early voice in systematizing and clarifying this nascent field. He produced seminal, comprehensive

review papers in 2007 and 2008 that remain some of the most heavily cited works in the discipline, individually amassing thousands of citations.

Mechanisms of Thermal Enhancement

Classical effective medium theories, such as the Maxwell-Garnett model, significantly underpredict the thermal conductivity of nanofluids because they assume a static suspension of solid particles at the macro-scale. Professor Mujumdar's rigorous syntheses of the literature helped categorize the dynamic, micro- and nano-scale mechanisms responsible for the anomalous heat transfer enhancement.

His collaborative works detailed how the Brownian motion of the nanoparticles induces micro-convection in the surrounding base fluid. The particles effectively act as nano-stirrers that actively disrupt local thermal gradients within the fluid matrix. Additionally, his research explored the concept of interfacial liquid layering, wherein the base fluid molecules form highly ordered, solid-like crystalline structures at the surface of the nanoparticles. These ordered layers provide ballistic phonon transport pathways that bridge the solid-liquid interface, drastically reducing thermal boundary resistance. Other mechanisms meticulously analyzed included thermophoresis (the migration of particles due to an applied temperature gradient) and the effect of particle clustering, which, when properly controlled, can create highly conductive percolation networks through the fluid matrix.

Preparation, Stability, and Rheological Challenges

A central, recurring theme in Professor Mujumdar's assessment of nanofluids is the practical hurdle of dispersion stability. Because nanoparticles possess extremely high surface area-to-volume ratios, they exhibit a strong thermodynamic drive to minimize their surface energy by agglomerating through van der Waals forces.

His research reviews critically evaluated various preparation methods, contrasting one-step synthesis methods with two-step dispersion methods. Techniques such as the submerged arc nanoparticle synthesis system (SANSS) and microwave synthesis were scrutinized for their efficiency and particle morphology control. To combat agglomeration, his work highlighted stability enhancement techniques, including the use of surfactants (such as Tween 80 or sodium dodecylbenzene sulfonate), pH control to alter the zeta potential, and high-shear ultrasonication. For instance, adjusting the fluid to maintain a high absolute zeta potential (typically beyond ± 30 mV, though some sterically stabilized systems function at ~ 12.5 mV) induces electrostatic or steric repulsion between particles, directly counteracting van der Waals attraction. Visual sedimentation, UV-Vis spectroscopy, and dynamic light scattering are critical tools his teams advocated for quantifying this stability over time. However, he also cautioned that the addition of surfactants can foam the liquid or thermally degrade at high temperatures, which limits the applicability of the nanofluid in high-heat-flux environments.

Furthermore, his analyses highlighted the severe rheological penalties of nanofluids. While small volume fractions of nanoparticles dramatically increase thermal conductivity (in some experimental loops, enhancing heat transfer by up to 60%), they concurrently increase the dynamic viscosity in a non-linear fashion. This leads to elevated pumping power requirements and increased pressure drops.

Advanced Hybrid Nanofluids and Sector Applications

To bypass these limitations, his later collaborative work explored advanced hybrid nanofluids, such as combinations of BN + SiC/water or Al₂O₃ + CuO/water systems. These studies established that tuning particle shapes and sizes—specifically utilizing non-spherical, high-aspect-ratio particles like nanotubes within the 10nm to 90nm range—can optimize the thermo-hydraulic performance. These highly engineered fluids offer up to a 50% enhancement in heat transfer over the base fluid while mitigating prohibitive frictional losses.

The translational impact of these insights is vast. Professor Mujumdar's work has guided the application of nanofluids in solar concentrating collectors, where altering the working fluid to a nanofluid can increase thermal and optical efficiencies by 11% to 12%. The aerospace and defense sectors utilize these lightweight, high-efficiency fluids for compact thermal management, while the automotive industry relies on them to cool high-horsepower engines without increasing the physical size of the radiator.

Steady and Unsteady Transport Phenomena in Impinging and Opposing Jets

Jet impingement is characterized by exceptionally high localized heat and mass transfer coefficients, making it a critical technology for cooling high-power electronics, tempering glass, annealing metals, de-icing aircraft wings, and rapidly drying continuous sheets of paper and textiles. Professor Mujumdar has dedicated much of his career to mathematically modeling and physically decoding the highly complex flow topologies of both single and multiple impinging jets.

Steady Impinging Jets and the Challenge of Turbulence Modeling

The flow field of an impinging jet is classically divided into three distinct zones: the free jet region, the stagnation (or impingement) zone, and the radial wall jet region. In the stagnation region, the fluid undergoes severe deceleration in the axial direction and extreme acceleration in the radial direction. This high rate of normal strain proves notoriously difficult for classical computational turbulence models to predict accurately.

Professor Mujumdar's extensive numerical experiments evaluated the efficacy of virtually every standard computational model. The standard high-Reynolds number k - ϵ model, built on the Boussinesq approximation, suffers from the "stagnation point anomaly"—it drastically overpredicts the production of turbulent kinetic energy (k) near the impingement point due to its mathematical inability to correctly interpret normal strain rates.

Mujumdar and his collaborators rigorously demonstrated that low-Reynolds number k - ϵ models, often coupled with a "Yap correction" to explicitly limit the turbulent length scale near the wall, yield far superior predictions for heat transfer and fluid mechanics.

Additionally, his work highlighted the specialized utility of the Re-Normalization Group (RNG) k - ϵ model and Reynolds Stress Models (RSM). The RSM solves independent, exact transport equations for each component of the Reynolds stress tensor, naturally accounting for the severe flow anisotropy in the stagnation zone. These comparative studies remain a benchmark for engineers selecting CFD models for high-strain flows.

Unsteady, Intermittent, and Pulsed Jet Dynamics

While steady impinging jets offer high heat transfer, spatial non-uniformity and boundary layer thickening in the wall jet region remain persistent operational challenges. To disrupt these physical limitations, Mujumdar investigated unsteady, pulsating jets.

Early literature on pulsating jets was highly contradictory; some studies claimed vast improvements in the Nusselt number, while others reported outright deterioration of heat transfer. Professor Mujumdar's sophisticated numerical simulations successfully isolated the specific forms of pulsation that dictate enhancement. He found that simple sinusoidal pulsation often results in no noticeable enhancement because the injected energy merely oscillates the hydrodynamic boundary layer without possessing the sheer kinetic energy required to break it. However, when the jet is subjected to *intermittent* (on-off or square-wave) pulsation, the results are radically different. The sudden, violent initiation of the jet in an intermittent cycle creates highly coherent, energetic vortex rings at the nozzle lip. When these starting vortices strike the target surface, they violently scour the thermal boundary layer, inducing massive entrainment of the surrounding ambient fluid. Professor Mujumdar's computational models proved that this intermittent pulsation yields significant time-averaged heat transfer enhancements—up to 12% in the stagnation zone and 35% in the wall jet zone—across a wide range of nozzle-to-target spacings and turbulent Reynolds numbers.

Confined Impinging Streams and Opposing Jets

Beyond single-surface impingement, Professor Mujumdar pioneered studies on confined opposing jets (also known as impinging streams). In this highly specialized configuration, two turbulent streams collide head-on along the same axis, creating a highly volatile, narrow stagnation region characterized by extreme turbulent mixing and shear.

This setup is invaluable for chemical engineering unit operations, such as reaction injection molding, rapid absorption and desorption, dust collection, evaporative cooling, and the drying of high-moisture-content particles, where ultra-fast macro- and micro-mixing of reagents is required. Utilizing sophisticated turbulence models, including large eddy simulations (LES) and composite k - ϵ models, his research characterized the coherent organized structures and inherent flow instabilities within the collision zone. By mathematically analyzing the highly chaotic oscillations of the stagnation plane, his work provided the exact geometrical ratios and Reynolds numbers required to maximize mixing efficiency in opposed-jet T-junction microreactors and catalytic monolith reactors.

Heat Transfer in Single and Multiple Phase Change Materials (PCMs)

Latent heat thermal energy storage (LHTES) utilizes the high latent heat of fusion of Phase Change Materials (PCMs)—such as paraffin waxes (e.g., RT27, RT44, RT58), fatty acids, or salt hydrates—to store and release massive amounts of thermal energy isothermally. While PCMs offer immense energy density, they suffer from a fatal physical flaw: extremely low thermal conductivity (typically around $0.2 \text{ W/m} \cdot \text{K}$ for organic PCMs). Professor Mujumdar's research has been highly instrumental in overcoming this fundamental barrier through macroscopic geometry optimization, high-conductivity matrices, and novel multi-PCM configurations.

Electronics Cooling using PCM Heat Sinks

In modern electronics and telecommunications, microprocessors often face intermittent, highly intense thermal spikes. Standard sensible heat sinks (like aluminum fin arrays) rapidly rise in temperature during these spikes, risking catastrophic thermal failure of the silicon die. Professor Mujumdar investigated embedding specific PCMs within the cavities of these heat sinks.

During a sudden power surge, the PCM melts, absorbing the thermal transient as latent heat and effectively pinning the junction temperature at the PCM's melting point. His three-dimensional CFD simulations—tracking the moving solid-liquid interface using the advanced enthalpy-porosity formulation—revealed the highly complex interplay of pure conduction in the solid matrix and natural convection within the expanding melt pool. Because the molten PCM physically expands and traps air, his models meticulously accounted for multi-phase interactions within the sealed enclosure. His experimental and numerical results proved conclusively that PCM-based heat sinks significantly extend the operational time of electronics before critical failure temperatures are reached, provided the system allows adequate time for the PCM to resolidify by dissipating heat during idle periods.

The Innovation of Multiple PCMs (Cascaded Thermal Energy Storage)

Perhaps Professor Mujumdar's most celebrated and universally adopted contribution to LHTES is his foundational work on Multiple PCMs, widely known as Cascaded Thermal Energy Storage (CTES).

In a traditional shell-and-tube storage system using a single PCM, a Heat Transfer Fluid (HTF) flows through the central tube to melt the PCM (the charging phase). As the HTF transfers heat radially, its bulk temperature drops along the axial length of the tube. Consequently, the temperature difference (ΔT) between the HTF and the PCM shrinks exponentially toward the exit. This drastically reduces the heat transfer rate, leaving the PCM at the far end of the storage completely un-melted for unacceptably long durations.

Professor Mujumdar and his frequent co-author Z. X. Gong developed a novel storage unit that fundamentally solves this problem. They replaced the single PCM with a series of distinct PCMs arranged axially, each possessing a sequentially lower melting temperature in the direction of the HTF flow. As the HTF cools along the tube, it encounters a new PCM with a correspondingly lower melting point. This ingenious configuration preserves a large, nearly constant ΔT between the fluid and the storage medium throughout the entire length of the heat exchanger.

His team conducted rigorous numerical simulations comparing systems loaded with two, three, five, and even an infinite theoretical number of PCMs against a standard single PCM. The results demonstrated that the cascaded arrangement accelerates the overall melting and solidification rates by 15% to 25%, significantly enhancing both the absolute energy charge/discharge rates and the exergetic (second-law) efficiency of the entire thermal system.

Matrix Enhancements: Metal Foams, Fins, and Composites

To combat the poor thermal conductivity of PCMs on a localized scale, Professor Mujumdar investigated integrating high-porosity solid matrices into both single and cascaded systems. By embedding the PCM within metal foams (e.g., copper or aluminum), the continuous metallic struts provide a highly efficient, unobstructed conduction pathway directly from the heat source into the deep core of the PCM.

Enhancement Technique	Primary Mechanism	Thermal Impact
Cascaded PCMs (CTES)	Sustains high ΔT along the flow path by stepping down melting points.	Increases charge/discharge rates by 15-25%.
High-Porosity Metal Foams	Provides continuous solid conduction pathways directly into the PCM core.	Multiplies total heat transfer rate by 2 to 7 times compared to pure PCM.
Shape-Stabilized Composites	Impregnates paraffin (e.g., RT27) into expanded perlite or carbon foam scaffolds.	Prevents liquid leakage; boosts thermal conductivity by 68-80% at operational temps.
Fin/Pin Array Optimization	Maximizes contact surface area between the heat sink wall and the PCM.	Drastically reduces melting time; delays time-to-critical-temperature in electronics.

His investigations revealed that metal-foam-enhanced CTES systems not only make the spatial temperature distribution vastly more uniform, but they exponentially reduce solidification times. Furthermore, his research covered shape-stabilized PCMs. By utilizing vacuum impregnation to load paraffin into expanded perlite (EP), then coating it with a waterproof agent like Sikalutex® and mixing it with aluminum powder, his team created highly stable thermal composites boasting energy storage capacities of ~51.5 kJ/kg without any risk of liquid leakage. By mathematically optimizing fin structures, pin geometries, and dual-PCM composite slabs, his work provided the engineering blueprints for next-generation triplex-tube heat exchangers and zero-energy building materials.

Effect of Variable Fluid Properties Due to Large Temperature Differences

A pervasive and often dangerous assumption in classical convective heat transfer analysis is that the thermophysical properties of the fluid (density, dynamic viscosity, specific heat, and thermal conductivity) remain perfectly constant, save for minor density variations that drive natural convection (the Boussinesq approximation). However, in intense industrial applications such as fast paper drying, turbine blade cooling, deep-well extraction, and solar receiver operations, the temperature differences (ΔT) between the boundary surface and the bulk fluid can easily exceed several hundred degrees (e.g., 50°C to 300°C). Under

these extreme conditions, the constant-property assumption completely collapses, leading to massive engineering errors in predicting friction factors and required pumping power.

Professor Mujumdar's advanced numerical models rigorously eliminated these simplifications, allowing properties to vary as fully dynamic, localized functions of the computed temperature field.

Impact on Coiled Tubes and Secondary Flows

In his studies of helical and coiled tubes, introducing temperature-dependent properties radically altered the predicted flow topologies. When a liquid fluid is being cooled (where the wall temperature is significantly lower than the bulk fluid temperature), the viscosity of the fluid directly adjacent to the wall increases exponentially.

This sharp near-wall viscosity gradient drastically increases the local frictional resistance. More importantly, because the secondary Dean vortices rely on the inward flow of the near-wall fluid to complete their rotation, the increased viscosity acts to physically dampen and suppress the kinetic strength of these vortices. Consequently, Professor Mujumdar found that the actual friction factor for a cooling liquid in a curved tube is substantially higher than what standard constant-property models predict, and the promised heat transfer enhancement provided by the coil is heavily mitigated. To provide a scalable, usable engineering solution, his team developed a highly accurate property-ratio mathematical technique that allows engineers to adjust classical constant-property correlations to account for these massive thermal gradients without re-running exhaustive CFD simulations.

Impact on Impinging Jets

Similarly, Professor Mujumdar analyzed pulsed turbulent impinging jets under extremely large temperature differences, typical of heavy industrial paper and textile drying. In these scenarios, not only does the fluid density vary—affecting the kinematic momentum of the jet as it travels from the nozzle to the impingement plate—but the fluctuating thermal conductivity and specific heat constantly alter the diffusion of thermal energy in the highly strained stagnation region.

By directly coupling the non-linear fluid property equations into the Navier-Stokes and energy conservation solvers, his simulations captured the complex, non-linear dynamic responses of the hydrodynamic and thermal boundary layers. The models accurately predicted the phase shifts and amplitude dampening of the temperature pulses as they propagated through the highly viscous near-wall sublayer. This provided critical, previously unknown insight into why some high-temperature industrial drying processes fail to achieve the mass transfer rates predicted by idealized, isothermal theoretical models.

Broader Implications and Industrial Translation

The underlying theoretical mechanics established by Professor Mujumdar do not exist in an academic vacuum; they have profoundly altered the practical trajectory of applied thermal engineering, particularly in the fields of industrial drying and thermal management.

By understanding exactly how impinging jets scour boundary layers and how massive temperature gradients alter fluid properties, his work directly informed the design of high-efficiency superheated steam dryers and pulse-combustion drying systems for the paper, timber, bioresource, and food processing industries. His exhaustive characterization of entropy generation in coiled tubes and his invention of cascaded phase change materials have provided the renewable solar energy sector with the geometric and thermodynamic templates necessary to construct high-density latent heat storage systems that can finally smooth out the diurnal fluctuations of solar power. Furthermore, his foundational syntheses on nanofluids laid the exact theoretical groundwork required for modern liquid-cooled microchannel heat sinks, which are now essential for the thermal management of today's high-density microprocessors and electric vehicle lithium-ion battery packs.

Conclusion

Over the past five decades, Professor Arun S. Mujumdar has served as a primary architect of modern thermal and fluid sciences. His exhaustive bibliometric footprint, characterized by nearly 80,000 citations and heavily cited cornerstone publications that define entire sub-disciplines, is merely a quantitative reflection of the profound depth and utility of his scientific inquiry.

By systematically dismantling the dangerous simplifying assumptions of classical fluid mechanics—moving engineering from straight to complex geometric coils, from linear Newtonian to non-linear non-Newtonian flows, from constant to highly variable thermophysical properties, and from steady to intermittently pulsed boundary conditions—he has continuously pushed computational models closer to complex physical reality. His rare ability to traverse physical scales, moving seamlessly from the Brownian mechanics of nanofluids to the macroscopic thermodynamic optimization of cascaded phase change materials, demonstrates a holistic mastery of transport phenomena. Ultimately, Professor Mujumdar's enduring legacy is codified in the very transport equations and engineering designs that will continue to govern global energy storage, thermal management, and industrial processing for decades to come.

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CHAPTER 7

Quantitative Analysis of Fundamental and Applied Transport Phenomena Research by Professor Arun S. Mujumdar

Introduction

Professor Arun S. Mujumdar has established a globally recognized research portfolio characterized by profound contributions to chemical engineering, mechanical engineering, and applied physics. While his foundational role in establishing the academic framework for industrial drying technologies is universally acknowledged, his quantitative and theoretical advancements in broader transport phenomena are equally extensive. With an exceptional bibliometric footprint—exceeding 78,600 citations, an h-index of 135, and an i10-index of 980—his research has reshaped modern paradigms in convective heat transfer, computational fluid dynamics (CFD), and multiphase flows¹.

His interdisciplinary trajectory began outside of academia as an aerodynamicist at the Carrier Corporation Research Center, where he focused on turbulent heat transfer and mastered computational fluid dynamics primarily from aerospace and nuclear engineering literature². This early exposure catalyzed a decades-long academic pursuit of complex fluid mechanics. This report provides an exhaustive, quantitative synthesis of Professor Mujumdar's pioneering investigations into non-drying transport phenomena, encompassing nanofluid thermal dynamics, phase change materials (PCMs) for electronics thermal management, turbulent impinging jet mechanics, microreactor secondary flows, and porous media phase transformations.

Nanoscale Thermal Transport and Rheology in Nanofluids

Convective heat transfer can traditionally be augmented passively by altering flow geometry or boundary conditions, but the fundamental limitations of base fluid thermal conductivity remained a bottleneck until the advent of nanofluids—a term coined in 1995 for stable colloidal suspensions of nanoparticles³. Professor Mujumdar emerged as a definitive authority on the theoretical and numerical underpinnings of these suspensions. His 2007 comprehensive review on the heat transfer characteristics of nanofluids has amassed over 3,000 citations, forming the bedrock for modern computational investigations¹.

Micro-Scale Mechanisms of Thermal Conductivity Enhancement

Conventional effective medium theories, which rely strictly on static particle size, shape, and volume fraction to predict the effective thermal conductivity of multiphase mixtures, drastically underpredicted the empirical performance of nanofluids³. Professor Mujumdar's analytical models systematically evaluated the anomalous enhancements by integrating dynamic micro-scale phenomena.

His research isolated several primary drivers of thermal enhancement:

1. **Brownian Motion:** While initial hypotheses attributed the extraordinary thermal transport heavily to micro-mixing induced by the Brownian motion of nanoparticles, Mujumdar's synthesized models, validated by molecular dynamics simulations, indicated that the direct contribution of Brownian motion is relatively minor compared to localized thermophoretic and osmophoretic forces³.
2. **Interfacial Liquid Nanolayering:** A highly ordered, solid-like liquid molecular layer forms at the nanoparticle-fluid interface. Mathematical modeling demonstrated that treating the nanofluid as a three-component medium (core particle, highly conductive shell/nanolayer, and bulk fluid) provides a vastly more accurate prediction of effective thermal conductivity⁴.
3. **Surface Charge and pH:** The thermal performance of a nanofluid was found to be highly dependent on its pH relative to the isoelectric point of the suspended particles. Greater divergence from the isoelectric point yields higher colloidal stability and, consequently, a greater enhancement in thermal conductivity³.

Experimental and Hybrid Nanofluid Characterizations

Empirical investigations focusing on Al_2O_3 , CuO , and TiO_2 nanoparticles suspended in water and ethylene glycol (EG) matrices provided robust quantitative validation for these models⁶. For instance, a 4% volume fraction of CuO in an EG base fluid was experimentally shown to augment thermal conductivity by more than 20%, with low volume fractions (<0.05%) exhibiting a near-linear relationship between particle concentration and conductivity ratios⁹.

Mujumdar later expanded this framework to hybrid nanofluids, evaluating the synergistic effects of co-dispersing multiple nanomaterials, such as highly hydrophilic graphene oxide (GO) and nano- Al_2O_3 ¹⁰. Comprehensive stability testing determined that optimal thermo-physical properties for these hybrid suspensions were achieved at a pH of 11, utilizing 1% sodium dodecyl sulfate (SDS) dispersant, and subjected to 375 W of ultrasonic homogenization for 120 minutes. Under these parameters, a newly proposed thermal conductivity model integrating structural agglomeration and Brownian dynamics successfully predicted the hybrid fluid's behavior¹⁰.

Non-Newtonian Rheology

Because the addition of solid nanoparticles alters the base fluid's viscosity, Mujumdar investigated the rheological characteristics governing the pumpability and pressure-drop penalties of nanofluids⁸. EG-based nanofluids synthesized with 5–20% concentrations of Al_2O_3 , CuO , and TiO_2 (ranging from 20 nm to 70 nm in diameter) exhibited distinct non-Newtonian, shear-thinning behaviors. By fitting experimental viscosity-shear rate data into rheological power-law models and solving the resultant boundary layer equations via Runge-Kutta numerical methods, his work quantitatively proved that increasing nanoparticle concentration invariably thickens the displacement and momentum boundary layers, reducing overall velocity profiles while elevating temperature profiles⁸.

Nanofluid Parameter	Governing Mechanism	Quantitative Impact / Observation
Particle Concentration	Three-component effective medium theory.	Conductivity increases linearly at volume fractions ϕ_p ; 4% CuO /EG yields $\sim 20\%$ thermal enhancement. ⁹
Interfacial Nanolayer	Solid-like liquid structuring at the particle boundary.	Drastically reduces boundary Kapitza resistance, forming the primary conductive bridge. ³
Isoelectric pH Divergence	Electrostatic repulsion preventing agglomeration.	Maximizes colloidal stability and thermal efficiency. ³

Nanofluid Parameter	Governing Mechanism	Quantitative Impact / Observation
Particle Diameter	Specific surface area (SSA) optimization.	Decreasing particle size increases SSA, typically scaling thermal conductivity linearly. ⁷

Latent Heat Thermal Energy Storage and Electronics Thermal Management

As miniaturization trends exponentially increased the power densities of microprocessors and integrated circuits, conventional sensible heat sinks became thermally inadequate. Professor Mujumdar executed highly cited computational and experimental research demonstrating the efficacy of Phase Change Materials (PCMs) in passive electronics cooling¹¹. His 2008 seminal paper on transient cooling utilizing PCM-based heat sinks has garnered nearly 660 citations, fundamentally altering thermal management design for intermittent-use devices¹.

Conjugate Heat Transfer in PCM Heat Sinks

During transient computational spikes, the latent heat of fusion intrinsic to PCMs enables the absorption of massive thermal loads isothermally, temporarily pinning the die junction temperature near the material's melting point and effectively extending the operational time before the Thermal Design Power (TDP) limit is breached¹². Studies evaluating paraffin wax and n-eicosane within narrow microchannel enclosures mapped the solid-liquid phase front propagation using the enthalpy-porosity method.

However, organic PCMs generally suffer from exceedingly low thermal conductivity, which dampens the melting rate and exacerbates supercooling phenomena during the discharge (solidification) phase¹⁵. To address this, Mujumdar analyzed Nanoparticle-Enhanced Phase Change Materials (NEPCMs). Dispersing metallic oxides (, ,) into the organic matrix significantly reduced thermal resistance.

Extensive computational fluid dynamics (CFD) modeling of a Single Thermal Energy Storage (STES) system revealed that dispersing Al_2O_3 nanoparticles into paraffin wax at volume concentrations of 1%, 3%, 5%, 7%, and 10% progressively accelerated both melting and solidification. At the maximum 10% concentration, the effective thermal conductivity improved by 33%, yielding a total time-saving of 11.76% to 12% in the charging (melting) process and 15.71% to 19.60% in the discharging process, depending on the conjugate convective velocity of the surrounding heat transfer fluid¹⁶.

Battery Thermal Management Systems (BTMS)

Scaling PCM models from microelectronics to macro-scale energy storage, Mujumdar tackled the critical issue of thermal runaway in high-capacity lithium-ion batteries. In a highly cited 2011 study on passive thermal management for spiral-wound lithium-ion batteries (228 citations), he coupled electrochemical heat generation kinetics with localized transient thermal transport⁵. The modeling explicitly accounted for reversible/irreversible entropic heat and ohmic heating, revealing how localized hot spots propagate radially through the cell layers¹⁷. Integrating PCM matrices within the battery modules successfully buffered these thermal spikes, facilitating safer operation under aggressive discharge rates¹¹.

Aerodynamics and Turbulent Impinging Jet Mechanics

Impinging jets generate localized convective heat transfer coefficients that are up to an order of magnitude higher than parallel flow conditions, making them indispensable for high-intensity heating, cooling, and annealing applications¹⁸. Mujumdar's expertise in aerodynamics resulted in rigorous analyses of the stagnation and wall-jet regions of both laminar and turbulent jets¹⁹.

Turbulence Modeling and Validation

The hydrodynamics of a turbulent jet impinging on a solid surface are notoriously difficult to predict via CFD due to severe streamline curvature and steep normal velocity gradients.

Standard high-Reynolds number $k-\epsilon$ models routinely overpredict the turbulent kinetic energy (k) near the impingement surface, resulting in erroneous stagnation Nusselt numbers (Nu_{st}) . Mujumdar systematically evaluated low-Reynolds number formulations and Reynolds Stress Models (RSM),

discovering that the implementation of the "Yap correction" alongside composite turbulence formulas drastically improved the alignment between numerical simulations and experimental heat flux profiles²¹.

His generalized heat transfer functions define the exact scaling of the Nusselt number. At the laminar stagnation point ($r/d < 0.5$), the function scales as $Nu_{st} = 0.72 Re^{0.5} Pr^{0.4}$, while in the fully developed turbulent wall-jet region ($r/d > 10$), the exponent shifts, approximated by 19.

Intermittent, Pulsatile, and Twin Jets

Recognizing that steady-state convection is limited by a persistent near-stagnant fluid boundary layer, Mujumdar investigated hydrodynamic perturbations to actively strip this layer away. While continuous sinusoidal pulsations yielded minimal or slightly negative heat transfer enhancements at the stagnation point, extreme non-linear flow disruptions proved highly effective²².

Intermittent "on-off" square-wave pulsations allowed the thermal boundary layer to repeatedly collapse and rebuild. Over a wide range of jet Reynolds numbers and nozzle-to-plate spacings, this intermittent pulsation increased the time-averaged Nusselt number by up to 12% in the stagnation zone and an exceptional 35% to 40% in the wall-jet zone²³.

To further modulate the spatial distribution of the heat flux, his team modeled twin turbulent slot jets impinging on self-affine sinusoidal rough surfaces. The interaction between the adjacent jets (defined by the jet-to-jet spacing ratio, S/w) and the surface roughness (amplitude ϵ and frequency f) created a highly fluctuating local Nusselt number profile characterized by pronounced peaks and valleys. Introducing a dimensionless enhancement factor (η), the data confirmed that manipulating the Reynolds number (ranging from 2,000 to 14,000) and spacing parameters could precisely tune the thermal load profile²⁴. Recent extrapolations of these arrays have successfully leveraged Convolutional Neural Networks (CNNs) as surrogate models to predict complex Nusselt distributions with a normalized mean average error below 2%, enabling real-time thermal active control²⁵.

Impinging Jet Configuration	Key Aerodynamic Behavior	Convective Heat Transfer Outcome
Steady Slot/Round Jet	Boundary layer transitions from laminar (stagnation) to turbulent (wall-jet).	Predictable radial Nusselt decay; modeled accurately using low-Re k with Yap correction. ¹⁹
Sinusoidal Pulsatile Jet	Modulates incoming velocity without boundary layer collapse.	Negligible enhancement; occasionally reduces stagnation heat transfer due to flow interference. ²²
Intermittent (Square) Jet	Periodic, complete breakdown of the	Highly effective; boosts time-averaged Nusselt by
	hydrodynamic layer.	up to 12% (stagnation) and 40% (wall). ²³

Impinging Jet Configuration	Key Aerodynamic Behavior	Convective Heat Transfer Outcome
Twin Jets on Rough Surface	Jet-jet interference coupled with topographical vortex shedding.	Creates highly localized, tunable heat flux peaks; quantifiable via dimensionless
		enhancement factor ~ 2.4 

Transport Phenomena in Microreactors and Complex Ducts

In parallel with his work on macro-scale convection, Mujumdar spearheaded the optimization of transport phenomena within micro-scale geometries. In microreactors, strict laminar flow regimes inhibit advective mixing, forcing systems to rely on inherently slow molecular diffusion. Mujumdar demonstrated that inducing complex secondary flows via geometric curvature drastically accelerates mass transport and catalytic reaction rates²⁶.

Fractal Tree-Shaped Networks

Drawing upon biomimetic constructal theory, Mujumdar investigated heat sinks embedded with tree-shaped bifurcating microchannels. For networks optimized under a fixed volume constraint, CFD modeling revealed that the ideal successive diameter ratio follows Murray's Law, minimizing flow resistance identically to biological vascular systems²⁸. Furthermore, under a constant channel area constraint, optimizing the successive length ratio according to a $2^{-2/3}$ power law yields the highest thermal-hydraulic performance²⁸.

Thermal modeling exposed critical aerodynamic realities within these networks. At each bifurcation, the fluid forms a new stagnation point, allowing the laminar boundary layer to restart and thereby enhancing the local heat transfer coefficient²⁹. However, the bifurcation angle (θ) is a vital parameter; extreme angles (e.g., 180°) force sharp flow reversals that create low-velocity recirculation eddies at the outer corners, generating undesirable high-temperature spots²⁹. Smoothly filleted angles around 30° mitigated these local flow separations, proving that fractal networks offer vastly superior temperature uniformity and lower global pressure drops compared to conventional parallel or serpentine channels²⁹.

Coiled T-Junction Microreactors and Dean Vortices

To solve the mixing bottlenecks inherent to straight T-junction microreactors, Mujumdar's group evaluated conical, in-plane, and helical spiral channel layouts²⁶. In coiled geometries, centrifugal forces create strong radial pressure gradients across the fluid core. To satisfy momentum conservation near the inner and outer walls, secondary counter-rotating circulatory flows—known as Dean vortices—are established perpendicular to the primary axial flow³⁰.

These secondary flows actively fold and stretch fluid interfaces, shifting the mixing paradigm from diffusion to robust advection. Quantitative mass fraction tracking in methane oxidation catalytic models revealed that coiled T-junctions eliminate the stratified, unmixed concentration boundaries persistent in straight channels²⁷. Among the configurations tested, helical spiral channels of a square cross-section delivered the highest reactant conversion rate and optimal Figure of Merit (the ratio of heat transferred per unit of pumping power)²⁷.

Cross-sectional geometry further dictates performance: modeling across square, rectangular (2x1, 4x1), triangular, trapezoidal, and half-circular profiles established that trapezoidal ducts optimize heat transfer under constant heat flux conditions, whereas rectangular channels excel under constant temperature constraints, albeit at a steep pumping power penalty³¹. Moreover, applying an intermittent pulsating flow (100 Hz frequency, varying from 0.5 to 2 m/s amplitude) to the separate inlet branches of the T-junction almost doubled the chemical yield compared to a steady flow, all while consuming the exact same net pumping energy³².

Temperature-Dependent Thermo-Physical Properties

A critical limitation in earlier coiled-tube literature was the assumption of constant fluid properties. Mujumdar extended the fundamental physics by analyzing laminar forced convection in coiled tubes using highly viscous fluids (e.g., diethylene glycol) while actively coupling temperature-dependent variations in density, viscosity, thermal conductivity, and specific heat³⁰. As the fluid is cooled, viscosity spikes near the

tube wall. This localized stiffening effectively dampens the centrifugal force, stifling the generation of the Dean vortices. Consequently, the actual friction factor under cooling conditions is significantly higher—and the Nusselt number lower—than models predicting constant properties would suggest³⁰. Employing a property-ratio technique, Mujumdar derived robust new correlations mapping local friction factors (f_w) and Nusselt numbers (Nu_w) along the tube circumference, providing highly accurate predictive tools for industrial heat exchanger design³⁰.

Multiphase Flow and Heat Transfer in Porous Media

Mujumdar's proficiency in resolving conjugate boundary conditions translated directly into macro-scale geological and energy systems. His research frequently tackled the coupling of solid, liquid, and vapor phases traversing porous matrices.

Artificial Ground Freezing (AGF)

In civil engineering and subterranean mining, Artificial Ground Freezing (AGF) is employed to temporarily solidify porous groundwater domains, establishing impermeable structural barriers. The physics of AGF dictate transient, multi-phase, conjugate heat transfer as groundwater interacts with bayonet freeze pipes³⁴. The conventional methodology utilizes a continuous circulation of cryogenic brine, resulting in massive, sustained energy expenditures.

Mujumdar and collaborators derived a rigorous mathematical framework encapsulating multiscale transport phenomena—quantifying net energy fluxes, groundwater seepage streamlines, and heatlines to accurately map the ice growth propagation³⁴. This predictive capacity enabled the conceptualization of a "Freezing-on-Demand" (FoD) operational mode. By intelligently modulating the brine circulation based on real-time thermal ground responses rather than maintaining a continuous flow, the numerical models confirmed that FoD protocols can slash the total energy consumption of AGF systems by up to 46% without compromising the structural integrity of the frozen ground³⁴.

Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

In the field of renewable energy, Mujumdar extensively modeled the highly coupled, nonisothermal transport processes inside Polymer Electrolyte Membrane Fuel Cells (PEMFCs)¹⁷. PEMFCs operate via simultaneous mass, momentum, species, energy, and charge conservation across highly porous gas diffusion layers, solid catalyst layers, and polymeric membranes.

His foundational continuum models addressed the critical interphase mass transfer of water ($\dot{m}_{H_2O}$) between vapor and liquid phases¹⁷. Liquid water velocity was strictly modeled taking into account membrane water content (λ) and phenomenological transport. The precision of these models is paramount: excess liquid water causes "flooding," physically occluding the catalyst sites from the reactant gases (O_2 and H_2), whereas insufficient hydration exponentially increases the ohmic resistance of the polymer membrane¹⁷. Furthermore, the energy equations synthesized volumetric heat source terms, isolating the exact contributions of reversible/irreversible entropic heat generated by the electrochemical reactions, the heat of water vaporization (H_{vap}), and the ohmic heating mapped by the effective ionic conductivity ($\sigma_{eff}(\nabla\phi)^2$)¹⁷. These mathematical insights dictate the geometric optimization of bipolar separator plates and flow fields, actively mitigating parasitic voltage losses.

Food Rheology and 3D/4D Bioprinting

Finally, Mujumdar applied complex non-Newtonian rheological principles to the emerging domain of 3D/4D printed Super Reconstructed Foods (SRFs). The printability of biopolymer inks (hydrogels, polysaccharides, protein-based smart materials) is entirely governed by fluid-like vs. solid-like transitional behavior during extrusion³⁵. By analyzing the shear-thinning characteristics, yield points, and thixotropy of these complex mixtures, his research facilitated the exact determination of the viscoelastic mechanical strength required to maintain post-extrusion structural integrity, opening new avenues for personalized nutrition and on-demand engineered textures³⁵.

Conclusion

Professor Arun S. Mujumdar has systematically advanced the theoretical frameworks and industrial applications of global transport phenomena. Excluding his widely celebrated methodologies in drying science, his mathematical modeling of non-isothermal, multiphase, and nanoscale systems stands as a monument to engineering rigor. By elucidating the interfacial thermal anomalies of nanofluids, quantifying the precise latent heat transfer of composite PCMs, mapping the aerodynamic vortex shedding of turbulent pulsatile jets, and exploiting the secondary Dean flows in fractal microreactors, he has consistently resolved the most complex bottlenecks in mass and energy transport. His contributions, supported by an immense bibliometric footprint, continue to shape the trajectory of modern thermal-fluid sciences, sustainable mining, and next-generation energy storage.

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CHAPTER 8

Advanced Additive Manufacturing of Novel Food Products: A Comprehensive Analysis of Professor Arun S. Mujumdar's Contributions

Introduction to Digital Gastronomy and Additive Manufacturing

The convergence of additive manufacturing (AM) and food engineering represents a paradigm shift in the fabrication, processing, and consumption of edible materials. Three-dimensional food printing (3DFP)—often referred to within the industry as digital gastronomy—facilitates the layer-by-layer deposition of edible inks driven by digital computer-aided design (CAD) models. This technology effectively eliminates the need for traditional molds, enabling unprecedented, programmatic control over structural geometry, internal porosity, textural properties, and targeted nutritional composition¹. Professor Arun S. Mujumdar, alongside leading collaborators such as Min Zhang and their extensive research teams at Jiangnan University and McGill University, has been instrumental in advancing the theoretical frameworks and applied dimensions of this field.

Traditionally recognized globally for his foundational work in drying technology, heat and mass transfer, and thermal processing, Mujumdar has successfully integrated these principles into the burgeoning discipline of food additive manufacturing⁴. This synthesis is critical: the transition from a digital model to a physically stable, palatable, and shelf-stable food product relies heavily on the precise manipulation of rheological properties and the highly controlled removal of moisture⁵. His collaborative research extends far beyond simple geometric novelty, delving into complex multi-material assemblies, coaxial printing for targeted nutrient delivery, four-dimensional (4D) stimulus-responsive transformations, and the engineering of Super Reconstructed Foods (SRFs) tailored for specific clinical populations, such as individuals suffering from dysphagia⁸.

Rheological Characterization and the Physics of Printability

The successful execution of extrusion-based 3DFP is fundamentally governed by the rheological and microstructural properties of the edible inks⁷. An optimal food ink must exhibit distinct shear-thinning behavior to allow smooth extrusion through a narrow nozzle under pneumatic or mechanical pressure. Immediately following deposition, the ink must demonstrate rapid structural recovery—characterized by a high yield stress and storage modulus (G')—to support the weight of subsequent layers without collapsing or suffering from phenomena such as splattering or layer delamination¹. Mujumdar's work places significant emphasis on identifying, modifying, and predicting these complex material characteristics.

Polysaccharide and Protein Network Modulation

Food inks are rarely single-component systems; they are complex hydrogels, oleogels, or emulsion-filled gels requiring precise stabilization. Research by Mujumdar and colleagues highlights the efficacy of combining varied biopolymers to achieve optimized printability. For instance, the incorporation of hydrocolloids like xanthan gum (XG) or carrageenan into starch-based or protein-based matrices acts as a highly effective rheological modifier⁷. In studies evaluating the printability of kudzu root and carrot powders, the addition of XG and soy protein isolate (SPI) significantly improved the structural fidelity of complex geometries, such as pyramids and caps, by fortifying the viscoelastic network¹⁴.

Similarly, research on lotus rhizome starch (LRS) demonstrates that the addition of specific carrageenan types (such as κ -carrageenan) facilitates the development of a robust binary hydrogel network. This modification not only enhances the water-holding capacity by altering starch molecular ordering but also

fine-tunes the mechanical resistance of the gel, rendering it highly suitable for structural deposition and subsequent oral processing¹⁶.

Protein-stabilized Pickering emulsions and bigels—biphasic systems combining hydrophilic and lipophilic domains—have also been engineered as advanced food inks⁷. These systems are particularly valuable for printing fat analogs, such as beeswax-based oleogels in potato starch-protein systems, and texture-modified products¹⁰. The introduction of structural modifiers reduces emulsion droplet size and fortifies the interfacial architecture, which directly translates to improved printing resolution, structural supportability, and high-fidelity shape retention¹³.

Furthermore, the addition of lupin callus tissue into λ -carrageenan inks has been shown to modulate gel porosity and stiffness, creating a stable, spongy network highly dependent on the volumetric fraction of the added cellular material¹⁷.

Advanced Diagnostic Methodologies: LF-NMR and Digital Simulation

A significant methodological breakthrough in Mujumdar's collaborative research is the application of Low-Field Nuclear Magnetic Resonance (LF-NMR) technology to evaluate and predict the printability of food inks prior to the physical extrusion process¹². LF-NMR provides non-destructive, real-time insights into the water distribution, molecular mobility, and microstructural phase separations within the hydrogel network¹⁸.

By analyzing transverse water relaxation times (T_2), researchers can determine the exact ratio of bound versus free water, which correlates directly with the macroscopic rheological properties of the paste. In studies focusing on mashed potato, soy protein isolate, and fish surimi systems, LF-NMR data, when coupled with machine learning algorithms such as artificial neural networks (ANN) or Fisher discriminant analysis, predicted the printability of the formulation with an accuracy exceeding 90%¹⁸.

Beyond LF-NMR, computational fluid dynamics (CFD) and multiphysics modeling are increasingly employed to simulate the extrusion process. For example, simulations of chitosan hydrogels assuming two-phase laminar flow have allowed researchers to map the impact of various extrusion velocities and apparent viscosities on the final printed filament¹⁷. This data- driven, predictive approach minimizes the traditional trial-and-error methodology inherent in early 3DFP, standardizing ink formulation and ensuring dimensional stability prior to physical fabrication¹⁰.

Modifying Agent / Technique	Base Material System	Rheological & Structural Impact	Reference
Xanthan Gum (XG) & SPI	Kudzu Root / Carrot Powder	Enhances shear-thinning; improves shape retention for complex geometries.	7

Modifying Agent / Technique	Base Material System	Rheological & Structural Impact	Reference
κ -Carrageenan	Lotus Rhizome Starch	Promotes helical conformation aggregation; strengthens the binary hydrogel network.	16
Lupin Callus Tissue	κ -Carrageenan Inks	Modulates gel porosity; creates a spongy network optimizing mechanical resistance.	17
LF-NMR coupled with ANN	Potato / Soy Protein / Surimi	Maps bound vs. free water relaxation times to predict printability with >90% accuracy.	18
CFD Multiphysics Modeling	Chitosan Hydrogels	Predicts two-phase laminar flow behavior to optimize extrusion velocity and pressure.	10

Coaxial 3D Printing: Interfacial Engineering and Multi-Material Structuring

Moving beyond homogeneous single-nozzle extrusion, a substantial portion of Mujumdar's work explores coaxial 3D printing. This sophisticated additive manufacturing technique utilizes a concentric nozzle design to extrude two or more different materials simultaneously, creating a core-shell continuous filament²¹. This internal architecture unlocks entirely new dimensions in personalized nutrition, functional food design, and targeted gastrointestinal delivery systems.

Encapsulation and Bioaccessibility Enhancement

One of the primary applications of coaxial printing in this research domain is the encapsulation of highly sensitive bioactive compounds. Vitamins, probiotics, antioxidants, and essential fatty acids are often susceptible to degradation from thermal processing, oxidation, light exposure, and the harsh, highly acidic environment of the human stomach⁶. By embedding these functional compounds within the core layer of the

filament and enveloping them with a robust, protective polysaccharide or protein shell, their biochemical stability and ultimate bioaccessibility are vastly improved⁹.

For instance, collaborative studies successfully utilized coaxial 3D printing to co-encapsulate lutein and anthocyanins. Utilizing a lutein-loaded zein core and an anthocyanin-loaded corn starch paste shell extruded in a spiral-cube geometry at temperatures between 45 °C and

85 °C, the system demonstrated significant improvements in chemical stability during long-term storage and enhanced targeted release profiles in the lower digestive tract⁹.

Similar methodologies have been applied to pH-responsive, in-situ crosslinking alginate-based hydrogels designed for the targeted delivery of curcumin, as well as the simultaneous, independent control of curcumin and phycoerythrin within customized orodispersible films²¹.

Furthermore, the incorporation of living probiotics (such as *Lactiplantibacillus plantarum*) within a brown rice matrix stabilized by chickpea protein and fenugreek gum Pickering emulsions has been shown to retain over 90–96% cell viability post-printing, and up to 80–85% viability following simulated gastric digestion. This confirms the exceptional efficacy of coaxial 3DFP in creating functional, microbiota-based nutritional interventions²¹.

Textural Stratification and Meat Alternatives

Coaxial extrusion also permits the precise spatial distribution of diverse textures and flavors within a single product, effectively mimicking complex natural biological structures⁷. By coupling a protein isolate isotropic phase with an anisotropic fiber phase, researchers can generate tunable, fibrous macrostructures that simulate the mouthfeel and tensile properties of animal muscle tissues²⁵.

This technique is highly relevant for the development of plant-based meat analogs and cellular agriculture scaffolds²⁴. In one study, the combination of chicken surimi with mealworm protein isolate via coaxial printing provided a nutrient-dense, highly digestible, fibrous structure²².

Moreover, researchers have developed novel coaxially printed reduced-fat cheeses incorporating resistant starch as an inner core material, providing a healthier lipid profile without sacrificing the mechanical integrity or sensory attributes associated with traditional dairy products¹⁷.

The Crucial Interplay Between 3D Printing and Advanced Drying Technology

As a leading global authority on drying science, Mujumdar has fundamentally redefined the role of moisture removal within the context of additive manufacturing. In conventional food processing, drying is primarily a preservation technique designed to lower water activity and extend shelf life. However, in 3D and 4D food printing, where formulations are deposited layer-by-layer to form self-supporting geometries, drying acts as a pivotal structural actuator, dictating mechanical integrity, porosity, and sensory attributes⁵.

Preserving Structural Integrity and Mitigating Defects

Once a complex 3D geometry is printed, it must be rapidly stabilized. The necessarily high moisture content inherent in printable hydrogels leaves the physical constructs vulnerable to structural collapse, gravity-induced creeping, and microbial spoilage⁵. Post-processing dehydration is strictly required; however, standard convective hot-air drying often induces irregular shrinkage, anisotropic warping, and surface cracking, thereby destroying the high-fidelity shapes achieved during the printing phase²⁸.

Mujumdar's research investigates advanced, highly controlled drying methodologies to preserve the structural fidelity of printed foods. Freeze-drying and spray freeze-drying are particularly favored for delicate, thermally sensitive protein or polysaccharide matrices. In these processes, the sublimation of ice prevents capillary stresses from collapsing the matrix, preserving intricate micro-porosity and minimizing the thermal degradation of encapsulated bioactives⁵.

Alternatively, Refractance Window (RW) drying has been analyzed as a highly efficient thermal processing method. In studies evaluating Spanish cherry pulp, increasing the RW drying temperature from 50 °C to 90 °C reduced the drying time dramatically from 320 to 80 minutes, while preserving phytochemical properties on par with freeze-dried samples⁴. Microwave vacuum drying (MVD) provides

rapid, volumetric heat generation that accelerates moisture removal from the inside out, maintaining internal structural homogeneity and reducing total drying time by up to 50% compared to traditional convective methods. This has been successfully applied to post-process 3D printed potato-based snacks, yielding high drying efficiency and excellent shape maintenance⁵.

Driving Functional Chemistry: "Drying with Chemical Reactions"

In Mujumdar's framework, drying is not merely a passive removal of water; it is an active thermal process that initiates a cascade of complex chemical reactions. He advocates for the paradigm of "drying with chemical reactions," where the drying environment is deliberately manipulated to steer pathways such as the Maillard reaction, caramelization, lipid oxidation, and the transformation of bound phenolic compounds into highly bioavailable free forms⁶.

By strictly controlling environmental parameters—such as minimizing atmospheric oxygen via nitrogen blanketing or superheated steam, and implementing hybrid energy sources like microwave-assisted or infrared heating—the drying phase of 3D printed foods can be used to generate natural colorants, enhance specific flavor profiles, and increase the total antioxidant capacity without the need for synthetic additives⁴. This synergistic integration of drying science with additive manufacturing defines the final sensory and visual experience of the printed product⁵.

Drying Technology	Mechanism of Action in 3D/4D Printed Foods	Structural / Chemical Outcome	Reference
Microwave Vacuum Drying (MVD)	Rapid volumetric internal heating combined with reduced atmospheric pressure.	Prevents surface hardening; reduces drying time by 50%; maintains internal homogeneity of potato snacks.	5
Freeze Drying (Sublimation)	Low-temperature sublimation of ice crystals under vacuum.	Prevents capillary stress collapse; preserves complex micro-porosity and heat-sensitive bioactives.	5
Refractance Window (RW) Drying	Thermal energy transfer via circulating water beneath an infrared-transparent plastic film.	Drops drying time significantly (e.g., 320 to 80 min at 50-90°C); exceptional phytochemical retention.	4

Drying Technology	Mechanism of Action in 3D/4D Printed Foods	Structural / Chemical Outcome	Reference
Atmospherically Controlled Drying	Exclusion of oxygen using nitrogen or superheated steam.	Suppresses lipid oxidation and vitamin degradation; steers Maillard reactions for customized flavor development.	4

Four-Dimensional (4D) Food Printing: Stimulus-Responsive Dynamics

Building directly upon the foundations of 3D printing and advanced drying technologies, 4D food printing introduces the functional dimension of time. In this advanced manufacturing paradigm, printed structures are formulated with smart, stimuli-responsive materials and programmed to undergo dynamic, predictable transformations in shape, color, flavor, or nutritional profile in response to highly specific external triggers, such as heat, microwave irradiation, pH shifts, or hydration⁷.

Shape Morphing via Programmed Dehydration

The integration of drying science is most vividly demonstrated in moisture-induced shape morphing. By engineering specific internal geometries—such as varying infill densities, structural intersections, and groove orientations—and modulating the rheological properties of the ink, controlled dehydration generates anisotropic stresses within the food construct⁵.

In comprehensive studies utilizing purple sweet potato (PSP) purees, the application of microwave dehydration triggered spontaneous, programmable shape changes. The exact degree, rate, and direction of this deformation were finely tuned through the formulation chemistry: the addition of salt reduced the dielectric constant but increased the dielectric loss of the purees, resulting in a reduced yield stress and an accelerated rate of deformation.

Conversely, the addition of fructose syrup decreased the maximum deformation degree, allowing researchers to 'program' the exact final geometry³¹.

Similarly, 3D printed pea protein isolate structures can be programmed to bend or fold into specific, complex configurations upon drying or frying. This morphing is highly dependent on the orientation of printed grooves and the resulting localized water diffusion gradients, a phenomenon explicitly observed and mapped using LF-NMR³⁵. This controlled deformation allows for the creation of flat-packed, two-dimensional foods that autonomously self-assemble into complex 3D structures upon heating or cooking, offering substantial logistical and sustainability benefits in commercial storage, packaging, and global transportation³⁵.

Nutritional Transformation and Smart Bio-Sensing

Beyond mechanical shape-shifting, Mujumdar's collaborative work explores 4D printing for active biochemical and nutritional activation. A landmark study demonstrated the use of microwave and ultrasound pretreatment, combined with targeted UV irradiation, to stimulate the conversion of naturally occurring ergosterol in 3D-printed mushroom waste (such as *Agaricus bisporus* and shiitake scraps) into highly bioavailable Vitamin D₂³⁶. The unique spatial arrangement afforded by the 3D printed models maximized the surface area exposed to the UV light, while the physical field pretreatments (microwave/ultrasound) increased the molecular susceptibility of the ergosterol to the radiation. This multi-stage 4D process resulted

in a 4.6-fold total increase in Vitamin D2 concentrations, with the physical pretreatment alone accounting for a 2.2- to 3.8-fold enhancement compared to untreated prints³⁶.

Furthermore, 4D printing has been leveraged to create intelligent packaging and interactive dining experiences. Research led by Mujumdar and Zhang developed 4D-printed hydrogel labels incorporating essential oil emulsions and environmentally sensitive color-changing compounds, such as curcumin or anthocyanins³⁸. For instance, curcumin embedded in a lotus root powder gel was shown to predictably shift from yellow to red in an alkaline environment induced by microwave heating³⁰. When applied to packaging, these responsive labels serve a dual function: they act as active preservation agents through the controlled release of antimicrobial essential oils, and they function as real-time visual sensors for food freshness, altering their shape and color in response to the specific volatile organic compounds and respiration rates emitted by climacteric fruits. This transformation can be tracked and analyzed via Deep Convolutional Neural Networks (DCNN) and machine learning algorithms to provide an automated, highly accurate quality assessment⁴.

Clinical Applications: Dysphagia Management and Super Reconstructed Foods

One of the most profound and immediate societal impacts of Mujumdar's work in 3D and 4D food printing resides in the medical and geriatric nutrition sectors. Traditional texture-modified diets prescribed for individuals with dysphagia (a medical condition characterized by swallowing difficulties) consist almost entirely of visually unappealing, homogenous purees. This lack of texture and visual identity frequently leads to appetite loss, psychological distress, severe malnutrition, and a significantly reduced quality of life²⁷.

3DFP provides the unique ability to digitally reconstruct pureed, nutrient-dense ingredients into visually recognizable, appetizing shapes that strictly adhere to the rheological safety standards set by the International Dysphagia Diet Standardisation Initiative (IDDSI)⁴¹.

Engineering Texture for Safe Swallowing

The formulation of dysphagia-friendly inks requires an incredibly delicate rheological balance: the printed food must possess enough structural stability to resemble the original ingredient (e.g., a chicken breast, a carrot, or a traditional pastry) but remain weak enough to yield and break down easily in the oral cavity without excessive mastication, thereby avoiding the critical risk of aspiration¹.

Mujumdar's collaborations have deeply explored the adaptation of traditional Asian foods for geriatric populations. For example, *Qingtuan*, a traditional Chinese pastry made from glutinous rice flour and a red bean filling, presents a significant choking hazard to the elderly due to its severe post-gelatinization adhesiveness and retrogradation hardness over time⁴¹. By intelligently integrating soluble soybean polysaccharide (SSPS) into the ink formulation and optimizing the filling densities utilizing a dual-nozzle 3D printer, researchers successfully suppressed starch retrogradation. The experimental data revealed that an exact 0.9% SSPS addition effectively reduced both the hardness and adhesiveness of the Qingtuan, yielding a pastry that met the strict IDDSI Level 6 (Soft & Bite-Sized) standard⁴¹.

Similar rheological principles were applied to the development of double-nozzle printed bean paste buns. By incorporating an optimal 6% buckwheat flour into the paste, utilizing a 21.6% filling ratio, and applying precise microwave heating at 560 W for 4 minutes, the required chewiness of the bun was reduced by 52.43% compared to traditionally molded and steamed counterparts¹¹. Furthermore, the combination of chicken surimi with mealworm protein isolate via coaxial printing provided a nutrient-dense, highly digestible, fibrous structure ideal for the elderly, addressing both texture modification and critical protein supplementation²².

Super Reconstructed Foods (SRFs) and FSMs

These targeted clinical interventions form the foundation of a new dietary classification that

Mujumdar and his colleagues term "Super Reconstructed Foods" (SRFs). SRFs represent an advanced class of edible products fabricated via 3D/4D printing that possess characteristics—specifically in terms of

nutritional density, customized bioaccessibility, variable rheology, and on-demand texture—that fundamentally surpass those of the raw input materials⁸.

SRFs are particularly vital for the development of Foods for Special Medical Purposes (FSMPs). The traditional FSMP market currently suffers from a lack of product diversity, inadequate formula design, and overwhelmingly poor sensory appeal⁴³. By utilizing 3DFP, manufacturers can achieve true precision medicine through personalized nutrition. Complex multi-pill architectures or core-shell food constructs can be digitally designed to modulate the rate of digestion, control the release of therapeutics or antacids in specific segments of the gastrointestinal tract, and perfectly match the exact macronutrient and micronutrient requirements dictated by a specific patient's metabolic profile or age group⁴³.

Dysphagia Application	Material Formulation	Processing Parameters	Clinical / Structural Outcome	Reference
Qingtuan (Traditional Pastry)	Glutinous rice flour, red bean, 0.9% SSPS	Dual-nozzle printing; 75% internal filling density.	Reduces hardness/adhesiveness; meets IDDSI Level 6 (Soft & Bite-Sized).	41
Bean Paste Buns	Bean paste + 6% Buckwheat flour	Dual-nozzle; 21.6% filling ratio; MW heating (560W, 4 min).	Chewiness reduced by 52.43%; highly digestible.	11
Fibrous Meat Analogs	Chicken Surimi + Mealworm Protein Isolate	Coaxial extrusion to generate anisotropic fibers.	Replicates muscle tissue mouthfeel while ensuring safe, low-force mastication.	22
Binary Hydrogels	Lotus Rhizome Starch + β -	Thermal gelatinization	Smooth cellular network;	16
	Carrageenan	and extrusion.	recognized as IDDSI Level 4 compliant.	

Future Trajectories: Food Additive Manufacturing 4.0 and Sustainability

The future maturation and commercial viability of 3D and 4D food printing hinge directly on its scalability and integration with broader smart manufacturing ecosystems. The collective research output indicates a clear trajectory toward "Food Additive Manufacturing 4.0," a paradigm which deeply integrates artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), robotics, and digital twin technology into the closed-loop production cycle¹⁰.

Currently, standardizing food inks on an industrial scale is complicated by the inherent biological variability of agricultural raw materials (e.g., fluctuating starch, moisture, or protein content across different crop seasons)⁴⁵. Intelligent process control systems address this variance by employing real-time computer vision and embedded sensor networks to continuously monitor the layer-by-layer deposition process⁷. If a structural anomaly—such as microscopic layer delamination, splattering, or improper moisture evaporation—is detected, AI-driven feedback loops can instantaneously adjust extruder pressure, nozzle traverse speed, or the ambient drying temperature inside the build chamber to correct the defect in real-time⁵.

Furthermore, digital twins—highly accurate virtual replicas of both the formulated food product and the thermodynamic environment of the 3D printer and subsequent dryer—allow researchers to run millions of simulations regarding coupled heat and mass transfer, complex fluid dynamics, and microstructural evolution before any physical printing begins⁵. This predictive modeling drastically reduces research and development time, minimizes physical material waste, and is absolutely essential for bringing highly customized, digitally fabricated food products out of the academic laboratory and into commercial kitchens, clinical hospital settings, and eventually decentralised on-demand production environments¹⁰.

Finally, the integration of 3DFP heavily promotes sustainability through the valorization of agricultural and industrial byproducts. By converting highly nutritious but aesthetically unappealing waste streams—such as mushroom scraps, fruit peels, edible insects, and algae—into visually stunning, personalized SRFs, additive manufacturing aligns perfectly with global circular economy goals, reducing total food waste while addressing the growing demand for functional nutrition².

Conclusion

Professor Arun S. Mujumdar's extensive body of work, achieved in close collaboration with leading food scientists and engineers, establishes a highly critical bridge between classic chemical engineering, thermal processing, and advanced digital fabrication. By systematically dissecting the exact rheological prerequisites of edible inks and pioneering the use of data-driven tools like LF-NMR and CFD for printability prediction, this research has stabilized the foundational mechanics of 3D food printing.

The expansion into coaxial printing enables sophisticated microstructural engineering, protecting sensitive bioactives from gastric degradation and mimicking complex biological textures to advance cellular agriculture and personalized nutrition. Crucially, by integrating his unparalleled foundational expertise in drying technology, Mujumdar has successfully repositioned moisture removal from a mere preservation step to a highly active, programmable functional actuator. This conceptual shift has directly enabled the frontier of 4D food printing, where programmed anisotropic dehydration, microwave stimulation, and UV irradiation drive dynamic shape-morphing and profound chemical and nutritional transformations.

Ultimately, these technological strides culminate in profound clinical and societal applications. The conceptualization and development of Super Reconstructed Foods and algorithmically optimized texture-modified diets ensure that vulnerable populations, particularly the elderly and those living with dysphagia, have access to safe, nutritious, and psychologically satisfying meals. As the field rapidly transitions toward AI-integrated intelligent processing and Food Additive Manufacturing 4.0, the physical and thermodynamic principles delineated in this body of research will continue to serve as the bedrock for the future of sustainable, personalized, and clinically vital digital gastronomy.

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CHAPTER 9

Transport Phenomena in Impinging Jets: A Comprehensive Five-Decade Review of Fundamental Dynamics and Industrial Applications

Introduction to Impinging Jet Transport Phenomena

The controlled impingement of fluid jets upon solid surfaces represents one of the most effective known mechanisms for enhancing convective heat and mass transfer in engineering applications. Characterized by the formation of extremely thin hydrodynamic and thermal boundary layers in the stagnation region, impinging jets are utilized across a vast array of industrial processes. These range from the rapid thermal drying of continuous porous sheets—such as paper, textiles, and nonwovens—to the precision thermal management of high-power-density microelectronics, the cooling of optical surfaces, and the internal cooling of gas turbine aerofoils¹.

For nearly five decades, beginning in 1972, the systematic investigation of impinging jet transport phenomena has been fundamentally shaped by an expansive body of research initiated at McGill University and subsequently broadened at the National University of Singapore (NUS). This comprehensive effort, spearheaded initially through collaborations with Professor W. J. M. Douglas, engaged numerous graduate students and postdoctoral fellows, including notable contributors such as S. Polat, N. R. Saad, A. R. P. van Heiningen, S. H. Seyedein, S. M. Hosseinalipour, and S. Devahastin³. The research network eventually spanned the globe, incorporating extensive collaborative projects with institutions in China (such as China Jiliang University and Huazhong University of Science and Technology), Australia, and Finland (focusing heavily on paper machine drying technologies)⁸.

This report provides an exhaustive, expert-level synthesis of this five-decade research continuum. It systematically examines the evolution of impinging jet research across a highly diverse parameter space. The investigation encompasses varying flow regimes (laminar and turbulent), fluid rheologies (Newtonian and non-Newtonian), flow dynamics (steady and pulsed), and geometric configurations (round, slot, and complex shapes; single jets and multiple arrays). Furthermore, it details the critical effects of cross-flow interactions, oblique impingement, and target surface permeability⁴. The evolution of Computational Fluid Dynamics (CFD) modeling required to accurately capture these highly anisotropic flows is analyzed in depth¹⁴. Finally, the report reviews the industrial consultations that adapted these fundamental fluid dynamic insights into applied technologies, specifically for the drying of photographic film, the cooling of nozzles in fiberglass production, and the thermal management of turbine vanes¹⁷.

Genesis of the Research: The Papridryer and Newsprint Drying Technology

In the early 1970s, the global paper manufacturing industry—particularly the dominant Canadian newsprint sector—faced significant operational bottlenecks regarding production capacity and energy consumption. The drying section of a standard paper machine is notoriously energy-intensive, typically consuming up to 40% of the total energy required in papermaking¹⁹.

Conventional drying relied upon massive arrays of steam-heated cylinders, a process limited by contact thermal resistance and the accumulation of vapor pockets. To overcome the limitations of traditional contact drying, research aggressively shifted toward high-intensity convective techniques, culminating in the development and refinement of the Papridryer concept.

The Physics of the Papridryer Configuration

The Papridryer relies on a highly synergistic combination of two distinct transport mechanisms: high-velocity jet impingement and through-flow (vacuum) drying. The apparatus consists of a high-velocity hood juxtaposed against a rotating vacuum cylinder. Hot combustion gases or air, heated to extreme

temperatures ranging from 250°C to 450°C, are accelerated to velocities between 60 and 100 m/s and directed as impinging jets against the wet paper web, which is supported on the highly permeable vacuum roll².

The fundamental thermodynamic and fluid dynamic advantage of this combined configuration lies in boundary layer manipulation. In a standard impinging jet over a non-porous surface, the flow decelerates upon impact, forming a high-pressure stagnation zone, and subsequently accelerates radially (or laterally) as a wall jet³. The accumulation of spent fluid on the surface creates a hydrodynamic resistance layer. However, in the Papridryer configuration, the application of a vacuum beneath the permeable web draws a predetermined fraction of the impinging fluid directly through the porous matrix of the paper.

This trans-web suction effectively thins the hydrodynamic and thermal boundary layers on the impingement surface, drastically reducing the boundary layer resistance to convective heat and mass transfer⁴. The synergistic effect means that the drying rates achieved are phenomenally higher than the simple additive sum of pure impingement and pure through-drying. The high stagnation pressure of the jet actively forces the hot gases into the interfiber voids, displacing liquid water mechanically while simultaneously evaporating it, allowing for the rapid removal of both surface moisture (in the constant rate period) and internal moisture (in the falling rate period)².

Extension to Tissue Paper and Yankee Dryers

The fundamental transport principles elucidated in the Papridryer research were systematically extended to the manufacturing of highly porous, low-basis-weight products, most notably tissue paper. Tissue manufacturing represents an extreme boundary in continuous sheet drying, requiring extraordinary machine speeds that frequently approach or exceed 2000 meters per minute, resulting in extremely short thermodynamic dwell times (as low as 0.25 seconds)²⁴.

In these configurations, large-scale Yankee cylinders are enveloped by high-temperature impingement hoods²¹. The research demonstrated that while continuous slot nozzles provide excellent two-dimensional uniformity in the cross-machine direction, their fabrication for machine widths exceeding 5 meters under severe thermal stress is economically and structurally prohibitive. Consequently, perforated plates generating dense arrays of round jets became the industry standard. The research established precise empirical correlations between nozzle-to-surface spacing (Δz), open area percentages, and the strategic placement of exhaust ports to maximize the local Nusselt (Nu) and Sherwood (Sh) numbers. Crucially, these parameters had to be optimized to prevent web detachment or localized deformation caused by extreme stagnation pressure gradients impinging on the fragile tissue web².

The Thermodynamic Paradigm Shift: Superheated Steam Drying (SSD)

While high-velocity hot air provided the necessary drying rates for paper and textiles, the use of elevated temperatures (frequently exceeding 400°C) introduced severe operational risks.

Foremost among these were the catastrophic hazards of fire and explosion within the dryer hoods, exacerbated by the presence of highly combustible paper dust, as well as the oxidative degradation of the cellulose fibers themselves²¹. To circumvent these fundamental limitations, the research trajectory pioneered a massive transition toward Superheated Steam Drying (SSD).

Thermodynamic Mechanics and the Inversion Temperature

Superheated steam drying fundamentally alters the convective process by replacing hot air with steam heated well beyond its saturation point²⁷. The physics of SSD present a unique thermodynamic anomaly known as the "inversion temperature." At lower operating temperatures, hot air generally provides a higher drying rate than superheated steam. This occurs because the temperature driving force (ΔT) between the hot air and the wet-bulb temperature of the drying solid is significantly greater than the ΔT between superheated steam and the saturation temperature of water (which the product surface assumes in an SSD environment)²⁹.

However, superheated steam possesses a specific heat capacity at constant pressure (C_p) that is approximately double that of air, and its transport properties—specifically its kinematic viscosity and thermal conductivity—scale highly favorably at elevated temperatures. Above a specific inversion temperature (typically ranging between 160°C and 180°C, highly dependent upon the specific fluid dynamics and geometry of the impingement array), the superior thermal conductivity and immense specific heat of the steam dominate the transport equations. Above this inversion point, the convective drying rates achieved with superheated steam vastly exceed those of air under identical mass flow conditions²⁶.

Energy Efficiency and Latent Heat Recovery

A primary and enduring driver for the widespread industrial adoption of SSD research is its profound impact on global energy efficiency. In conventional hot air drying, the latent heat of vaporization supplied to remove water from the wet web is permanently lost to the atmosphere via the exhaust stream, which is highly diluted with air. Because an SSD system operates in an oxygen-free, closed-loop environment, the exhaust stream consists purely of steam.

This pure composition allows for the complete recovery of the latent heat of vaporization through condensation heat exchangers, or through mechanical and thermal vapor recompression, which elevates the specific enthalpy of the exhaust for immediate reuse in the dryer or elsewhere in the plant. This closed-loop recovery radically reduces the net energy consumption of the drying process, making SSD a critical technology for carbon footprint reduction in heavy industries²⁶.

Material Science: Effects on Paper Properties

Beyond fluid dynamics and thermodynamics, the research exhaustively quantified the material science implications of SSD. Drying paper in an oxygen-free, superheated steam environment fundamentally alters the resulting physical properties of the web. For paper manufactured from pure mechanical pulps, such as Thermomechanical Pulp (TMP) and Chemi-Thermomechanical Pulp (CTMP), SSD operates at temperatures and moisture contents that push the residual lignin past its glass transition temperature.

This plasticizes the lignin, promoting enhanced inter-fiber bonding and consolidation during the drying process. As a result, steam-dried mechanical pulps exhibit significantly improved dry tensile strength, lower optical scattering coefficients, and reduced tinting compared to air-dried equivalents³². Conversely, pure chemical pulps (like Kraft paper), which lack significant residual lignin, do not exhibit these same strength enhancements, indicating that SSD is uniquely suited for high-yield mechanical pulps³³.

Drying Medium	Heat Transfer Mechanism	Product Quality Impact	Energy Efficiency Potential	Fire/Explosion Risk
Hot Air	Convective transfer limited by low air specific heat. Surface assumes wet-bulb temp.	Susceptible to oxidative damage, case-hardening, and fiber stiffening.	Low (latent heat largely lost to exhaust air dilution).	High (requires strict temperature limits and spark suppression).

Drying Medium	Heat Transfer Mechanism	Product Quality Impact	Energy Efficiency Potential	Fire/Explosion Risk
Superheated Steam	High specific heat convection. Surface assumes saturation temp. Faster above inversion temp.	Eliminates oxidation. Enhances lignin flow in TMP, improving tensile strength.	Extremely High (exhaust is pure steam; latent heat easily recovered).	Zero (oxygen-free environment wholly prevents combustion).

Fundamental Fluid Dynamics of Impinging Jets

To optimize macroscopic drying and cooling systems, the research necessitated a rigorous, microscopic dissection of the fluid mechanics governing impinging jets. The studies meticulously characterized the topology of the flow field, identifying and modeling three distinct hydrodynamic regions.

Anatomy of the Jet Flow Field

1. **The Free Jet Region:** As the fluid exits the nozzle (whether a round orifice or a two-dimensional slot), it forms a potential core where the exit velocity remains uniformly constant. A highly turbulent shear layer immediately develops at the boundary between the jet and the ambient, quiescent fluid, expanding inward toward the centerline. Once these shear layers merge, the potential core is entirely consumed, and the jet enters a decaying, developing profile characterized by a bell-shaped velocity distribution⁵. The length of this potential core dictates the optimal nozzle-to-plate spacing (H/D or H/d).
2. **The Stagnation (Impingement) Region:** Upon approaching the target surface, the flow rapidly decelerates in the axial direction and turns 90 degrees to flow parallel to the wall. This region is characterized by a sharp spike in static pressure and an extreme compression of the hydrodynamic and thermal boundary layers. This compression leads to the highest local heat and mass transfer coefficients, resulting in a peak Nusselt number exactly at or slightly offset from the stagnation point⁵.
3. **The Wall Jet Region:** The deflected fluid accelerates radially (for round jets) or laterally (for slot jets) parallel to the surface. As it moves outward, the boundary layer grows continuously due to shear friction against the solid wall, while the outer edge of the wall jet entrains ambient fluid. This leads to a gradual decay in velocity and a corresponding drop in heat transfer rates as the fluid moves outward from the stagnation point⁵.

Multiple Jets and Jet-to-Jet Interaction

While single jets provide excellent fundamental data, industrial applications (such as Yankee hoods or turbine blade cooling) rely on extensive arrays of multiple jets. The research deeply investigated the complex aerodynamics of these arrays, noting phenomena that are entirely absent in single-jet configurations.

When two adjacent wall jets collide midway between their respective nozzles, they form an upwelling "fountain" flow²². If the nozzle-to-plate spacing (H/D) is large and the jet-to-jet spacing is tight, these fountains interact aggressively with the incoming free jets. This creates massive, recirculating vortices that

degrade the kinetic energy and thermal potential of the incoming fluid before it even strikes the surface, significantly depressing the average heat transfer coefficient²².

The Cross-Flow Effect

A critical engineering challenge addressed exhaustively by the research is the "cross-flow" effect. In a large array, the spent fluid (exhaust) from the inner, central jets must flow laterally outward to exit the system. As it moves outward, this cross-flow sweeps across the outer jets. The momentum of the cross-flow deflects the outer jets, destroying their stagnation zones, thickening their boundary layers, and drastically reducing their local Nusselt numbers. The research demonstrated that varying the open area of the nozzle arrays and strategically placing exhaust ports directly within the array (rather than relying solely on edge exhaust) minimizes cross-flow deflection. For example, comparing a 3% open area to a 20% open area array revealed that while the 3% array generated higher peak heat transfer rates, the 20% array provided far superior uniformity, which is critical for preventing uneven drying or thermal stress warping in sensitive products like photographic film⁴.

Oblique Impingement and Surface Permeability

The investigations also extended to oblique impingement, where the jet strikes the surface at an angle other than 90 degrees. This creates a highly asymmetric flow field. The maximum stagnation pressure and the peak heat transfer shift away from the geometric center of the jet axis. Furthermore, the boundary layer development is fundamentally altered, with the "uphill" side of the flow experiencing early separation and the "downhill" side accelerating rapidly¹³.

Furthermore, impingement onto porous and permeable surfaces—highly relevant to paper, nonwovens, and granular beds—was modeled and validated. The penetration of the stagnation pressure into a porous matrix creates a complex sub-surface flow field. This intra-matrix flow augments convective heat transfer within the uppermost layers of the material, a phenomenon critically important for the initial stages of combined impingement and through-air drying, confirming the early hypotheses of the Papir dryer mechanism⁴.

Advanced Flow Modalities: Pulsation, Swirl, and Complex Fluids

Recognizing that steady-state turbulent jets ultimately face a hard theoretical limit in heat transfer due to the persistence of a viscous sublayer at the wall, the research sought to actively disrupt this layer through advanced, transient flow modalities.

Intermittent and Pulsating Flows

A major breakthrough in the research was the introduction of flow pulsation. Early literature and initial studies utilizing simple sinusoidal pulsation showed negligible or even detrimental effects on heat transfer enhancement. However, the group's application of *intermittent* (square-wave or on/off) pulsation yielded dramatic, non-linear enhancements⁸.

Extensive numerical and experimental investigations revealed that intermittent pulsation—when applied at specific optimal frequencies and large amplitudes—prevents the steady-state thermal boundary layer from fully establishing itself. The abrupt starting and stopping of the jet generate highly coherent, high-energy vortex rings. When these vortex rings strike the target surface, they aggressively scour the stagnant fluid layer held by viscosity⁸.

The research quantified that for nozzle-to-surface distances shorter or longer than the length of the jet potential core, there exists a highly dependent threshold frequency for enhancement³⁸. Under optimal conditions, time-averaged Nusselt numbers could be increased by up to 12% in the stagnation zone and an astounding 35% in the wall jet zone compared to steady jets operating at the exact same time-averaged mass flow rate⁸. This represented a paradigm shift in active heat transfer enhancement.

Swirling Impinging Jets

The introduction of swirl (angular momentum) into the impinging jet was also rigorously investigated. The addition of swirl was found to dramatically enhance radial spreading rates, dependent upon both the swirl number and the inlet swirl velocity profile. At large swirl numbers, the centrifugal forces generate an intense, toroidal recirculation zone directly in the stagnation region³.

While this localized recirculation is highly beneficial for mixing operations (such as in impinging stream chemical reactors), the toroidal bubble acts as a thermal insulator, depressing the local heat transfer rate at the exact point where it is typically highest. Thus, the research provided crucial design boundaries, demonstrating that swirl must be carefully calibrated or avoided if pure heat transfer is the objective, but aggressively pursued if chemical mixing is the goal.

Rheological Complexities: Non-Newtonian Fluids and Nanofluids

Extending beyond conventional Newtonian fluids like air and steam, the research incorporated complex fluid rheologies. The use of shear-thinning (pseudoplastic) non-Newtonian fluids, such as aqueous carboxymethyl cellulose (CMC) solutions (ranging from 200 to 2000 ppm), revealed highly unique heat transfer behaviors¹².

In the impingement zone, the extreme velocity gradients and shear rates cause a localized, severe drop in the apparent viscosity of the power-law fluid. This localized thinning of the fluid dramatically reduces the local Prandtl number within the boundary layer, leading to unexpected, non-linear enhancements in local heat transfer coefficients compared to Newtonian fluids of equivalent zero-shear viscosity¹².

More recently, the research adapted to the advent of nanofluids (e.g., Al₂O₃-water suspensions). Computational studies analyzed the complex interplay between nanoparticle volume fraction, jet Reynolds number, and surface curvature. The data demonstrated that the enhanced thermal conductivity of the nanofluid, coupled with the characteristically thin boundary layers of the impinging jet, provides extraordinary heat flux capabilities, making it an ideal candidate for extreme thermal management scenarios in next-generation electronics⁴⁰.

Computational Fluid Dynamics (CFD) and Turbulence Modeling

A defining hallmark of this five-decade endeavor has been the rigorous application, interrogation, and advancement of Computational Fluid Dynamics (CFD). The inherently complex, highly curved, and anisotropic flow field of an impinging jet serves as one of the most severe benchmark tests for turbulence models⁵.

The Stagnation Point Anomaly in Eddy Viscosity Models

The standard $k-\epsilon$ turbulence model—the historical workhorse of industrial CFD—relies heavily on the Boussinesq approximation, which assumes an isotropic eddy viscosity that is proportional to the turbulent kinetic energy (k) and inversely proportional to its dissipation rate (ϵ).

✦). The research exposed a fundamental mathematical flaw in this approach when applied to impinging jets.

In the stagnation region, the fluid undergoes severe irrotational straining (normal stress) as it rapidly decelerates axially and accelerates radially. The standard $k-\epsilon$ model mathematically treats this irrotational normal strain in the exact same manner as shear strain. Consequently, the model computes a massive, highly unphysical overproduction of turbulent kinetic energy in the stagnation zone¹⁵. This spurious, mathematically generated turbulence artificially inflates the turbulent thermal diffusivity, leading to a severe overprediction of the stagnation point Nusselt number—often overestimating verified experimental data by more than 100%⁷.

Low-Reynolds Number Models and the Yap Correction

To resolve this anomaly, the research group systematically evaluated advanced turbulence closures. Standard wall functions, which assume a fully developed boundary layer profile, were discarded as entirely inappropriate for impingement flows. Instead, the models were integrated directly to the wall using low-Reynolds number (LRN) models, which apply specific damping functions to account for molecular viscosity dominance within the viscous sublayer.

Among these, the Lam-Bremhorst (LB) model showed significant promise but still suffered from the stagnation point overprediction. The pivotal, permanent solution explored and validated in the research was the implementation of the **Yap correction**⁷.

The Yap correction introduces a nonlinear source term directly into the ϵ (dissipation) transport equation. This source term is proportional to the departure of the calculated turbulent length scale (ℓ) from the equilibrium near-wall length scale (ℓ_w). By mathematically forcing a rapid increase in the dissipation rate whenever the computed length scale becomes too large, the Yap correction actively suppresses the spurious overproduction of turbulent kinetic energy in the stagnation region. The research definitively proved that combining low-Re models with the Yap correction yielded Nusselt number profiles that captured both the magnitude and the complex shape (including secondary off-stagnation peaks) of experimental data⁷.

Turbulence Model Formulation	Near-Wall Treatment Strategy	Performance in Impinging Jets	Key Limitation / Theoretical Advantage
Standard High-Re $k - \epsilon$	Log-law Wall Functions	Extremely Poor. Massive overprediction of Nu at stagnation point.	Completely fails under strong irrotational strain and adverse pressure gradients.
Lam-Bremhorst (LB) LRN	Integration directly to wall	Moderate. Captures profile shape but overestimates peak.	Better boundary layer resolution, but still highly susceptible to overproduction.

Turbulence Model Formulation	Near-Wall Treatment Strategy	Performance in Impinging Jets	Key Limitation / Theoretical Advantage
LB with Yap Correction (LBY)	Integration directly to wall	Excellent. Accurately captures stagnation and wall jet heat transfer.	Forces turbulent length scale to realistic near-wall values; highly accurate and computationally efficient.
Reynolds Stress Model (RSM)	Integration directly to wall	Very Good. Captures anisotropy inherently without Boussinesq assumption.	Computationally expensive; requires solving individual stress transport equations for all tensor components.
Large Eddy Simulation (LES)	Subgrid Scale (SGS) filtering	Superior. Resolves transient vortex rings and flapping instabilities.	Requires massive computational resources; used primarily for fundamental physics extraction rather than rapid design.

Advanced Closures: RSM, v2f, and LES

Beyond two-equation eddy viscosity models, the research extensively utilized full Reynolds Stress Models (RSM). RSM discards the isotropic Boussinesq approximation entirely and solves individual transport equations for each component of the Reynolds stress tensor. The RSM proved highly capable of modeling the strong streamline curvature and turbulence anisotropy inherent in the wall jet turning region¹.

In later decades, as computational power expanded exponentially, the research incorporated advanced formulations like the v^2-f model and Large Eddy Simulation (LES). LES, utilizing dynamic Subgrid Scale (SGS) models like WALE, successfully captured the highly transient chaotic structures, vortex shedding, and Kelvin-Helmholtz instabilities that dictate instantaneous heat transfer fluctuations, providing a fully time-resolved understanding of jet impingement physics¹⁴.

Industrial Consultations and Technology Transfer

The rigorous fundamental insights generated by the group's five decades of research did not remain confined to academic literature; they were systematically translated into actionable solutions for highly diverse, high-stakes industrial applications through extensive global consultation.

Photographic Film Drying

The drying of continuous webs of photographic films presents an extreme engineering constraint: the substrate is highly sensitive to both thermal degradation and mechanical deformation. Uneven drying or excessive shear stresses can induce physical defects, cracking, or optical warping in the emulsion layers. The impinging jet research was utilized to design highly specific, high-density nozzle arrays that deliver exceptionally uniform, high-mass-transfer boundary layers without ever exceeding the critical shear stress

thresholds on the delicate film surface. By utilizing large H/D spacings and high open-area geometries, the consultations ensured rapid drying without compromising optical integrity¹.

Thermal Management of Gas Turbine Vanes

Modern aerospace and power-generation gas turbines operate with combustor exit temperatures far exceeding the metallurgical melting points of the turbine blades and vanes (often reaching 1400°C)¹⁸. To prevent catastrophic failure, compressor bleed air (at roughly 600°C) is routed through internal passages within the blades and impinging aggressively against the inner leading-edge walls.

The research on highly confined impinging jets, the effects of strong surface curvature (utilizing concave targets to represent the blade interior), and the highly destructive nature of cross-flow was directly applied to optimize these internal cooling passages. The findings helped dictate the exact spacing of impingement nozzles and the routing of effusion film-cooling holes to maximize the local heat transfer coefficient (reaching extreme values up to 3000 W/m²K). This maximized thermal protection while minimizing the required mass flow of bleed air, thereby preserving overall engine cycle efficiency¹⁸.

Fiberglass Production and Advanced Cooling

The cooling of delicate extrusion nozzles in fiberglass production was another direct beneficiary of the group's geometric and flow-regime optimizations, where the prevention of thermal warping is paramount for consistent fiber diameters¹⁷. Furthermore, as the miniaturization of microelectronics led to unprecedented heat flux densities, the fundamental work on liquid impinging jets, nanofluids, and intermittent pulsation provided the thermal-fluid blueprints for advanced heat sinks. By mapping the exact limits of nozzle-to-plate spacing and evaluating the transient thermal response under constant heat flux boundary conditions, the research enabled the design of impingement cooling mechanisms capable of preventing thermal runaway in high-power semiconductor devices¹.

Synthesis and Future Outlook

The trajectory of research into impinging jet transport phenomena spanning the period from 1972 to the present stands as a masterclass in the evolution of engineering science. What began as a highly applied mandate to alleviate the extreme energy burdens of the Canadian newsprint industry via the Papridryer catalyzed a profound, foundational exploration into the mechanics of fluid dynamics, phase change thermodynamics, and computational turbulence modeling.

The strategic transition from high-temperature hot air impingement to superheated steam drying revolutionized the conceptual boundaries of thermal efficiency and product quality management, proving that latent heat recovery could transform the economics of industrial dehydration.

Simultaneously, the exhaustive dissection of the flow topology—from steady to pulsating, from single to multiple interacting arrays, and from simple Newtonian gases to complex non-Newtonian rheologies—provided the empirical and theoretical scaffolding necessary for engineers to harness these chaotic flows globally.

Crucially, the rigorous interrogation of CFD turbulence models, particularly the identification of the stagnation point anomaly and the championing of robust corrective mechanisms like the Yap correction within low-Reynolds number frameworks, elevated the predictive capabilities of the entire fluid dynamics community. By consistently bridging the gap between molecular-level boundary layer physics and macro-scale industrial machinery, this expansive body of work has indelibly shaped the thermal management, processing, and energy-recovery paradigms across the global paper, aerospace, materials, and electronics industries.

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APPENDIX A — Critical Reviews in Drying & Process Engineering

Critical Reviews in Drying & Process Engineering

A Bibliographical Catalog of Peer-Reviewed Review Publications by Professor Arun S. Mujumdar (Since January 1, 2000)

Executive Summary

Professor **Arun S. Mujumdar** is globally recognized as the founding father of modern drying research. Over a career spanning more than four decades, his pioneering research has systematically transformed drying from a purely empirical, hardware-focused industrial craft into a rigorous, interdisciplinary academic discipline. Under his guidance, the global drying community has integrated advanced principles of **transport phenomena, multi-scale mathematical modeling, material science, and process intensification** into drying systems design.

This catalog presents a comprehensive compilation of **191 critical review articles** authored or co-authored by Professor Mujumdar in peer-reviewed journals and academic volumes since January 1, 2000. These review publications have served as cognitive blueprints for academic researchers and industrial practitioners alike. By synthesizing vast amounts of disparate experimental data, outlining thermodynamic constraints, and identifying technology bottlenecks, his reviews have guided the field towards greater energy efficiency, minimal carbon footprints, and advanced digital control.

To facilitate targeted study, the catalog is structured into **five core thematic sections** that represent the pillars of Professor Mujumdar's post-2000 review contributions:

1. **Theme 1: Smart Drying, AI & Industry 4.0** (65 publications) — Exploring the frontier of intelligent drying systems, real-time adaptive control, machine learning, computer vision, and additive manufacturing (3D/4D/5D food printing).
2. **Theme 2: Food Processing, Quality & Drying of Biomaterials** (54 publications) — Focusing on chemical, nutritional, and structural preservation, browning kinetics, texture preservation, and processing of novel, sustainable food resources.
3. **Theme 3: Industrial, Novel & Physical Field-Assisted Drying** (22 publications) — Reviewing process intensification via microwave, radio frequency, ultrasound, electrostatic, and intermittent drying configurations, alongside specialized mining and coal dewatering.
4. **Theme 4: Pharmaceutical, Micro/Nano-Scale & Particle Engineering** (19 publications) — Examining spray/freeze drying for drug formulation, pulmonary delivery powders, microfluidic droplets, and nanofluid heat transfer.
5. **Theme 5: Sustainable Solar Drying, Energy Optimization & Global R&D Trends** (31 publications) — Addressing greenhouse solar drying, energy and exergy efficiency, book series histories, and global R&D surveys.

In each theme, we present an **Impact Analysis** outlining the core contributions of Professor Mujumdar's reviews, followed by a **Curated Catalog** of landmark papers with deep, analytical discussions. We close each section with a **Complete Bibliography** of all other post-2000 reviews in that category.

Theme 1: Smart Drying, AI & Industry 4.0 Impact Analysis

This theme represents the modern frontier of process engineering—the digitization and intelligent control of drying operations (often termed 'Drying 4.0'). Professor Mujumdar's reviews in this category have pioneered the integration of **artificial intelligence (AI), machine learning, artificial neural networks (ANN), computer vision, and fuzzy logic** into thermal dehydration. In parallel, his work has defined the emerging fields of 3D, 4D, and 5D food printing, showing how thermal and rheological properties of food gels and inks dictate printability, structural stability, and stimulus-responsive dynamic changes (4D). These reviews have bridged the gap between computer science and process engineering, offering

strategies to transition from static, inefficient drying hardware to highly adaptive, self-optimizing thermal systems that monitor shrinkage, moisture, and nutritional parameters in real-time.

Curated Catalog: Landmark Reviews

✦ Smart Quality Control in Logistics for Fresh Edible Nuts/Fruits with Rich Lipid: Research Progress, Challenges and Potential Applications

Full Reference (ACS Style):

Zhou, Z.; Zhang, M.; Mujumdar, A. S.; Rui, L. Smart Quality Control in Logistics for Fresh Edible Nuts/Fruits with Rich Lipid: Research Progress, Challenges and Potential Applications. *Food Reviews International* **2026**, 42 (3), 1558–1586.

DOI: [10.1080/87559129.2025.2520456](https://doi.org/10.1080/87559129.2025.2520456)

Brief Discussion:

This landmark review introduces a cutting-edge framework for integrating Industry 4.0 logistics with post-harvest quality control of lipid-rich nuts and fruits. The article discusses the use of smart sensors, machine learning algorithms, and computer vision to monitor rancidity, lipid oxidation, and insect infestations in real-time. By bridging the gap between hardware-centric storage logistics and adaptive computational control, this review outlines how predictive modeling can dramatically decrease product degradation during shipping and warehousing, offering a blueprint for modern agricultural cold chains.

✦ Organic nanomaterials applied to the manufacturing of personalized future 3D-printed foods: A review

Full Reference (ACS Style):

Guo, Q.; Zhang, M.; Mujumdar, A. S.; Li, C. Organic nanomaterials applied to the manufacturing of personalized future 3D-printed foods: A review. *Trends in Food Science and Technology* **2025**, 156, Art. No. 104835. DOI: [10.1016/j.tifs.2024.104835](https://doi.org/10.1016/j.tifs.2024.104835)

Brief Discussion:

Focusing on the physical chemistry of food inks, this critical review explores how organic nanomaterials (such as nanocellulose, Pickering emulsions, and starch-based nanoparticles) modify rheology to resolve structural collapse in 3D-printed food matrices. Professor Mujumdar and co-authors detail how these nanomaterials establish robust self-supporting networks through tailored shear-thinning and yield stress behaviors. The paper outlines the path towards personalized nutrient delivery, detailing how functional bioactives can be encapsulated in nano-scale domains and distributed precisely in 3D printed configurations.

✦ 4D printing: Recent advances and proposals in the food sector

Full Reference (ACS Style):

Teng, X.; Zhang, M.; Mujumdar, A. S. 4D printing: Recent advances and proposals in the food sector. *Trends in Food Science and Technology* **2021**, 110, 349–363.

DOI: [10.1016/j.tifs.2021.01.076](https://doi.org/10.1016/j.tifs.2021.01.076)

Brief Discussion:

This widely cited paper defines the foundational principles of '4D food printing,' where the 3D-printed food structure undergoes time-dependent physical changes (such as shape, color, flavor, or nutritional release) in response to external stimuli (like hydration, temperature, pH, or microwave heating). The review details the material science behind stimulus-responsive hydrogels, starch-rich pastes, and anthocyanin-rich systems, analyzing the physics of internal stresses that drive predictable deformations. It has profoundly shaped the fields of personalized nutrition, gastronomy, and sensory design.

✂ Recent progress in AI applications for drying

Full Reference (ACS Style):

Martynenko, A.; Mujumdar, A. Recent progress in AI applications for drying. *Drying Technology* **2025**, *43* (7), 1117–1118. DOI: [10.1080/07373937.2025.2510760](https://doi.org/10.1080/07373937.2025.2510760)

Brief Discussion:

This critical review synthesizes the shift from empirical, steady-state drying models to adaptive, real-time control loops driven by artificial intelligence. Professor Mujumdar analyzes how neural networks (ANN), genetic algorithms, and fuzzy logic controllers can process multi-sensor inputs (e.g., computer vision for shrinkage, hyperspectral imaging for moisture distribution) to dynamically adjust drying parameters (air velocity, temperature, microwave power). The review outlines how AI-driven predictive control reduces energy consumption by 15–30% while preserving heat-sensitive bioactive compounds.

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Theme 2: Food Processing, Quality & Drying of Biomaterials Impact Analysis

Drying of biomaterials is highly challenging because agricultural produce and biological systems are extremely sensitive to heat and moisture gradients. Professor Mujumdar's reviews in this theme establish a rigorous scientific foundation for **food quality preservation, browning reaction kinetics, and structural collapse prevention** during dehydration. His reviews analyze how heat and mass transfer match the biochemical degradation rates of micronutrients, antioxidants, and cellular matrices. Furthermore, his recent reviews address the processing of **novel food resources** (such as insect proteins, plant-derived non-starch polysaccharides, and probiotics), discussing how drying alters prebiotic activity, allergenicity, and consumer acceptance. These articles have defined quality-centric drying, proving that the success of a drying operation must be evaluated by the rehydration ratio, nutrient retention, and structural integrity of the final product, rather than simple moisture removal rates.

Curated Catalog: Landmark Reviews

✦ Recent developments in high-quality drying of vegetables, fruits, and aquatic products

Full Reference (ACS Style):

Zhang, M.; Chen, H.; Mujumdar, A. S.; Tang, J.; Miao, S.; Wang, Y. Recent developments in high-quality drying of vegetables, fruits, and aquatic products. *Critical Reviews in Food Science and Nutrition* **2017**, 57 (6), 1239–1255. DOI: [10.1080/10408398.2014.979280](https://doi.org/10.1080/10408398.2014.979280)

Brief Discussion:

A cornerstone of food drying literature, this review examines the thermodynamic and biochemical degradation mechanisms in high-moisture agricultural and aquatic materials. It establishes how convective drying causes cellular collapse, browning, and thermal degradation of vitamins and polyphenols. The review advocates for combined or hybrid drying technologies (such as microwave-vacuum, freeze-drying combined with infrared preheating) as the optimal method to optimize heat-mass transfer, accelerate drying kinetics, and preserve structural integrity, color, and nutritional density.

✦ Conventional and novel peeling methods for fruits and vegetables: A review

Full Reference (ACS Style):

Zhou, Y.; Vidyarthi, S. K.; Yang, X.; Duan, X.; Liu, Z.; Mujumdar, A. S.; Xiao, H. Conventional and novel peeling methods for fruits and vegetables: A review. *Innovative Food Science and Emerging Technologies* **2022**, 77, Art. No. 102961.

DOI: [10.1016/j.ifset.2022.102961](https://doi.org/10.1016/j.ifset.2022.102961)

Brief Discussion:

Peeling is a critical first-stage unit operation in fruit and vegetable processing. This review compiles and evaluates conventional peeling (mechanical, chemical, steam) against emerging physical field-assisted peeling (infrared, pulsed vacuum, enzymatic, and ultrasonic methods). It discusses the fundamental physical and chemical principles of each, detailing energy efficiency, peel-loss percentages, and environmental impacts (e.g., wastewater reduction).

This review has had a major industrial impact by helping processors select peeling systems that balance yield, energy, and effluent generation.

✦ Progress of plant-derived non-starch polysaccharides and their challenges and applications in future foods

Full Reference (ACS Style):

Guo, Q.; Zhang, M.; Mujumdar, A. S. Progress of plant-derived non-starch polysaccharides and their challenges and applications in future foods. *Comprehensive Reviews in Food Science and Food Safety* **2024**, 23 (4), Art. No. e13361. DOI: [10.1111/1541-4337.13361](https://doi.org/10.1111/1541-4337.13361)

Brief Discussion:

This comprehensive review examines plant-derived non-starch polysaccharides (such as pectin, hemicelluloses, and mucilages) and their dual roles as prebiotic fibers and structural thickeners in processed foods. It explains how drying processes (spray-drying, freeze-drying) alter their molecular weight, branch structure, and water-holding capacity. By linking drying engineering with food chemistry, the review provides critical insights into how to stabilize these macromolecules during drying to retain their health-promoting, prebiotic properties and technological functionality in food formulations.

✦ Intrinsic and extrinsic factors influencing *Bacillus cereus* spore inactivation in spices and herbs: Thermal and non-thermal sterilization approaches

Full Reference (ACS Style):

Leishangthem, C.; Mujumdar, A.; Xiao, H.; Sutar, P. Intrinsic and extrinsic factors influencing *Bacillus cereus* spore inactivation in spices and herbs: Thermal and non-thermal sterilization approaches. *Comprehensive Reviews in Food Science and Food*

Safety **2025**, 24 (1), Art. No. e70056. DOI: [10.1111/1541-4337.70056](https://doi.org/10.1111/1541-4337.70056)

Brief Discussion:

This crucial review addresses safety in post-harvest processing by analyzing the resistance mechanisms of *Bacillus cereus* spores in dehydrated spices and herbs. The authors detail how intrinsic food factors (like water activity and composition) and extrinsic process variables (such as temperature, dosage, and exposure time) govern spore inactivation. It compares conventional thermal sterilization against non-thermal technologies (like cold plasma, irradiation, and pulsed light), outlining how to achieve microbial safety without compromising volatile essential oils and thermolabile bioactive compounds.

Thematic Bibliography (Other Critical Reviews)

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5. Okaiyeto, S. A.; Yu, S.; Deng, L.; Wang, Q.; Sutar, P. P.; Wang, H.; Zhao, J.; Mujumdar, A. S.; Ni, J.; Lv, W.; Xiao, H. How to enhance the acceptability of insects food—A review. *Food Frontiers* **2024**, 5 (2), 311–328. DOI: [10.1002/fft2.349](https://doi.org/10.1002/fft2.349)
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DOI: [10.1080/07373937.2023.2269224](https://doi.org/10.1080/07373937.2023.2269224)
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Theme 3: Industrial, Novel & Physical Field-Assisted Drying Impact Analysis

Process intensification is essential to reduce energy consumption and improve throughput in industrial drying. This theme compiles Professor Mujumdar's reviews on **physical field-assisted drying technologies**, which utilize electromagnetic waves (microwave, radio frequency), acoustic waves (ultrasound), electrostatic

fields, and time-varying process parameters (intermittent drying) to bypass conventional convective heat transfer resistances. His reviews analyze the fundamental physics of these technologies—such as the dielectric properties of bulk foods, electromagnetic penetration depths, acoustic cavitation, and moisture diffusion dynamics. These publications demonstrate how combined or hybrid drying systems (e.g., microwave-vacuum, ultrasound-convective) and non-stationary drying conditions (intermittency) can eliminate case hardening, reduce drying times by 50–80%, and lower energy consumption, while successfully extending these concepts to heavy industrial drying such as coal dewatering and cyclone processing.

Curated Catalog: Landmark Reviews

✦ Review of recent applications and research progress in hybrid and combined microwave-assisted drying of food products: Quality properties

Full Reference (ACS Style):

Zielinska, M.; Ropelewska, E.; Xiao, H.; Mujumdar, A. S.; Law, C. L. Review of recent applications and research progress in hybrid and combined microwave-assisted drying of food products: Quality properties. *Critical Reviews in Food Science and*

Nutrition **2020**, 60 (13), 2212–2264. DOI: [10.1080/10408398.2019.1632788](https://doi.org/10.1080/10408398.2019.1632788)

Brief Discussion:

This critical review addresses the dielectric heating properties of high-moisture biomaterials, focusing on hybrid microwave systems (e.g., microwave-vacuum, microwave-convective). It explains how uneven heating and hot-spotting (classic defects of microwave drying) are resolved through structural modifications and time-varying power inputs. The authors detail how combined microwave configurations accelerate the falling-rate drying period, reduce drying times by up to 80%, and preserve critical quality indicators like ascorbic acid, texture, and volatile aroma profiles.

✦ New Development in Radio Frequency Heating for Fresh Food Processing: a Review

Full Reference (ACS Style):

Guo, C.; Mujumdar, A. S.; Zhang, M. New Development in Radio Frequency Heating for Fresh Food Processing: a Review. *Food Engineering Reviews* **2019**, 11 (1), 29–43.

DOI: [10.1007/s12393-018-9184-z](https://doi.org/10.1007/s12393-018-9184-z)

Brief Discussion:

Focusing on radio frequency (RF) heating (typically operating at 13.56, 27.12, or 40.68 MHz), this review analyzes its deep penetration depths and rapid volumetric heating capabilities. The paper details how RF energy can be utilized for post-harvest disinfestation, pasteurization, thawing, and drying of bulk foods. The authors outline key electromagnetic constraints (such as dielectric properties and electrode geometry) that dictate heating uniformity, providing engineering solutions to prevent runaway thermal localized heating in packaged foodstuffs.

✦ Developments in intermittent and non-stationary drying technologies

Full Reference (ACS Style):

Jangam, S.; Mujumdar, A. S. Developments in intermittent and non-stationary drying technologies. *Intermittent and Nonstationary Drying Technologies: Principles and Applications* **2017**, 1–17. DOI: [10.4324/9781351251303](https://doi.org/10.4324/9781351251303)

Brief Discussion:

This book-length review establishes the mathematical and physical frameworks for intermittent drying—the practice of varying drying parameters (temperature, humidity, air velocity, or energy input) over time.

Professor Mujumdar explains how incorporating 'resting periods' allows internal moisture to diffuse to the product's surface without consuming thermal energy. This strategy resolves the severe surface-hardening defect, reduces energy usage by up to 40%, and preserves thermal-sensitive nutrients, making it one of the most cost-effective drying optimizations available.

✂ Advances in dewatering and drying in mineral processing

Full Reference (ACS Style):

Chaedir, B. A.; Kurnia, J. C.; Sasmito, A. P.; Mujumdar, A. S. Advances in dewatering and drying in mineral processing. *Drying Technology* **2021**, 39 (11), 1667–1684.

DOI: [10.1080/07373937.2021.1907754](https://doi.org/10.1080/07373937.2021.1907754)

Brief Discussion:

This critical review addresses agricultural waste valorization, focusing on drying tomatoes and their processing by-products (pomace, seeds, and skins). The authors analyze how convective, vacuum, and freeze-drying affect the extraction and preservation of lycopene, carotenoids, and phenolics. The review outlines the mass transfer resistances encountered during waste drying and proposes optimized drying strategies to transform tomato waste into high-value functional food ingredients, contributing to circular economy principles in food engineering.

Thematic Bibliography (Other Critical Reviews)

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Theme 4: Pharmaceutical, Micro/Nano-Scale & Particle Engineering Impact Analysis

This theme focuses on the intersection of drying science, nanotechnology, and pharmaceutical formulation. Professor Mujumdar's reviews in this area have established **drying as an active particle engineering tool** rather than a simple solvent removal step. By analyzing droplet atomization, rapid spray-drying solidification, and low-temperature freeze-drying kinetics, his reviews provide a systematic guide to controlling crystallographic structure, particle size distribution, porosity, and powder flowability. This is vital for stabilizing delicate proteins, engineering pulmonary inhalation powders, and optimizing drug delivery systems. Additionally, his reviews on nanofluids—suspensions containing nanoparticles designed for advanced heat transfer—synthesized the physical mechanisms driving thermal conductivity enhancement (such as Brownian motion and nanoparticle clustering), serving as pioneering works in micro-scale thermal management.

Curated Catalog: Landmark Reviews

✦ A meticulous overview on drying-based (spray-, freeze-, and spray-freeze) particle engineering approaches for pharmaceutical technologies

Full Reference (ACS Style):

Pardeshi, S.; More, M.; Patil, P.; Pardeshi, C.; Deshmukh, P.; Mujumdar, A.; Naik, J. A meticulous overview on drying-based (spray-, freeze-, and spray-freeze) particle engineering approaches for pharmaceutical technologies. *Drying Technology* **2021**, 39 (11), 1447–1491. DOI: [10.1080/07373937.2021.1893330](https://doi.org/10.1080/07373937.2021.1893330)

Brief Discussion:

This comprehensive review bridges the fields of drying engineering and pharmaceutical formulation. It analyzes the thermodynamics of droplet formation and evaporation during spray-drying, freeze-drying, and spray-freeze-drying. The authors discuss how these drying operations act as precise particle engineering tools to control crystallographic form, particle size, porosity, and surface energy. The review provides detailed guidelines for designing pulmonary inhalation powders, stabilizing monoclonal antibodies, and encapsulating highly hydrophobic active pharmaceutical ingredients (APIs).

✦ Heat transfer characteristics of nanofluids: a review

Full Reference (ACS Style):

Wang, X.; Mujumdar, A. S. Heat transfer characteristics of nanofluids: a review. *International Journal of Thermal Sciences* **2007**, 46 (1), 1–19.
DOI: [10.1016/j.ijthermalsci.2006.06.010](https://doi.org/10.1016/j.ijthermalsci.2006.06.010)

Brief Discussion:

This foundational review, which has accumulated thousands of citations, synthesizes global research on nanofluids—liquid suspensions containing nanoparticles (< 100 nm) designed for enhanced thermal conductivity. Professor Mujumdar and co-author analyze the microscopic mechanisms behind thermal transport (e.g., Brownian motion, nanoparticle clustering, and liquid-layering at interfaces). It reviews experimental results and numerical heat transfer models for nanofluids in microchannels and heat exchangers, serving as a classic reference in modern advanced thermal management.

✦ Combined microfluidics and drying processes for the continuous production of micro-/nanoparticles for drug delivery: a review

Full Reference (ACS Style):

Patil, A.; Patil, P.; Pardeshi, S.; Shrimal, P.; Rebello, N.; Mohite, P. B.; Chatterjee, A.; Mujumdar, A.; Naik, J. Combined microfluidics and drying processes for the continuous production of micro-/nanoparticles for drug delivery: a review. *Drying Technology* **2023**, 41 (10), 1533–1568. DOI: [10.1080/07373937.2023.2167827](https://doi.org/10.1080/07373937.2023.2167827)

Brief Discussion:

This review explores the synthesis of highly monodisperse drug carriers by integrating microfluidics with downstream drying technologies (such as spray drying). It details how microfluidic chips can produce emulsions with exact droplet sizes, which are subsequently dried into spherical particles with consistent release rates. The review discusses how to encapsulate delicate proteins, nucleic acids (like mRNA), and target therapeutics, outlining the fluid dynamic constraints, scaling challenges, and future biomedical prospects of continuous microfluidic-drying systems.

✦ Spray freezing: An overview of applications and modeling

Full Reference (ACS Style):

Mohit, M.; Xu, M.; Kurnia, J. C.; Mujumdar, A. S.; Sasmito, A. P. Spray freezing: An overview of applications and modeling. *Drying Technology* **2025**, *43* (1-2), 34–52.

DOI: [10.1080/07373937.2024.2361360](https://doi.org/10.1080/07373937.2024.2361360)

Brief Discussion:

Focusing on spray freezing as a critical step in spray-freeze-drying, this critical review examines droplet atomization and solidification kinetics. It details the heat and mass transfer models that describe droplet interactions with cryogenic gases or liquids. The review discusses applications in biotechnology, food powder production, and cold energy storage, explaining how rapid freezing rates prevent macromolecular denaturation and structural collapse, resulting in porous particles with superior dissolution rates.

Thematic Bibliography (Other Critical Reviews)

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Theme 5: Sustainable Solar Drying, Energy Optimization & Global R&D Trends Impact Analysis

Sustainable engineering requires minimizing energy consumption and carbon emissions. Professor Mujumdar's reviews in this category address **sustainable post-harvest processing** through the development of advanced solar and greenhouse drying systems, analyzing their thermodynamics, natural convection fluid dynamics, and integrated thermal energy storage. In parallel, this theme covers his highly influential **meta-reviews, historical retrospectives, and global drying R&D surveys**. These papers discuss the role of expert reviews in steering research, historical accounts of drying books, and the impact of the International Drying Symposium (IDS) series on global academic-industrial partnerships.

These reviews have played an essential role in mapping out the scientific agenda of the drying community, highlighting energy and exergy efficiency, and advocating for low-cost, sustainable technology transfer to developing nations.

Curated Catalog: Landmark Reviews

✦ Expert reviews for assessment of recent developments and future perspectives of global drying R&D

Full Reference (ACS Style):

Pani, A.; Shirkole, S. S.; Mujumdar, A. S. Expert reviews for assessment of recent developments and future perspectives of global drying R&D. *Drying Technology* **2023**, *41* (3), 335–338. DOI: [10.1080/07373937.2023.2164671](https://doi.org/10.1080/07373937.2023.2164671)

Brief Discussion:

This meta-review details the methodology of utilizing expert review papers to assess global R&D trends. Professor Mujumdar and co-authors describe how structured reviews capture key technology transitions (such as fossil-fuel-free drying, solar hybrid dryers, and digital twins) across different countries. It analyzes how review articles serve to resolve conflicting experimental data in the literature and acts as a compass for funding agencies, industrial consortia, and doctoral researchers to identify high-value, unexplored research fields.

✦ Natural convection and direct type (NCDT) solar dryers: a review

Full Reference (ACS Style):

Chavan, A.; Vitankar, V.; Mujumdar, A.; Thorat, B. Natural convection and direct type (NCDT) solar dryers: a review. *Drying Technology* **2021**, *39* (13), 1969–1990.

DOI: [10.1080/07373937.2020.1753065](https://doi.org/10.1080/07373937.2020.1753065)

Brief Discussion:

This paper tackles the challenge of sustainable drying in developing agricultural economies. It reviews the design parameters, thermal efficiency, and aerodynamics of natural convection and direct-type solar dryers. The authors analyze how basic passive designs suffer from poor drying control, slow drying rates, and susceptibility to weather variations. The review proposes practical engineering solutions, including thermal energy storage (using phase change materials or gravel beds) and hybrid solar-biomass heaters, to make solar dryers highly productive and affordable for smallholders.

✦ Facilitating drying R&D via critical review papers

Full Reference (ACS Style):

Shirkole, S. S.; Mujumdar, A. S. Facilitating drying R&D via critical review papers. *Drying Technology* **2020**, 38 (14), 1817–1818. DOI: [10.1080/07373937.2020.1822080](https://doi.org/10.1080/07373937.2020.1822080)

Brief Discussion:

This review conceptualizes the scientific and educational value of critical review papers in drying science. The authors argue that as global scientific output grows exponentially, critical reviews act as filters that synthesize disparate data, highlight thermodynamic contradictions in published work, and build unified mathematical frameworks. The review serves as a guide for academic authors, detailing how to structure critical reviews that go beyond simple summarization to produce deep intellectual synthesis and direct new experimental designs.

✦ Perspectives on role of IDS series on global R&D in drying

Full Reference (ACS Style):

Mujumdar, A. S. Perspectives on role of IDS series on global R&D in drying. *Drying Technology* **2021**, 39 (2), 133. DOI: [10.1080/07373937.2019.1560963](https://doi.org/10.1080/07373937.2019.1560963)

Brief Discussion:

This review provides a historical and retrospective analysis of the International Drying Symposium (IDS) series, founded by Professor Mujumdar in 1978. It traces the forty-year evolution of drying R&D from mechanical engineering and hardware optimization to multi-scale physics, computer simulation, and product-quality-centric designs. The article highlights how the IDS series fostered global academic-industrial partnerships, promoted technology transfer to developing nations, and established drying technology as a highly respected, interdisciplinary academic domain.

Thematic Bibliography (Other Critical Reviews)

1. Mujumdar, A. S. Advances in Drying Science and Technology. *Particulate Drying: Techniques and Industry Applications* **2023**, vii.
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APPENDIX B — Academic Publication List

Publication List Year

2026

1. Barzigar, A.; Hosseinalipour, S. M.; Mujumdar, A. S. Artificial intelligence application for optimal solar dryer design for agricultural produce. *Drying Technology* **2026**, *44* (1), 4–5. DOI: 10.1080/07373937.2025.2544254
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Year 2025

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10. Guo, Q.; Zhang, M.; Mujumdar, A. S.; Rui, L. Effects of electric field-assisted freeze-thaw cycle on arrowhead (*Sagittaria sagittifolia* L.) quality and the structural and physicochemical properties of starch. *Innovative Food Science and Emerging Technologies* **2025**, *103*, Art. No. 104047. DOI: 10.1016/j.ifset.2025.104047
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List of Publications by Prof. Arun S. Mujumdar from Jan 2026

1. Allahyari, S., et al., *Modeling and assessment of a hybrid pyramid solar still-humidification-dehumidification desalination system for sustainable freshwater production in SWGHs: A case study*. Solar Energy Advances, 2026. **6**.
2. Barzigar, A., S.M. Hosseinalipour, and A.S. Mujumdar, *Artificial intelligence application for optimal solar dryer design for agricultural produce*. *Drying Technology*, 2026. **44**(1): p. 4-5.
3. Barzigar, A., et al., *Drying technologies as a catalyst for advancing human nutrition*. *Drying Technology*, 2026. **44**(10): p. 1375-1376.

4. Barzigar, A., A.S. Mujumdar, and S.M. Hosseinalipour, *Role of drying in 3D/4D printing of foods*. Drying Technology, 2026. **44**(7): p. 883-884.
5. Barzigar, A., A.S. Mujumdar, and S.M. Hosseinalipour, *Drying of textiles and coated webs: Balancing efficiency, quality, and sustainability in dyeing, finishing, and functional coatings*. Drying Technology, 2026.
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16. Li, M., et al., *Simultaneous freshness and ambient humidity sensing in agri-fresh food using a fluorescent sensor array and DCNN*. Advanced Composites and Hybrid Materials, 2026. **9**(4).
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18. Mujumdar, A.S., A. Barzigar, and S.M. Hosseinalipour, *Integrating drying technologies with hydrogen production: Toward a circular and sustainable future*. Drying Technology, 2026. **44**(4): p. 415-416.
19. Mujumdar, A.S., A. Barzigar, and S.M. Hosseinalipour, *Innovative sustainable sludge drying technologies: Turning waste into resource*. Drying Technology, 2026.
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29. Shen, D., et al., *Multi-Dimensional Analysis of Sensory Properties, Bioactivity and Stability of Different Essential Oil of Spices*. Food and Bioprocess Technology, 2026. **19**(2).
30. **SHI, H., ET AL., EFFECT OF ELECTRIC AND ELECTROMAGNETIC FIELDS TREATMENTS COMBINED WITH MODIFIED ATMOSPHERE PACKAGE ON THE STORAGE QUALITY OF FRESH-CUT CUCUMBERS (CUCUMIS SATIVUS L.). FOOD CONTROL, 2026. 180.**
31. Wang, Z., et al., *Potential of Functional Factors in Foods for 3D Printing to Manage Metabolic Syndrome: A Comprehensive Review*. Food Reviews International, 2026. **42**(4): p. 2617-2641.
32. Wang, Z., et al., *NIR and machine learning for apple freeze-drying moisture prediction*. Drying Technology, 2026. **44**(11): p. 1685-1699.

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35. Yu, Q., et al., *Real-time spoilage monitoring of aquatic products using advanced sensors and novel equipment*. Journal of Food Measurement and Characterization, 2026. **20**(4): p. 3829-3850.
36. Yu, Q., et al., *Intelligent freshness assessment of aquatic products through multimodal sensing and Machine learning*. Computers and Electronics in Agriculture, 2026. **245**.
37. Zhang, J., et al., *Sustainable development of drying technologies for agricultural products: recent advances, challenges, and future prospects*. Renewable and Sustainable Energy Reviews, 2026. **226**.
38. Zhou, Z., et al., *Smart Quality Control in Logistics for Fresh Edible Nuts/Fruits with Rich Lipid: Research Progress, Challenges and Potential Applications* Food Reviews International, 2026. **42**(3): p. 1558-1586.

List of Publications by Prof. Arun S. Mujumdar in 2026

1. Allahyari, S., et al., *Modeling and assessment of a hybrid pyramid solar still-humidification-dehumidification desalination system for sustainable freshwater production in SWGHs: A case study*. Solar Energy Advances, 2026. **6**.
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