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TRAINING MANUAL

National Training Program on

"Innovations in Post-Harvest Machinery: Design, Development, and Digital Advancements"

September 8–14, 2025 (Online Mode)

Training Director

Dr. P. K. Sahoo

Course Directors
Dr. R. Pandiselvam
Dr. Rajeev Kumar

Co-Course Directors
Dr. Sangeeta Chopra
Dr. Roaf Ahmad Parray

कृषि अभियांत्रिकी संभाग
भा. कृ. अनु. प.- भारतीय कृषि अनुसन्धान संस्थान, नई दिल्ली -110012
Division of Agricultural Engineering
ICAR-Indian Agricultural Research Institute, New Delhi-110012

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Training Manual

Innovations in Post-Harvest Machinery: Design, Development and Digital Advancements

September 2025

Compiled and edited by:

R. Pandiselvam

Rajeev Kumar

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Head,

Division of Agricultural Engineering

ICAR-Indian Agricultural Research Institute, New Delhi-12.

Phone: +91-11-2584294

Email: head_ engg@iari.res.in

Preface

The agricultural sector is undergoing a rapid transformation with the integration of modern engineering, automation, and digital technologies. In this context, the training program on "Innovations in Post-Harvest Machinery: Design, Development, and Digital Advancements" has been designed to bridge the gap between conventional practices and emerging innovations in post-harvest handling, processing, and value addition.

This program, organized under the guidance of Dr. P. K. Sahoo, Head, Division of Agricultural Engineering, ICAR–Indian Agricultural Research Institute (IARI), Pusa, New Delhi, provides a unique platform for researchers, academicians, industry professionals, and students to engage with the latest developments in post-harvest machinery and digital technologies. It aims to address pressing challenges such as efficiency, sustainability, quality assurance, and automation in food and agricultural processing systems.

The training brought together a diverse set of renowned resource persons who delivered sessions covering both foundational principles and advanced applications. Topics such as post-harvest equipment design (Dr. R. Pandiselvam), innovations in plantation crops processing (Dr. M. R. Manikantan), and specialized machinery for spice processing (Dr. E. Jayashree) will highlight targeted crop-specific interventions. Advances in cashew mechanization (Dr. D. Balasubramanian), tuber crop processing equipments (Dr. T. Krishnakumar), and paneer processing automation (Dr. N. Karpoora Sundara Pandian) showcase practical solutions for diverse food systems.

The program also emphasized sustainable energy solutions, with sessions on solar-powered equipment design (Dr. Sangeeta Chopra), hybrid dryers (Dr. Arun Prasath Venugopal), and solar thermal systems for seafood processing (Dr. Murali). Alongside, futuristic interventions such as 3D printing applications in food (Dr. Rajeev Kumar), automation in 3D printing for farm and food machinery (Dr. Dilip Kumar Kushwaha), and cold plasma design (Dr. Sellam Perinban) explore the frontier of digital manufacturing and non-thermal processing.

Quality and precision in food processing were addressed through sessions on advanced food quality assessment techniques (Dr. Roaf Ahmad Parray), fuzzy logic modeling (Dr. V. Chandrasekar), and hyperspectral imaging with NIR spectroscopy (Dr. M. Naveen Kumar). Equally, the integration of automation, sensors, and smart agriculture tools were highlighted by Dr. Syed Imran, Mr. Subeesh, and others, reflecting the digital shift in agricultural engineering.

By encompassing a wide range of themes—from traditional crop-specific machinery to cutting-edge digital tools—this training provided a comprehensive learning opportunity. It not only enhanced technical knowledge but also to inspired innovative thinking for solving emerging challenges in the agricultural and food sectors.

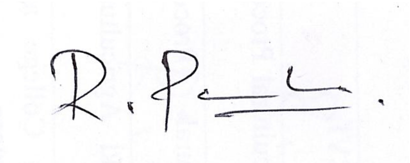
R. Pandiselvam **Rajeev Kumar**

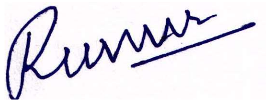
Acknowledgment

We express our sincere gratitude to Dr. Ch. Srinivasa Rao, Director & Vice Chancellor, ICAR-IARI, for his constant encouragement and visionary leadership in promoting innovation and capacity building. We also extend our heartfelt thanks to Dr. Anupama Singh, Joint Director (Education) & Dean, for her support in shaping educational programs of national relevance, and to Dr. Viswanathan Chinnusamy, Joint Director (Research), for his guidance in strengthening research–training linkages.

Our special appreciation goes to Dr. P. K. Sahoo, Head, Division of Agricultural Engineering, for his initiative and dedicated efforts in conceptualizing and coordinating this program. We gratefully acknowledge the contributions of all esteemed resource persons for sharing their expertise and insights, and the organizing team for their tireless efforts in ensuring the success of this training.

We are confident that this program will enrich participants with practical knowledge, innovative perspectives, and futuristic approaches in post-harvest machinery, contributing significantly to the advancement of agricultural engineering and food processing.





R. Pandiselvam **Rajeev Kumar**

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List of Participants

1. **Kota Nikhila**
   M.Sc Food Technology
   Vikrama Simhapuri University, Nellore, Andhra Pradesh.
2. **Sheethal B R**
   M.Sc Horticulture in Postharvest Management,
   University of Horticultural Sciences, Bagalkot.
3. **Er. Ann Annie Shaju**
   Ph.D. Scholar, Department of Processing & Food Engineering,
   Kelappaji College of Agricultural Engineering and Food Technology, Tavanur.
4. **Laishram Basantarani**
   Ph.D. Scholar, Department of Food Technology
   Mizoram University, Mizoram.
5. **S. Ashwin Kumar**
   Senior Research Fellow
   National Institute of Food Technology, Entrepreneurship and Management - Thanjavur
   (NIFTEM – T), Pudukkottai Road, Thanjavur, Tamil Nadu.
6. **Dr. G. Jeevarathinam**
   Associate Professor and Head,
   Department of Food Technology,
   Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu.
7. **Er. K.R. Poornima**
   Ph.D. Scholar, Division of Agricultural Engineering
   ICAR-Indian Agricultural Research Institute (IARI), New Delhi
8. **Chaudhary Mohd Kashim**
   Ph.D. Research Scholar,
   Institute of Food Technology, Bundelkhand University, Jhansi (U.P.)
9. **Mr. Banoth Jeeva Kiran**
   Ph.D. Scholar, Department of Food Engineering,
   National Institute of Food Technology Entrepreneurship and Management, Kundli.
10. **Alavala Jeevana**
    M.Sc Food Technology
    Vikrama simhapurii university, Nellore, Andra Pradesh
11. **C. Agritha**
    Project Associate
    National Institute of Food Technology Entrepreneurship and Management – Thanjavur, Tamil Nadu
12. **B. Yashvashri**
    Assistant Professor, Department of Food Technology,
    Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu.
13. **P.N. Guru Raj**
    Research Scholar

National Institute of Food Technology Entrepreneurship and Management –
Thanjavur, Tamil Nadu
14. **P. Rahini**
Junior Research Fellow
National Institute of Food Technology, Entrepreneurship and Management -
Thanjavur
(NIFTEM - T), Pudukkottai Road, Thanjavur, Tamil Nadu
15. **Bhargavi Bethamala**
M.Sc Food Technology
Vikrama simhapuri university, Nellore, Andhra Pradesh
16. **Dr. Ashwini Mugale**
Assistant Professor, Department of Dairy & Food Technology,
Parul University, Vadodara
17. **Ms. T. Archana Devi**
Assistant Professor
Department of Food Technology,
Hindusthan College of Engineering and Technology, Coimbatore
18. **Er. Anisha Pradhan,**
Ph.D. Scholar,
Department of Renewable Energy Engineering,
College of Agricultural Engineering and Post Harvest Technology, Ranipool, Sikkim
19. **Er. Dhamchoe Dolma Bhutia**
Ph.D. Scholar
Department of Processing and Food Engineering
College of Agricultural Engineering and Post Harvest Technology, Ranipool, Sikkim
20. **Ms. Vismaya K Sachithanandhan**
Assistant Professor
Department of Food Technology
Hindusthan College of Engineering and Technology, Coimbatore
21. **Shubham Chandrakar**
Research Scholar,
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur
(NIFTEM-T), Thanjavur, Tamil Nadu
22. **Er. Apeksha**
Ph.D. Scholar
Department of Processing and Food Engineering
College of Agricultural Engineering and Post harvest Technology, Ranipool, Sikkim
23. **Er. Ravikant Biradar**
M. Tech. Processing and Food Engineering
Dr Rajendra Prasad Central Agricultural University, Pusa, Bihar
24. **Mr. S. Charan Adithya**
Assistant Professor
Department of Food Technology
Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

25. **Mr. N. Sharath Kumar**
Scientist (Food Technology),
ICAR-Central Institute of Temperate Horticulture, Srinagar, J&K
26. **Dr. Aastha Dewan**
Assistant Professor
Department of Food Technology
Guru Jambheshwar University of Science and Technology, Hisar, Haryana
27. **Rentapalli Jahnavi**
M.Sc Food Technology
Vikrama Simhapuri University, Nellore, Andhra Pradesh
28. **Ms. N. Karunyah Amirthadharshini**
Assistant Professor
Hindusthan College of Engineering and Technology, Coimbatore.
29. **Ms. R. Abinaya**
Assistant Professor
Department of Food technology,
Hindusthan College of Engineering and Technology, Coimbatore.
30. **Dr. Kusuma Guturu**
Scientist,
Regional Agricultural Research Station, Anakapalle, ANGRAU, Andhra Pradesh
31. **Mallela Prem Kumar**
Ph.D. Scholar
Processing and Food Engineering
ICAR - Indian Agricultural Research Institute (IARI), New Delhi
32. Er. Gourab Choudhury
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi
33. Er. S. Sanjitha
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi
34. Er. Anurag Kushwaha
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi
35. **Shubhangi Sunil Ahirrao**
M.Tech Student (Processing and Food Engineering)
Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra
36. **M. Likitha Gowda**
M.Sc. Horticulture (Postharvest Management),
University of Horticultural Science, Bagalkot
37. **Dr. M. Abhinaya**
Assistant Professor, School of Agriculture,
Mohan Babu University, Tirupati, Andhra Pradesh.
38. **Rokalla Preethi**
Ph.D. Scholar,

Dept of Food Packaging Technology,
CSIR- Central food technological research institute, Mysore, Karnataka

39. **Dr. Perumalla Srikanth**
Assistant Professor,
Department of Agricultural Microbiology,
Mohan Babu University, Tirupati, Andhra Pradesh.
40. **Dr. Ch. Vidhyashree Venkatarao**
Assistant Professor,
School of Agriculture, Mohan Babu University, Tirupati, Andhra Pradesh.
41. **P. Paulin Patricia**
Research Scholar,
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur (NIFTEM-T), Thanjavur, Tamil Nadu
42. **Dr. Sachin**
Assistant Professor,
Amity Institute of Horticulture Studies and Research (AIHSR), Amity University, Noida, Uttar Pradesh, India
43. **Koduri Madhu Malathi**
Ph.D. Scholar
Farm Machinery and Power Engineering
Division of Agricultural Engineering
ICAR-Indian Agricultural Research Institute (IARI), New Delhi
44. **Sajja Poojith**
Ph.D. Scholar (FMPE),
Division of Agricultural Engineering
ICAR-Indian Agricultural Research Institute (IARI), PUSA, New Delhi
45. **Er. V. Manoja**
D Scholar (Food Process Engineering),
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur (NIFTEM-T), Thanjavur, Tamil Nadu
46. **Mr. Sudarshan Ramanathan,**
Junior Research Fellow - ANRF DST,
Division of Food Processing Technology,
Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu
47. **Rameshwari, M**
Ph.D. (Food Processing and Engineering),
Karunya Institute of Technology and Science, Coimbatore, Tamil Nadu.
48. **Alok Kumar**
Ph.D. Scholar (SWCE),
College of Agricultural Engineering and Technology,
Dr. Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Bihar
49. **Suneel Subray Hegde,**
Ph.D. Scholar,
Division of PHT & AE, ICAR- Indian Institute of Horticultural Research, Bengaluru

50. **Dr. Jalli Nagaraju**
Department of Food Technology
Vikrama Simhapuri University, Nellore, Andhra Pradesh
51. **Sruthy G Nair**
Ph.D. Scholar,
Food Process Engineering,
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur (NIFTEM-T), Thanjavur, Tamil Nadu
52. **Santoshi Rawat**
Ph.D. Scholar,
Food Process Technology,
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur (NIFTEM-T), Thanjavur, Tamil Nadu
53. **Ms. Shravya,**
Assistant Professor, Department of Food Science and Nutrition,
Yenepoya institute of Arts, Science, Commerce and Management (YIASCM), Mangalore, Karnataka
54. R. Sathishkumar
PG Student,
Food Processing and Engineering, Karunya Institute of Technology and Sciences, Coimbatore.
55. **Linda Maria Benoy**
PG Student
Food Processing Engineering,
Department Karunya Institute of Technology and Sciences, Coimbatore
56. Dr. S. Shahir
Associate Professor,
Kalasalingam Academy of Research and Education
(Deemed to be University)
Krishnankoil – 626128
57. Dr. Krishna Kumar
National Institute of Food Technology, Entrepreneurship and Management-Thanjavur (NIFTEM-T), Thanjavur, Tamil Nadu
58. Dr. Smita Agrawal
Department of Horticulture,
B.M.College of Agriculture ,Khandwa
59. Dr. Mrudula Guggilla
Assistant Professor, Parul Institute of Technology,
Parul University.
60. Dr. Sumit Pathak
Assistant professor from Division of Food Processing Technology,
Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu.
61. Dr. Mahipal Singh Tomar
Assistant Professor

Department of Food Science and Technology
Amity University, Punjab

62. **Dr. R. Navarasam**
Assistant Professor,
Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu.

63. **Dr. Rajesh Kumar**
Department: Food Technology
Eternal University, Baru Sahib, Himachal Pradesh

64. **Dr. Anamika Das**
Associate Professor
Dept. of Dairy Chemistry
Sanjay Gandhi Institute of Dairy Technology,
Bihar Animal Sciences University, Patna-14

65. **Er. Ram Kishore**
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi

66. **Er. Saurabh Kumar Gupta**
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi

67. **Er. Swati Singh Maravi**
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi

68. **Er. Subrata Mandal**
Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute, New Delhi

69. **Er. Mohd. Ghalib Khan**
Ph.D. Scholar (PFE)
Dr. Rajendra Prasad Central Agriculture University, Pusa

Chapter 1

Engineering the Essentials: Foundations of Post-Harvest Equipment Design

Dr. R. Pandiselvam
Senior Scientist, Division of Agricultural Engineering,
ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India.

Introduction

This section explains the most relevant engineering-property findings from our recent research work on tender coconut and coconut meat and translates them into practical, design-oriented guidance for post-harvest machines such as trimming/peeling units, punching/piercing devices, slicing and grating machines, rotor cutters (snowball machines), and seed/kernel separation equipment. The training material highlights which measurable properties (size, mass, husk profile, density, moisture, cutting/punching forces and energies, and textural/meat firmness) matter for each unit operation, summarizes the observed ranges and variability across cultivars and maturity, and explains clear implications and recommendations designers and operators should apply when building, specifying or commissioning coconut-processing machinery. The market and operational drivers behind mechanization rising demand for minimally processed tender coconut and export-oriented presentation formats make improved mechanization both timely and commercially important.

Why engineering properties matter for machine design

The engineering properties of coconut (both the whole drupe and the kernel/meat) are the physical and mechanical inputs that determine contact geometry, required tool strength and hardness, actuator torque and power, structural stiffness, conveyor and hopper geometry, and packaging/handling ergonomics. For example, intact nut weight, diameter and height set the geometry of holders and knife reach; husk thickness and its spatial distribution determine the cutting/punching contact depth and the required knife bevel and clearance; bulk and true densities plus porosity influence the mass that a holder or conveyor must carry and the torque required to rotate or orient fruits; and the cutting/punching forces and energies (both for husk and for meat) directly set tool strength, blade selection and motor sizing. The studies explicitly show that tender coconut cultivars differ markedly in size, husk profile and density, and that those differences translate to large changes in required cutting/punching forces and energies design inputs that cannot be ignored.

Key physical properties

Designers should collect a short, consistent set of measurements on the target cultivar(s): intact fruit weight, equatorial diameter, overall height, husk thickness at several positions, shell diameter/height/thickness, husk moisture and husk weight, bulk density, true density and porosity, and kernel (flesh) thickness and water volume. For tender coconuts of commonly used Indian cultivars, measured examples illustrate the magnitude of variation: intact weights ranged roughly from 1.32 to 2.34 kg, diameters from about 109 to 170 mm, and heights from ≈141 to 186 mm across cultivars studied (COD, KGD, GB, MOD, AGT). Bulk density and true density also varied by cultivar (e.g., bulk density values on the order of 256–356 $kg.m^{-3}$ and true densities in the ~1,196–1,686 $kg.m^{-3}$ range were observed), producing porosities often above 70% in tender nuts — all factors that affect holder design and transportation packing density.

The husk thickness profile is particularly critical for trimming and dehusking machines: specific thickness measures (vertical distance between external skin and shell at several points) were found to vary significantly by cultivar (for example, AGT showed substantially greater values than COD), and these local thicknesses correlate strongly with husk weight and overall fruit size. Designers should therefore base knife reach, shoulder height and trimming-knife travel on observed husk-thickness distributions rather than on weight alone, or else provide automatic adjustment for size/cultivar variability.

Mechanical and textural properties

The mechanical tests on tender coconut husk (punching and cutting of whole fruits) and on dehusked coconut meat reveal two complementary domains of force that a machine must handle: (a) husk/pelage forces (hundreds of newtons) that power trimming/dehusking and punching operations on the intact fruit, and (b) kernel/meat textural forces (tens of newtons, but with much higher energy requirements in some cutting/punching tests) that govern grating, slicing and fiber extraction designs.

For intact tender-coconut husk, peak punching forces measured across cultivars and loading positions ranged from about 103 N up to 536 N, and peak cutting forces ranged roughly from 372 N up to 987 N depending on cultivar and orientation (bottom/middle/top) — the bottom (near fruit base) position normally required the largest forces and the top (near perianth) the least because fiber density and lignification increase toward the base. These force ranges set the baseline for actuator sizing and shear-blade strength on trimming or mechanical dehusking equipment.

Punching and cutting energies measured for the husk show additional design insight: punching energy values for husk tests were relatively small in absolute joules (examples reported for different cultivar × position combinations span from below 1 J up to about 7 J in the husk tests), while cutting energy for husk cutting was higher. These energy figures are useful for transient motor sizing, clutch and rotor inertia design, and for estimating heating or wear rates in continuous operations.

Coconut meat (kernel) textural tests — the part relevant to grating, slicing, chips and fiber extraction — show a different scale and trend: punching forces on meat (for 9–11 month maturity samples) rose substantially with maturity and toward the bottom section of the kernel; for the oldest tested samples the bottom section punching force could approach ~39 N, with punching energy for meat recorded high value for MOD at 11 months, bottom section in our previous work. Cutting force and energy of the kernel also increase strongly with maturity and with the selected bevel/knife geometry: a 45° bevel cutting tool showed lower cutting forces than a 30° bevel in the cited slicing tests, indicating that bevel angle is an actionable design lever for blade selection. These meat properties directly affect blade selection (material and thickness), bevel choice, rotor diameter and speed, and feed-rate control for slicing and grating machines.

How engineering properties translate into machine design decisions

Designers can translate the measurements into concrete components and specifications as follows. For trimming/peeling machines, the fruit holder diameter and locking geometry must accommodate the measured diameter/height spread; the body-trimming knife length and shoulder and base knives must be adjustable (or spring-mounted) to match size classes, since cultivars like AGT can be up to ~2× larger in local husk thickness than COD in certain orientations. Automatic or pneumatic size adjustment, or machine-vision based knife positioning, will reduce rejects and operator workload when multiple cultivars are processed on the same line.

For knife and blade design, the measured cutting forces and observed effect of bevel angle mean that designers should select blade material (high carbon steels are commonly employed for heavy duty cutting tools) and bevel geometry to keep contact stresses low while minimizing required motor power; the texture tests showed a measurable reduction in cutting force with a 45° bevel versus a 30° bevel in kernel slicing tests, so bevel angle is a trade-off between sharpness, edge life and contact area that must be evaluated for the specific product (chips vs. grated vs. slices).

For punching/piercing devices (for making filling holes or for automated water-extraction/“snowball” operations), use the peak punching force (worst-case orientation) plus a suitable safety factor to calculate actuator torque: torque = force × lever arm (m); motor power should be sized for the required cutting/punching speed and the measured punching energy per operation. The mechanical tests provide both the peak forces and the area-under-the-curve energies, allowing both steady-state and transient power requirements to be determined.

For rotor and grater design used in snowball machines or continuous shredders, consider the cutting energy per unit piece and the meat’s maturity-dependent hardness: more mature kernels require higher energy and produce more fiber; the textural work shows that meat punching/cutting energy increases with maturity and at bottom positions, so rotor inertia, blade spacing, and feed control must be designed to handle the worst-case energies without stalling, jamming or excessive fines.

Textural Properties of Coconut

For seed/kernel separation, shell thickness and kernel density drive separator type and vibratory feeder settings: thicker shells and variable kernel thickness require separators that can handle a wider range of impact or frictional interactions, and the published shell/thickness data should be used to set clearance and impact energy thresholds.

Practical design and testing workflow

Begin with a brief field survey of the actual cultivars and maturity stages that will be processed; measure the minimum dataset (weight, diameter, height, h1–h4 at a minimum, husk moisture and a small sample of punching/cutting forces using a texture analyzer or instrumented knife) and compare to the literature ranges provided here. Use the cultivar-specific worst-case values (largest husk thickness, highest cutting force orientation) plus a safety factor (typically 1.25–2 depending on production criticality) to size shafts, bearings and motors. Prototype knives and rotors should be made from the high-carbon steels commonly used for these applications and bench tested at the measured cutting speeds while monitoring vibration, surface finish and tool life. In parallel, test several bevel angles and blade thicknesses on dehusked meat samples to optimize between force, product integrity and edge life; the cited data show that a 45° bevel reduces force in many kernel cutting tests. Finally, add pneumatic/spring adjustment or a simple vision sensor to the trimming station if multiple cultivars or size classes will be processed on the same line, since cultivar clustering analyses indicate that some groups (e.g., GB, KGD, MOD) are similar but others (AGT, COD) differ substantially.

Operator ergonomics, sanitation and materials

Machines should be designed for fast, safe blade change and cleaning; high-carbon steel blades are effective but must be designed for safe removal and sharpening. Because tender coconut husk moisture can be very high (reported ranges for green husks are near 65–80% w.b.), corrosion-resistant materials for non-cutting surfaces, and easy washdown access for food safety, are essential. The internal fiber structure that causes orientation-dependent cutting forces is biological and not easily changed; the practical response is adjustable tool geometry and routine maintenance schedules to manage wear.

Ready reference for designers

Typical engineering design anchors derived from the studies: intact weights ~1.3–2.3 kg, diameters ~109–170 mm, heights ~141–186 mm; husk/bulk density and porosity vary strongly by cultivar (bulk density examples ~256–356 $kg \cdot m^{-3}$; true density ~1,196–1,686 $kg \cdot m^{-3}$); punching forces for intact husk span ~102.8–536.4 N and cutting forces ~372–987.5 N (orientation and cultivar dependent); husk punching energies in the trimming context are typically sub-10 J per operation while husk cutting energies lie in the single to low-tens of joules, whereas kernel/meat punching energies can reach two- or three-digit joules for mature kernels in particular geometries — all of which must be accounted for when sizing drives, selecting blade geometry, and specifying safety factors. These anchor numbers should be validated with a small local sample before finalizing production equipment.

Conclusion

For students and faculty participating in this training, the key takeaway is that empirical measurement of engineering properties is not optional — it is the bridge between biological variability and robust machine design. Use the provided ranges and correlations as starting points, but always measure the specific cultivars and maturity stages you intend to process, then design adjustability and safety margins into holders, knives, rotors and drives. Where possible, include quick-adjust or automated positioning for trimming knives and provide blade/bevel options for slicing rigs so that a single machine can be tuned economically for different products (snowball-style pentagonal trimming, juice extraction, chips slicing, or fiber extraction).

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Engineering Innovations for Plantation Crop Processing

Dr. M. R. Manikantan,
Principal Scientist (AS&PE), ICAR- Central Plantation Crops Research Institute (CPCRI), Kasaragod, Kerala, India

Introduction

Coconut palm (*Cocos nucifera* L.), a perennial horticultural crop, is a symbol of national and international integration involving more than 93 producing countries and more than 140 consuming countries. It is eulogised as 'Kalpavriksha'- the '*tree of heaven*' as each and every part of the palm is useful to mankind in one way or other. There are countless uses of this coconut palm. It is bestowed with multiple benefits like health, wealth and shelter to mankind. It is also denoted as "heavenly tree", "tree of abundance" and "nature's supermarket". The largest producers of coconut are Indonesia and Philippines followed by India. In India, Kerala ranks first in production followed by Tamil Nadu, Karnataka and Andhra Pradesh. These states account for more than 90 per cent of the area and production of coconut in India. However, it is also cultivated with varying success in other states like Assam, Goa, Gujarat, Maharastra, Nagaland, Orissa, Tripura, West Bengal, Andaman and Nicobar Islands, Lakshadweep and Puducherry.

Coconut is mainly consumed as fresh nuts, tender coconuts, coconut oil and copra meal. Around 50 per cent of the world production is consumed in the form of fresh nuts and tender nuts. Close to fifty percent of the nut production is converted into copra and consumed as coconut oil and copra meal. Around 2.52 per cent is consumed as desiccated coconut. The Indian consumption pattern indicates that 56 percent of the produce is utilized for domestic and religious purposes, 35 percent for coconut oil production, 7 per cent for making edible copra and 2 per cent for manufacturing coconut powder. In India, annual consumption of tender coconut is about 200 million. The coconut palm also provides a series of by-products such as fiber, charcoal, handicrafts, vinegar, alcohol, sugar, furniture, roofing, fuel, etc. and it has more than 200 diversified local uses. The products and by-products of these crops form vital inputs for many of the industries and support the livelihood of many millions. They contribute a significant amount to the national exchequer and country's exports by way of excise and export earnings. They also provide direct and indirect employment to a large number of people in the country. The potential of converting coconut into different emerging value added products such as desiccated coconut powder, virgin coconut oil, coconut chips, coconut milk, preserved tender nut water & coconut inflorescence sap and coconut sugar is realized in view of globalization over the traditional processed products of copra and coconut oil.

Post-harvest technologies and machineries

Coconut serves as the basic raw material for a series of agro – processing activities and sustains the lively hood of over 10 million people in the country. The main unit operations in copra processing are splitting, de-shelling and drying. The following machinery has been developed for the benefit of coconut community. The following post harvest machineries are developed by CPCRI to enhance the coconut value addition, product diversification, labour saving etc.

Coconut Splitting Device

To solve the problem of splitting of coconuts by holding it in hand, a manually operated splitting device is developed at CPCRI (Fig. 1). Knife of the machine is made of spring steel and is kept at a bevel angle of 25 degree. As the cutting blade is made of spring steel, it does not require frequent sharpening. Nut is split manually by the impact force and the nut water is collected at the bottom.

Fig. 1: Coconut Splitting Device

Dryers

The common practice of making copra is by sun drying the fresh coconut kernel on cement floor or on sand floor for seven to nine days. Unlike in other crops, the endosperm of coconut is exposed while drying and so is susceptible for contamination due to dirt. Prolonged drying, especially during monsoon, also results in microbial infection. The energy efficient dryers developed by CPCRI produce dust and microbial contamination free copra in a short period.

Shell Fired Copra Dryer

The copra dryer (Fig. 2.) is working on indirect heating and natural convection principles using coconut shell as fuel. This dryer requires less amount of fuel, makes copra in short time and less expensive too. Capacity of the dryer is 1000 nuts per batch. The quality of copra obtained is light brown in colour which fetches good price in the market. The burner designed generates heat for 5 hours without tending and the residual heat is retained for one more hour. The average drying time is 24 h.

Fig. 2: Shell Fired Copra Dryer

Solar tunnel dryer

A solar tunnel dryer with a capacity of 1500 coconuts/ batch is developed that produces good quality copra in a shorter time (Fig. 3.). It consists of a semi cylindrical shape tunnel structure having a transparent cover made from UV stabilized polyethylene film of 200-micron thickness. The solar collector is the black polyethylene film of 250-micron thickness spread on the ground inside the dryer for better absorption of solar heat. The temperature inside the dryer is 20 - 25ºC higher than the ambient and the R.H. value is 20 - 22% lower than the ambient. The copra in this is less infested by fungi and bacteria than that produced by open sun drying. Drying time taken to dry copra is 32 sunshine hours. The cost of the dryer is Rs 45000/ and the cost of drying one kg of copra is Rs. 2.15 and for that for pepper is Rs.3. The dryer can also be used to dry other plantation crops produces.

Solar drying relies on the sun as the source of energy. For cloudy and rainy days, a multi source dryer also has been developed with solar energy as the main source of energy and electricity as alternate sources of energy.

Fig. 3: Solar tunnel dryer with electricity as an alternate source of energy

Solar cum electrical dryer with agricultural waste as third source of energy:

Solar drying relies on the sun as the source of energy. It generates higher air temperature and consequential lower relative humidity. For cloudy and rainy days, a multi source dryer has been developed with solar energy as the main source of energy and electricity and biofuel as alternate sources of energy. The dryer (Fig. 4.) consists of a semi circular parallel plate solar collector, electric heaters of 1000 W (6 numbers), blower cum exhaust motor and the drying chamber. It is a auto regulated dryer with temperature and humidity control. It is a batch type dryer and the capacity of the dryer is 2000 coconuts / batch. The dryer can be used to dry other crops such as cardamom and arecanut. Cost of the dryer is Rs. 80000/ and cost of drying per kg of copra approximately Re. 4.5/- if electric heaters are used and Rs.2.70/- if bio fuel is used.

Fig. 4 : Solar cum electrical dryer with agricultural waste as third source of energy

Coconut De-Shelling Machine

A power operated batch type coconut de-shelling machine (Fig. 5.) has been developed to separate shell and copra after partial drying. Capacity of the machine is 400 half cups per batch. The optimum average moisture content for maximum de-shelling efficiency (92.16 %) is 35 % d.b. The optimum speed of the de-shelling machine is 10 RPM and the time taken for de-shelling is 4 minutes per batch. Estimated cost of de-shelling machine is Rs. 50,000/- and cost of de-shelling 1000 nuts is approximately Rs. 60.00/ 1000 nuts.

Fig. 5: Coconut De-Shelling Machine

Copra moisture meter

The quality of milling copra ultimately determines the quality of the oil and the residual cake. Good quality copra will yield oil without refining with free fatty acid content (FFA) of less than one percent. Moisture is the most important factor influencing the quality of copra. Copra with a moisture content of less than six percent is considered good quality as it is not easily damaged by insects, moulds or microorganisms. At the CPCRI, Kasaragod, an electronic moisture meter was developed (Fig. 6.) to determine the moisture content of copra, based on the electrical conductivity of the kernel. The instrument can read moisture content from 5 to 40 percent. It is very handy and the accuracy is more than 94 percent in the lower levels of moisture content readings.

Fig. 6: Copra moisture meter

Coconut Chips Making Machine

Chips making machine (Fig. 7.) has been developed at CPCRI to slice coconut kernel to make chips. The machine can produce coconut chips of required uniform thickness much faster. The machine consists of two stainless steel slicing blades fixed on a circular blade supporting disc, a feeder to insert coconut endosperm for slicing, an exit guide to guide the sliced coconut chips towards the outlet and an electric motor as a prime mover. The electric motor rotates the blade supporting disc using a V-belt. When coconut endosperm comes in to contact with the blades it gets sliced. The sliced coconut chips are then guided towards the outlet by the exit guide and are collected in a container. Coconut chips of uniform and required thickness could be produced using this machine. Provision is made in the slicer to slice tuber crops, banana and vegetables. Capacity of the machine is 50 coconuts per hour. Fabrication cost of the machine is Rs.80,000/-.

Fig. 7: Coconut Chips Making Machine

Manually Operated Coconut Slicing Machine

A Manually Operated Coconut Slicing Machine (Fig. 8.) has also been developed to produce coconut chips. The machine is quite user friendly especially for ladies who knows operation of sewing machine and does not require electricity. Approximately 25 coconuts can be sliced in one hour using this machine. Fabrication cost of the machine is Rs. 25,000/-.

Fig. 8: Manually Operated Coconut Slicing Machine

Coconut Chips Dryers

Two types of dryers are developed to dry the sliced coconut kernel to the desired moisture content. The electrical dryer (Fig. 9.) developed consists of a set of 10 trays with wire mesh screens for loading coconut slices. Temperature in the dryer is controlled automatically by a sensor and electronic control unit. Though the dryer is designed for 50 coconuts, the size could be enhanced to any desired capacity.

Another prototype of chips dryers that uses agricultural waste as fuel (Fig. 90.) has been developed. Furnace of this indirect dryer is conveniently placed outdoor and the drying unit indoor. Temperature is controlled by a butterfly valve in the hot air inlet. Cost of drying would be less than that of electrical dryer.

Fig. 9: Electrical and Agricultural waste fired coconut chips dryer

Coconut Testa Removing Machine

Testa removing is an important operation during the process of making many high value coconut products like desiccated coconut, virgin coconut oil, etc. Traditionally testa is removed using a hand held tool similar to 'potato peeler' or by a knife. Both the methods are cumbersome and time consuming. The Coconut testa remover is a circular wheel covered with an emery cloth or water paper attached to a prime mover, an electric motor (Fig. 10.). One person can remove testa of about 75 coconuts per hour. Fabrication cost of the machine is Rs.85, 000/-.

Fig. 10: Coconut Testa Removing Machine

Coconut Grating Machines

Two coconut gratings machines were developed to enhance the grating efficiency. First one is of single user (Fig. 11.) and the second one is of multi user (four grating blades) type (Fig. 12.). The motorized coconut grating machines developed scrapes off the deshelled coconut flesh into fine gratings with the help of stainless steel blade. The single user machine has a capacity of 60 nuts/hr and the multi user has a capacity four times of the first one.

Fig. 11: Coconut Grating Machine-Single user

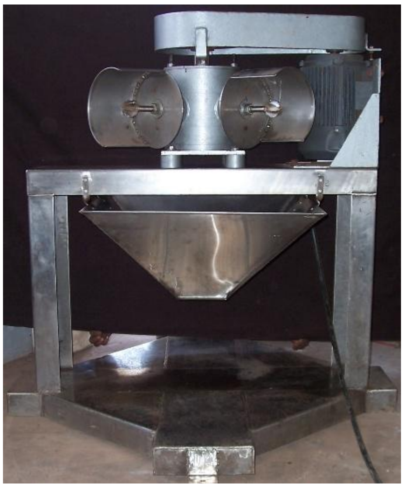


Fig. 12: Coconut Grating Machine-Multi user

Coconut Milk Extractors

Four different coconut milk extractors are developed to enhance the milk extraction efficiency. Two are manually operated and two are hydro pneumatic coconut milk extractors.

Manually operated

Both the manual operated machines (Fig. 13.) are similar to a hand operated vertical screw press. The grated coconuts are kept in a perforated cylinder and by rotating the handle provided at the top of the screw the gratings are pressed. In the first machine the whole pressing process is done manually by rotating the handle. In the second machine an additional hydraulic jack is provided at the bottom.

Fig. 13: **Manually operated** Coconut Milk Extractors

Hydro Pneumatic Coconut Milk Expellers

Two hydro pneumatic coconut milk extractors (Fig. 14.) of different capacities were also developed for large scale extraction of coconut milk. The operation of both the machines is completely automated using a programmable logic controller circuit. The user can programme the machines using the programmable logical controller as per his requirement.

Fig. 14: Hydro Pneumatic Coconut Milk Expellers

Screw Type Coconut Milk Expellers

Two screw type coconut milk expellers, single (Fig. 15.) and double (Fig. 16.) screw, with different capacities have been developed to extract coconut milk. The screw type expellers have the maximum extraction efficiency among different types of coconut milk extractors. The third expeller is a single screw type with an inbuilt cooling mechanism (Fig. 17.) to extract coconut milk at room temperature.

Fig. 15: Single Screw Coconut Milk Expeller

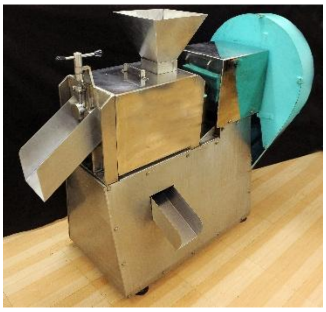


Fig. 16: Double Screw Coconut Milk Expeller

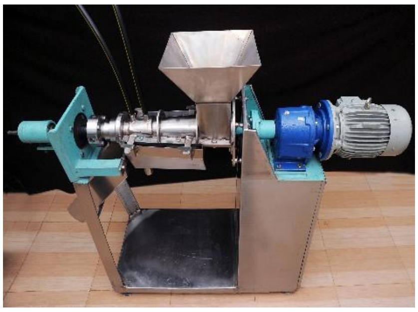


Fig. 17: Single Screw Type Coconut Milk Expeller with cooling mechanism

Virgin Coconut Oil Cooker

The Virgin Coconut Oil Cooker (Fig. 18.) developed by the institute consists of a double jacketed vessel filled with thermic fluid. The thermic fluid ensures efficient and uniform heat transfer to coconut milk kept in the cooker. Four Teflon tipped stirrers are provided to stir coconut milk. This helps the cooker to distribute heat energy uniformly within the coconut milk kept in the cooker. The stirrers are powered by an electric motor with a reduction gear. An outlet with a door attached to a lever is provided at the bottom of the cooker to take out the extracted oil. A thermometer is provided to measure the temperature of the thermic fluid so that it can be kept from 100-120^{0}C. A safety valve is provided for releasing the pressure developed, if any, in the thermic fluid chamber. The cooker is heated by two burners provided at the bottom of the heating chamber. Biogas or LPG could be used as fuel. Virgin coconut oil cookers of any capacity could be fabricated. Virgin coconut cil cooker given in the drawing is of 125 litre capacity and cost Rs. 3,25,000/- for fabrication including material cost.

Fig. 18: VCO Cooker

Tender coconut punch and cutter

Tender nut punch and cutter (Fig. 19.) is a simple device to pierce the six to seven months old nuts and to cut open it after drinking the water inside. The punch consists of a square base made of MS angle of 40 cm length. The tender nut is placed on the nut holder which is a circular and hollow in shape with a diameter of 10 cm. The tender nut can be placed on the nut holder and by operating the lever mechanism a hole of 12 mm diameter is made in just 4-5 seconds. A straw is put in the hole and one can drink the nut water. Tender Coconut Cutter consists of a wooden base of 50 cm length, a stand, a knife and a hand lever. The stand is mounted on the base. The cutting blade is mounted concentric to the stand and retained at a height of 15-20 cm. Tender coconut, after drinking the water, is placed on the wooden platform and cut open by pressing the lever attached to the blade. Using these machines 20 tender coconuts per hour could be served.

Fig. 19: Tender Coconut Handy Punch cum Splitter

The punching mechanism contains a 19 mm diameter stainless steel pipe with a profile at the end to pierce the tender coconut. To reduce the friction between inner tube and pierced tender coconut cork, tube entry diameter is reduced to some distance. The piercing tube is moved up and down using a manually operated lever. Tubular adjuster is provided at the base to the center of the punching pipe to accommodate the various sizes of tender coconut. The splitting is done using a stainless steel blade fitted with extended lever. The base of the splitting blade is placed at certain angle, to transfer the cutting load to the center of the frame. A stopper is provided perpendicular to the base frame to place the tender coconut in a balanced position. (http://www.tradeindia.com/fp1296725/Tender-Coconut-Opener.html).

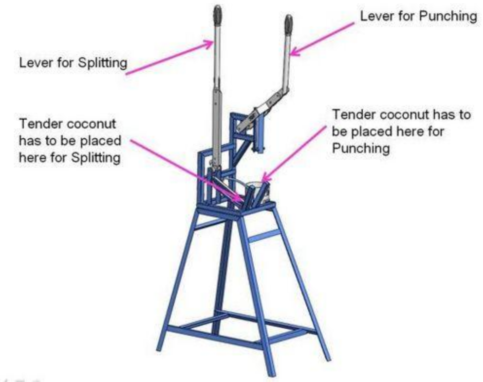


Fig. 20: Tender coconut handy punch cum splitter

Tender coconut punch cum splitter

The machine (Fig. 21) has a container at the base which has two compartments, one to store tender coconuts and the other with bag holding hooks for storing consumed tender coconuts. On the top of the container, the punching and splitting mechanism is placed.

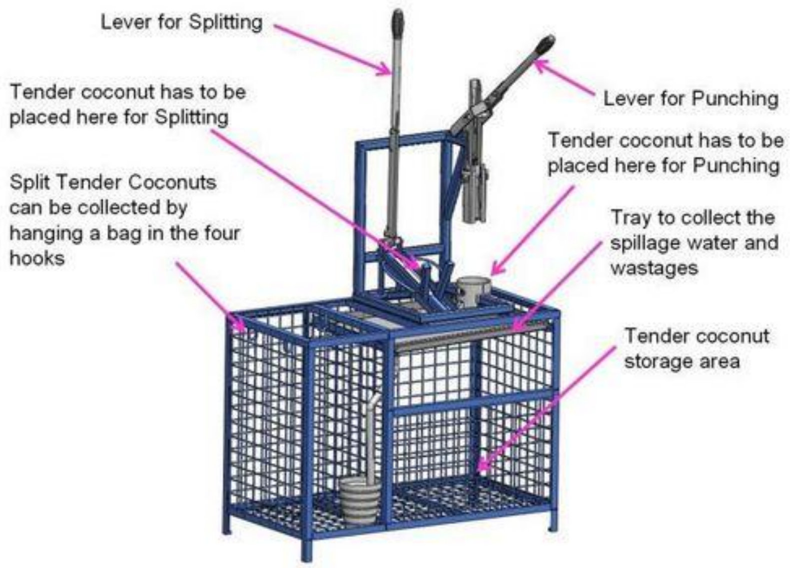


Fig. 21: Tender coconut punch cum splitter

Tender coconut opener

The tender coconut opener is a tool designed to make a hole in top of the tender coconuts to drink the water. It was made from a 19mm diameter stainless steel tube which was moulded with an ergonomically designed plastic handle. The end of the stainless steel is having a cutting profile like a reversed saw tooth with sharp cutting edge along the periphery. In clockwise rotation, it will have smooth cutting edge which will cut the soft tender coconut

fibers and not to pull the fibers. In anticlockwise rotation, it will cut the hard shell like a sharp saw tooth. The tender coconut opener is having a plastic moulded stem in the middle of the tube for pushing out the material inside the tube, after opening the tender coconut. In the top end of the stem, it has snap fit such that it will lock to safeguard the sharp cutting edge during accidental falling and avoid contact to the fingers when not in use.

(http://www.tradeindia.com/fp1296725/Tender-Coconut-Opener.html).

Snowball Tendernut Machine

Snow ball tender coconut is globular tender coconut kernel containing tender coconut water inside. The ball scooped out with the help of specially devised tool after cutting the shell of tender coconut of 7-8 months maturity by using snow ball tender coconut machine (Fig. 22.). The SBTN thereafter is made free of the adhering testa, packed hygienically to use either fresh or after refrigerated storage. Unit cost of the machine is Rs.25000 and output capacity is 250 coconuts in 8 hours by a person.

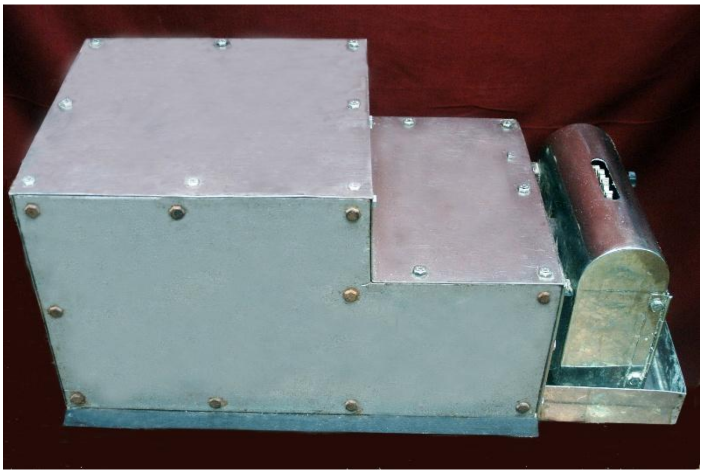
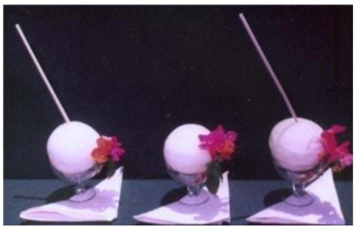


Fig. 22: Snowball Tendernut Machine

Snow ball tender nut is a tender coconut without husk, shell and testa which is ball shaped and white in colour. This white ball will contain tender coconut water, which can be consumed by just inserting a straw through the top white tender coconut kernel. Seven to eight month old nut is ideal for making Snow ball tender nut in which there is no decrease in quantity of tender nut water and the kernel is sufficiently soft. The technology for preparing snow ball tender nut (SBTN) has been developed at ICAR-CPCRI, Kasaragod. This is served in an ice cream cup. The user can drink the tender nut water by piercing the kernel with a straw. After drinking water, the kernel can be consumed using a fork. The coconut water is not exposed to the atmosphere and is natural and sterile



The machine consists of a circular blade having 24 teeth of 8 mm width that rotates at a speed of 1440 rpm. The prime mover of the machine is a 0.5 HP single phase electric motor. The prime mover attached with the circular blade is fixed on an angle iron frame with a covering made of mild steel sheet. A stop cutter box of stainless steel with a clearance of 15mm is used to cover the circular blade. The adjustable stop cutter box helps the user to control the depth of cut and protects the user from possible injury while operating the machine. A flexible knife known as scooping tool also has been developed for scooping out the tender nut kernel from the shell. The scooping tool is made of nylon and is flexible at one end. The scooping tool is inserted in between the kernel and shell through the groove and is rotated slowly to detach the entire kernel from the shell.

Coconut inflorescence sap / Neera / Kalparasa

Coconut phloem sap popularly known as neera is a natural health drink traditionally collected from the coconut spadix rich in sugars, protein, minerals, antioxidants, vitamins, etc., utilized by the plant for the growth and development of tender or mature coconut. As the flow of sap is slow and highly prone to fermentation, collection of unfermented sap is a challenging task and that has been resolved with the development of CPCRI developed 'Coco sap chiller'. The sap collected by coco-sap chilller at low temperature is observed to be entirely different from the neera collected by traditional method with or without preservatives; hence it was christened as "Kalparasa". Sap collected using the coco-sap chiller is golden brown in color, delicious and free from contaminants like insects, ants, and pollen and dust particles.

Coco-sap chiller (Fig. 23) is a portable device characterized by a hollow PVC pipe of which one end is expanded into a box shape to house a sap collection container bound by ice cubes and the other end is wide enough to insert and remove a collection container of 2 to 3 litres capacity. Each side walls of the pipe from outside are covered with an insulating jacket excluding the portion of spadix holder which retains the internal cool temperature for a longer period. This coco-sap chiller is lighter in weight, water proof, easy to connect to the spadix, requires less ice, and retains low temperature for longer period as compared to commercially available ice boxes.

Fig.23: Coco sap chiller

Kalparasa collected by coco-sap chiller under low temperature meets the Codex Alimentarius (International Food Standards WHO/FAO) definition of juice as "unfermented but fermentable juice, intended for direct consumption, obtained by the mechanical process from extractable fluid contents of cells or tissues, preserved exclusively by physical means". Thus it is amenable to be sold as fresh juice under local market with the adherence to quality standards prescribed by CPCRI. It does not require lot of machineries but requires cold chain or refrigerated system

Quality standards

CPCRI has developed simple quality standards to check the quality of sap. pH of the sap can be easily measured by hand held commercial pH meters. Fresh sap has anything above 7 to 7.5 pH. Depending on the pH sap can be used for different purposes.

pH > 7 ideal for promotion to health drink

pH>6.5 Good for preparation of sugar

pH> 6.0 Can be used for jaggary

pH> 5.5 for concentrate.

Below pH 5.5 is not good for the above value added products but can be used for the preparation of vinegar. Other quality parameters easily judged are brix around 14; color golden brown; and taste sweet and delicious.

Quality attributes of sap

Distinct differences are noticed between the sap collected by traditional method and CPCRI technique (Table 1.) Fresh sap collected by CPCRI technique is slightly alkaline in pH, golden brown or honey colour, sweet and delicious.

Table 1: Quality attributes of sap collected by CPCRI technique and traditional technique

Attribute	CPCRI Technique	Traditional technique
Soluble solids (°Brix)	15.5 to 18	13 to 14
pH	7 to 8	6 or low
Colour	Golden brown or honey	Oyster white
Defects, decay, insects, pollen, dust	Absent	Present
Flavour	Sweet and delicious	Harsh odour
Pathogens, chemicals and extraneous matter	Absent	Present
Microbial load	Low	High

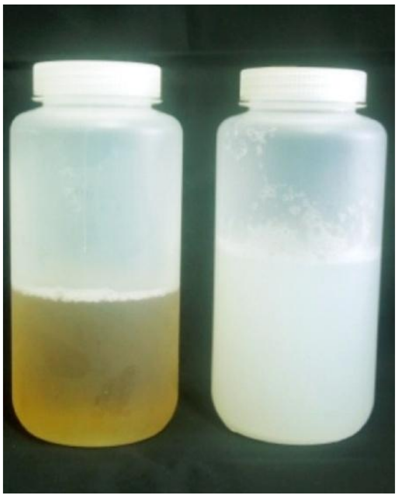


Fig.24: Coconut sap collected by coco-sap chiller (left) and traditional method (right)

Storage: The collected sap can be stored for any length of time under subs zero temperature. Deep freezers are used for the purpose. The sap gets freezed and just before use it is thawed to get the original liquid form. However, under refrigerators the quality gets deteriorated within few hours.

Techno economic details

Machineries/ devices required	Tapping gear (knives, tapping stick, scissor, mallet etc), o-sap chillers, neera collection ice box, ice carrying box, ph meter, measurement jug, neera storage container, neera transport box, freezer, neera dispenser etc.
Capacity	1000 liter of sap per day
Capital investment	Rs. 35,10,200
Operational cost per month	Rs. 75,875
Total cost of production	Rs. 1,06,91,785
Total sap production (l)	Rs. 3,65,000
Selling cost	Rs. Rs 50/ l
Unit cost of production	Rs. Rs. 29/l
Breakeven period	Rs. 176
Net profit %	Rs. 41.41

Coconut Sugar

The hygienic, zero alcoholic sap collected by CPCRI method is easy to process in a natural way without the use of chemicals into various value added products which fetches premium prices both in domestic and international markets. Very good quality coconut sugar, jaggery, nectar or syrup can be produced in double jacketed cookers with temperature regulation and stirring facility.

Coconut sugar is the best natural sweetner also has several health benefits and thus has a high market potential. It contains all essential amino acids required for protein synthesis; contains considerable amount of minerals like calcium, magnesium, zinc, iron and copper; rich in electrolytes like sodium and potassium; abundant in dietary fibers which normalizes bowel movements and digestion; rich source of phenolics which are potent and important contributors in reducing oxidative stress due to their antioxidant activity. Moreover its glycemic index (GI) is low and is in the range of 35 to 54 GI/ serving and eating a low glycemic index diet reduces the risk of chronic diseases such as Type 2 diabetes.

Fig.25: Coconut sugar and Jaggery

Techno economic details

Labour cost	Rs. 5,04,000
Total fixed cost	Rs. 20,19,975
Total variable cost	Rs. 1,01,72,500
Total cost of production	Rs. 1,21,92,475
Total sugar production (kg)	Rs. 54,750
Selling cost	Rs. 275/kg
Unit cost of production	Rs. 223
Breakeven period	Rs. 150
Net profit %	20

Kalpa Bar

It is a coconut sugar based chocolate purely from plant based ingredients without milk is prepared. It is a joint venture between ICAR-CPCRI and CAMPCO (Central Arecanut and Cocoa Marketing and Processing Cooperative Ltd.). It contained cocoa powder, coconut sugar, natural vanilla extract and GMO free sunflower lecithin. It is low in glycemic index. It does not contain any added artificial ingredients. It is delicious dark chocolate for a healthy life and can be stored under room temperature and does not melt. It is available in 30 g slabs.

Fig.26: Kalpa Bar Dark chocolate from coconut sugar

Kalpa Drinking Chocolate

It is an instantised blend of low GI coconut sugar, crafted from fine cocoa powder formulated to produce the delicious drinking chocolate. It is to titillate the taste buds of drinking chocolate lovers who want a healthier life style. It does not contain any artificial ingredients. The product is produced by a unique technology of instantisation and agglomeration technique that makes the product soluble instantly in hot or cold milk releasing the chocolate aroma. The product is filled in 200g PET jars duly sealed, case corrugated.

Fig.27: Kalpa Drinking Chocolate

Methodology for the preparation of fresh coconut inflorescence sap (Kalparasa) based milk sweets have been standardized at West Bengal. The advantage is, it is another way of transporting neera to long distance in the form of sweets. These sweets impart the minerals, vitamins, valuable fiber which will not be available in the normal cane sugar based milk sweets and their glycemic index is low and hence good for healthy life.

Fig.28: Sweets prepared from Kalparasa

Kalpa Krunch

Kalpa Krunch is a coconut milk residue enriched ready to eat extruded snacks. It is prepared from 60% rice flour, 25% corn flour and 15% coconut milk residue flour. It is coated with natural and healthy flavours. The flavours are formulated from ten different types of spices and vegetables including coriander, garlic, turmeric, clove, cinnamon, chilli, mint, cardamom, tomato and celery. Kalpa Krunch is rich in dietary fiber, protein, fat and carbohydrate with antioxidant activity. The steps involved in extrusion process are mixing, extrusion (140°C extrusion temperature and 220 rpm screw speed), drying (130°C for 20 min), flavour coating and packaging. The torque should be maintained around 12-14 for uniform and high expansion ratio.

The ratios of CMR, corn, and rice flour were 15:25:60. All the raw materials were mixed in a laboratory mixer (Basic Technology Pvt. Ltd., India) for 15 min. The initial moisture content of blend was determined using infrared moisture analyzer. Hence, before extrusion, calculated amount of water sprayed onto the flour blend to achieve the required moisture content of 14% and blend again for 10 min.

The prepared homogenous blends were extruded in a co-rotating twin screw extruder (Basic Technology Private Ltd, Kolkata, India). An extruder dies with a diameter of 3 mm was used for all trials. The screw speed and barrel temperature of the last zone was 220 rpm and 140 °C. Extrudates were collected after 5 min of steady state processing and dried in a coating machine (M/s Pharma Fab Industries, Mumbai, India) at 130 °C for 20 min. The dried extrudates can coat with different flavours. The oil should be sprayed before coating of flavours.

Techno economic details

Cost of Machinery	Rs. 44,00,000
Working capital	RS.47,80,000
Selling cost	Rs. 5 / packet
Unit cost of production	Rs.3
Breakeven period	Rs. 131.9
Net profit %	21

Fig.29: Kalpa krunch

Coconut delicacy

It is a non-dairy probiotic vegan product. Its ingredients are coconut milk/cream, coconut sugar, tender coconut water, tender coconut pulps, and stabilizers with incorporation of air during freezing process. ICAR-CPCRI has developed a complete process protocol for the production of different types of coconut based ice cream depending upon the need of the entrepreneurs. For this, one pilot plant for the production and demonstration. Three entrepreneurs from Karnataka, Kerala and Tamil Nadu have already adopted this technology and successfully ventured in this enterprise.

Frozen coconut delicacy with coconut sugar

Frozen coconut delicacy with refined sugar

Conclusion

Coconut has the greatest importance in the national economy as a potential source of employment and income generation among the plantation crops. The demand for coconut is high because of its usage and the adaptability of coconut palm to grow under various climatic and soil conditions. With the use of coconut oil in the production of soap and margarine in Europe in the 19th century, it was converted into a commercial crop. In the beginning of 20th century copra was the king among the oil seeds. In East Indies it was known as green gold. However, the period after the Second World War saw the substitution of vegetable oils and oleo chemicals for coconut oil in international trade. Price of coconut oil fluctuated heavily due to frequent short supply situations. A campaign against coconut oil alleging that it causes cardiovascular diseases aggravated the situation. The newly industrialized countries in the East such as Taiwan, South Korea are fast emerging as key importers of coconut product. One of the main reasons for the fall in price of the coconut and its products is dependency of price of coconut oil which again depends on the cost of other vegetable oils. Thus, product diversification of coconut and development of value added products become very important in the coconut industry. Effective market promotion activities are also to be organized by way of organizing exhibitions, workshops and trade fairs in order to create consumer awareness and boost the demand of coconut products to keep the wheel of the coconut industry moving fast for doubling the income of coconut farmers for their sustainable livelihood.

Post-Harvest Processing to Produce Quality Spices

Dr. E. Jayashree

Principal Scientist, ICAR-Indian Institute of Spices Research (IISR), Vellimadukunnu, Kozhikode, Kerala, India

Spices are high value export-oriented crops extensively used for flavoring food and beverages, medicines, cosmetics, perfumery etc. Spices constitute a significant and indispensable segment of culinary art and essentially add flavour, color and taste to the food preparations. The farm level processing operations are the most important for value addition and product diversification of spices. These post-harvest operations which leads to value addition include proper harvesting, washing, threshing, blanching, drying, cleaning, grading, storing and packaging. It is essential that these operations ensure proper conservation of the basic qualities like aroma, flavour, pungency, colour etc. Each of these operations enhances the quality of the produce and the value of spice. Some of the spices discussed here are black pepper, cardamom, turmeric, ginger, chillies, nutmeg, cinnamon and clove. The clean raw material form the basis for diversified value added products.

(i) Black pepper

Pepper *(Piper nigrum)* takes about 180 to 230 days after flowering to reach full maturity. Harvesting is generally done when the berries are fully mature and few starts turning from yellow to red in each spike. The stage of maturity at harvest varies depending on the final value added product to be prepared from pepper. In case of white pepper production, harvesting fully ripe pepper would yield white pepper of better quality and for extraction of oil and oleoresin, black pepper is harvested 12-20 days before maturity. The operations involved for the production of black pepper are detailed as follows;

- *Threshing*: The berries are separated from the spike by using threshers. Mechanical threshers with capacities varying from 200 kg/h to 1200 kg//h are available which can thresh quickly and provide cleaner products.
- *Blanching*: The quality of the black pepper can be improved by a simple treatment of dipping the mature berries taken in perforated vessel in boiling water for a minute before drying. This results in a uniform-coloured black pepper and removes the extraneous impurities on the berries.
- *Drying:* The berries are then spread on clean dry concrete floor / bamboo mats/ PVC sheets and dried in the sun for a period of 5 - 6 days. The moisture content is brought down from about 70% to 11%. The average dry recovery varies from 33-37%.
- *Cleaning / garbling and grading*: During threshing and drying, extraneous matters like broken spikes, pinheads, stones, soil particles etc. creep into the produce. These impurities are removed by winnowing the produce manually or by using a blower. Multiple sieve-cum air classified type of machine whereby the impurities are easily removed is used for grading at the farmers and trader's level.

- *Packing and storage*: The graded produce is bulk packed separately in jute bags, multi-layer paper bags or woven polypropylene bags.

(ii) Cardamom

Cardamom *(Elettaria cardamomum)* plants take about two years to bear capsules and takes about 3 months after flowering for fruit maturity. Harvesting of cardamom is taken up at a time when the seeds inside the capsules have become black in colour. The pericarp at this stage will still be green in colour. Green cardamom and white cardamom are the two important products obtained from fresh cardamom. The post-harvest operations involved in the value addition of cardamom are as follows:

Green Cardamom

- ***Washing and Alkali treatment***: The harvested capsules carry soil or dirt on their surface and hence they are washed thoroughly in water. The capsules are then treated with 2% sodium carbonate solution for 10 minutes which enables to retain green colour and prevent mould growth.
- ***Drying:*** The colour of cardamom gets bleached away when exposed to sun light. Therefore, conventionally green cardamom is dried in flue type kiln or electrical drier. The cleaned capsules are dried to reduce the moisture content from 80 per cent to 10%.
- ***Garbling:*** It is the process of removal of flower stalk from the dried cardamom. Traditionally this is achieved by rubbing the cardamom capsules against coir mat or wire mesh and winnowed to remove any foreign matter. Hand operated mechanical garbling units are available which increases garbling efficiency and reduces damage.
- ***Grading:*** The partly cleaned cardamom by garbling is to be further cleaned to remove the impurities and grade them according to size. Cleaning of cardamom by removing the discoloured ones, split capsules and other impurities is done manually. Hand operated cleaner cum grader provided with suitable sieves can be used for better grading of cardamom.
- ***Packing:*** Cardamom capsules are packed in jute bags or wooden containers suitably lined with polythene or craft paper.

White Cardamom

Bleaching is the important post-harvest operation involved in the production of white cardamom.

- ***Bleaching:*** Freshly harvested or dry capsules of cardamom can be used as starting material for bleaching. Sulphur bleaching of dry cardamom capsules is the widely practiced method. Here the capsules are soaked in 2% bleaching powder solution (20 g/L of water) for one hour and spread on wooden trays which are arranged inside airtight chambers. Sulphur- di- oxide is produced by burning sulphur (15 g/kg of capsules) and made to pass over the trays. The process of soaking and drying is to be carried out for 3-4 times depending up on the intensity of white colour required. The bleached cardamom is creamy white or golden yellow in colour

(iii) Turmeric

Turmeric (*Curcuma longa*) is ready for harvest in about 7-9 months depending up on the variety, when the leaves of the plant turn yellow and starts drying. At the time of harvest the land is ploughed and the rhizomes are gathered by handpicking or the clumps are carefully lifted with a spade. The post-harvest processes involved for producing dried turmeric rhizomes are described as follows:

- ***Cleaning:*** Harvested turmeric rhizomes are washed in water to remove mud and other extraneous matter adhering to them. Only good fingers are separated from the bulbs and used for further processing.
- ***Boiling:*** Turmeric rhizomes are boiled in pure water in mild steel or galvanized iron pans till the fingers become soft. Generally, it takes about 45-60 min for complete cooking of fingers and about 90 min for bulbs, and completion of cooking can be tested by piercing a wooden needle. The needle will pass through the fingers without much resistance. The cooked fingers are heaped on a cleaned drying floor and left undisturbed for 1-2 hours. Cooking of turmeric is to be done with in 2 or 3 days after harvest. Boiling helps to enhance the colour and the shelf life of turmeric.
- ***Drying:*** The cooked fingers are dried in the sun by spreading in thin layer on a bamboo mat or clean drying floor. It takes 10 to 12 days for drying in the sun. When fully dried, the rhizomes become hard, stiff and brittle. Dried turmeric usually has moisture content of about 10%. The yield of the dry product varies from 18-23% depending on the variety and the location where the crop is grown
- ***Polishing:*** Polishing of boiled dried turmeric rhizomes is done to smoothen the rough and hard outer surface. It improves the colour and the appearance of the dried rhizomes. Hand polishing is done by rubbing the dried rhizomes against hard clean surface of the drying floor. This is followed by winnowing to separate scales and root bases. Power operated turmeric polishers provided with wooden drum is used for polishing especially when the rhizomes have to be used for powder making.
- C***leaning and Grading:*** Cleaning and grading is generally done manually.
- ***Packing:*** The graded turmeric rhizomes are bulk packed separately in jute or woven polypropylene bags.

(iv) Ginger

Ginger *(Zingiber officianale*) is used both as a fresh vegetable and as a dried spice. The crop is ready for harvest in about 8 months after planting when the leaves turn yellow and start drying up gradually. The clumps are lifted carefully with spade or digging fork and the rhizomes are separated from the dried up leaves, roots and adhering soil. Harvesting is to be done from the 6th month onwards when used as green ginger. The various post harvest operations involved in obtaining clean dried ginger are,

- ***Washing:*** It is done to remove dirt, spray residues and other foreign materials. In this process ginger is soaked in still water overnight and in the next day water is sprayed over to clean it.
- ***Peeling:*** Peeling hastens the process of drying and maintains the epidermal cells of the rhizomes, which contain essential oil responsible for aroma of ginger. Indigenously, peeling is performed by rubbing the ginger pawns soaked in water over night against jute bags or by scraping with sharpened bamboo splinters. The scrapped or peeled rhizomes are again washed well and put for drying on clean drying yard.
- ***Drying:*** The cleaned and peeled ginger with moisture content of about 80% is spread thinly under sun and the moisture content is brought down to 10% for safe storage. It takes about 10 -15 days for complete drying. The dry ginger so obtained is known as rough or unbleached ginger. The yield of dry ginger is 19-25 per cent of fresh ginger depending on the variety and the location where it is grown.
- ***Bleaching:*** The peeled ginger is soaked in thick lime water for some time and it is then fumigated with sulphur fumes for 12 hours and sun dried for a day. The process is repeated once or twice to obtain a fully bleached white produce which is thoroughly dried and stored.
- ***Grading:*** The dried ginger rhizomes are manually graded based on the external appearance.
- ***Packing:*** The graded ginger is bulk packed separately in jute or woven polypropylene bags.

(v) Chillies

Chilli (C*apsicum annum)* is the most widely cultivated crop among the spices grown in India. Chillies are harvested when the pods are well ripened and partially wither at the plant itself. At this stage they would have superior pungency and colour.

The harvested pods are kept in heaps either indoor or in shade away from direct sun light for 2-3 days so as to develop uniform red colour. Subsequent to this the pods are dried under the sun by spreading them out on clean, dry mat, cemented or concrete surface. The harvested chillies in ripe condition have moisture content of 70-80% and need to be dried for 13-15 days for the reduction of moisture to a safe moisture content of 10% and then stored.

In mechanical drying, the chillies are dried at a drying temperature of 50°C and at air velocity of 1.5 m/s. Solar cabinet driers and waste fired driers are also developed for drying of chillies.

Packing of dry chillies is done using jute cloth, paper or paper cartons with polythene lining of 300 gauge.

(vi) Nutmeg and Mace

Nutmeg and mace are two different parts of the same fruit of the nutmeg tree, *Myristica fragrans*. The fruits are harvested when they split open on ripening. Cleaning and drying are the important post harvest operations involved.

- *Cleaning*: The fruits drop on to the ground while harvesting. The fruits are picked up and washed in water to remove dirt and mud adhering to the outer pericarp.
- *Drying:* The unshelled nutmeg is dried in the shade or under sun. The seed cover is removed mechanically or manually. It is dried to a safe moisture content of 10%.

Mace is detached from the nut carefully soon after harvest, washed, flattened by hand or between boards and then sun dried till they become brittle. Hot air oven can be used for drying and colour retention is much better than sun dried mace.

(vii) Cinnamon

Cinnamon (*Cinnamomum zeylanicum*) is obtained by drying the central part of the bark after the second or third year of planting. It is harvested from the branches which have attained greenish brown colour indicative of maturity and when the bark peels of easily. The shoots are cut for bark extraction. Following are the stages in the production of quills:

- *Peeling:* The rough outer bark is first scraped off with a special knife. Then the scraped portion is polished with a brass rod to facilitate easy peeling. A longitudinal slit is made from one end to other and the bark is peeled off.
- *Rolling:* The barks are packed together and placed one above the other and pressed well. The bark slips are reduced to 20 cm length and are piled up in small enclosures made by sticks. Then they are covered with dry leaves or mat to preserve the moisture for the next day's operation and also to enhance slight fermentation.
- *Piping:* Rolled slips are taken to the piping yard for piping operations. The outer skin is scraped off with a small curved knife. The scraped slips are sorted into different grades according to thickness. The graded slips are trimmed; ends are cut and pressed over pipes. Slips are rolled into pipes and soon after they are allowed to dry. During drying, smaller quills are inserted into the bigger ones, forming smooth and pale brown compound quills, which are known as pipes. The quills are arranged in parallel lines in the shade for drying, as direct exposure to the sun at this stage would result in warping. The dried quills, thus obtained, consist of a mixture of coarse and fine types and are yellowish brown in colour. The quills are bleached, if necessary, by sulphur treatment for about 8 hours.

  The process of producing quills has several by-products, which are used in further processing:

- *Quillings:* These are broken pieces of quills used mainly for grinding but also for distillation of oil. The pieces vary considerably in size, being about 5 to 15 or 20 cm in length and about 10-25 mm in diameter.
- *Feathering*: These are short shavings and small pieces of leftovers in the processing of the inner bark into quills. Collectively, featherings present a shade darker colour than the quills and a shade lighter than the chips.

- *Chips:* These are small pieces of bark, grayish brown on the outer side and a lighter brown on the inside. They are deficient in both aroma and taste and are not to be compared to the quills for flavour.

(viii) Clove

Clove is the small, reddish brown unopened flower bud of the tropical evergreen tree *Syzygium aromaticum*.

- *Harvesting*: Cloves are harvested when the trees are 6-8 years old. The correct time of harvest is when the outer green leaves (the calyx) of the flower bud change from olive green to yellow pink and before the petals fall to expose the stamens. Harvesting is done before the flowers start opening while the tip is fully developed and round in shape. The buds are handpicked and the length varies from 13 to 19 mm. It is also important that the branches are not removed as this will reduce the yield in the future crop.
- *Pre-treatment:* The buds are detached from the stalks by holding the cluster in one hand and pressing against the palm of other hand slowly by twisting so that buds fall off.
- *Drying:* Clove buds are dried quickly as they start to ferment. Cloves are usually sun dried by spreading it on clean mats. The cloves should be raked and turned frequently to ensure they develop an even brown colour. The drying process takes about four to five days and the final moisture content is about 10%.

Conclusion

Post-harvest management of spices has great scope considering present international trade scenario**.** We expect a huge jump in the export of curry powders and other value-added products in the coming decade**.** The research programmes should orient for this demand by focusing more attention on better agro techniques in product diversification, varieties suitable for such products and following good agricultural practices. Considering the huge potential of spices as source of ecofriendly nutraceuticals, agro techniques which release such compounds needs to be formulated.

Chapter 4

Mechanization in Cashewnut Processing: Shelling to Packaging

Dr. D. Balasubramanian,
Principal Scientist (AS & PE), ICAR-Directorate of Cashew Research (DCR), Puttur, Karnataka, India

1. Introduction

Cashew industries in India is a sunrise sector that has gained prominence for quite a long time. Availability of raw materials, changing lifestyles and appropriate fiscal policies have given a considerable impetus to the industry's growth. This sector serves as a vital link between the cashew farmers and the industrial segments of the economy. Strengthening this link is of critical importance to elevate rural economy; improve its utilization and nutritive value; ensure remunerative prices to farmers as well as affordable prices to consumers. Amidst recently developed strong domestic market, India continues to be a leading exporter of cashew and its byproducts. In order to ensure that this sector gets the stimulus it deserves, Government agencies have been implementing a number of programmes towards self-reliance of raw cashewnuts production, Infrastructure development, technology up-gradation and modernization, human resources and research and development.

Processing of cashewnuts offers great scope for conversion into edible cashew kernels and in the process, it reduces wastage, increases shelf-life resulting in value addition and higher income transfer to the farmers as the processed cashew has wider market. Cashew processing is one of the critical sectors of the economy due to its enormous contributions to farmers income, employment creation and foreign exchange earnings. In this context, this chapter explores the intricate nexus of cashew processing, import/export dynamics, and product diversification, shedding light on the opportunities and challenges facing the global cashew industry.

2. India's position in the globe

Tree nuts played an important role in diets of many cultures and civilizations for centuries owing to their rich nutritional content, distinct flavours, and high energy density. Among the tree nuts, Cashewnuts stands out as a significant cash crop with multifaceted importance in the global agricultural landscape. Over five centuries ago, Portuguese explorers introduced cashew to India, marking the beginning of its journey as a widely cultivated and highly valued commodity. Today, cashew cultivation spans in 46 countries in the warm humid tropics across the globe, with major production hubs including Ivory Coast, India, Vietnam, Cambodia, Benin, Tanzania Nigeria, and Brazil. Among the various Agri- Horticultural commodities in the global trade, cashew ranking among the top ten agricultural export commodities contributing nearly 0.25% of the export earning of the country has attained a prominent position by providing significant contribution to Indian exchequer.

3. Production Vs Processing

Presently, the established processing capacity of raw nuts in India is around 20-25 lakh MT, whereas the domestic contribution is around 7.8 lakh MT. Moreover, the import and export potential of cashew play a pivotal role in shaping global trade patterns and agricultural economies. Presently India is importing raw nuts from other producer countries to the tune of 13.5 lakh tonnes to meet the demand of domestic cashew processing industries (Fig 1). Currently the import possibility from many countries is dwindling, as several countries have setup processing facilities and also due to the competition for procurement of raw nuts by other major cashew processing and exporting countries, like Vietnam.

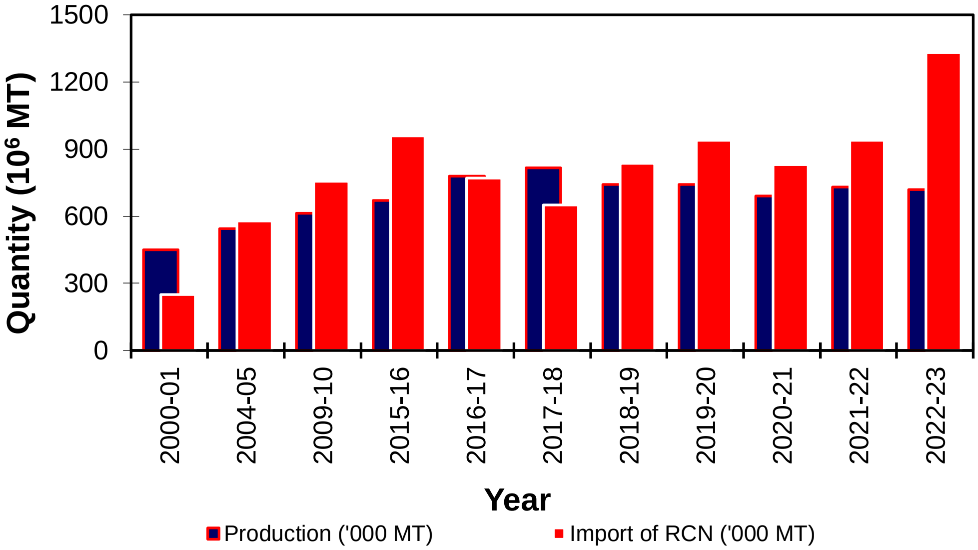


Fig 1. Quantity of raw cashewnuts processed in India – Domestic Vs Import (2000-2023)

During early 60's traditional method of Pan roasting' replaced by drum roasting method and oil bath roasting seldom followed. Cost effective steaming mode is practiced in majority of the units due to financial and environmental benefits. India's low labour costs enabled it to sustain this method and maintain a quality advantages in the industry. But now, crisis of workforce griped the cashew industry and switching over to mechanization is inevitable in order to remain competitive in the global market. A new era in cashew processing system started with introduction of automated machinery which has not only streamlined processing operations but also catalysed economic growth within the sector.

4. Import and export scenario

A total of 13.5 lakh MT of raw cashewnuts is imported especially from East and West African countries to cater to the need of the processing facility developed in the country, which is equivalent to 65% of the total processed quantity (Table1). As far as cashew market is concerned, it is expected to grow from USD 2,313.03 million in 2023 to USD 2,787.20 million by 2028, at a CAGR of 3.80% during the forecast period (2023-2028). Processed kernels from India are exported to more than 60 countries in the world and USA, Middle

East, EEC, Japan, Australia, etc. are the major importing countries. Export of cashew kernels was around 1,01,866 MT during the year 2012-13 and has declined to 47,560 MT in the last fiscal. Comparing to any other cashew producing and processing countries, India has very strong domestic market and about 90.47 % of the total production is consumed locally. A phenomenal growth in domestic consumption recorded since 2000 i.e., from 0.93 lakh MT to 4.27 lakh MT primarily due to awareness on health benefit of cashew and improvement in standard of living and affordability. Presently, per capita consumption of cashew kernels in India, is around 230 g and it is a positive factor for promoting cashew processing in this country and aided in growth of this sector.

Table 1. Proportion of import of raw cashewnuts and export of cashew kernels

Year	Raw nut processed (MT x10^5)	Raw nut Imported (MT x 10^5)	**% Raw nut import**	Kernel export (MT x10^5)	Domestic consumption (MT x10^5)	**% Domestic consumption**
2001-02	8.27	2.49	**30.11**	0.98	0.93	**48.71**
2004-05	11.23	5.79	**51.56**	1.27	1.32	**50.96**
2009-10	13.69	7.56	**55.22**	1.08	2.07	**65.66**
2014-15	15.65	8.40	**53.67**	1.19	2.41	**66.95**
2019-20	16.80	9.38	**55.80**	0.68	3.18	**82.40**
2022-23	20.52	13.32	**64.91**	0.45	4.27	**90.47**

Export earning of Rs 1093 in the beginning of the century declined to -11530 crores, primarily due to investment on import of raw cashewnuts from African countries to fulfil the requirement of cashew processing facility of this country amidst stagnation of domestic cashew supply. Besides, a very strong domestic consumption and unit price value for cashew kernels prevented processor to export cashew kernels. A phenomenal change in the value realized from cashew business could be seen after the introduction of mechanization since 2018.

5. Cashewnut processing technology

5.1. Raw cashewnuts

Raw cashew nut is kidney shaped one with approximately 3.5mm thick leathery outer skin (Epicarp) and thin hard inner skin (Endocarp). The most significant difficulty in processing cashew nuts is that the hard outer shell, which contains the edible kernel, contains a caustic oil which can burn the skin and produces noxious fumes when heated. The oil, referred to commercially as cashew nut shell liquid (CNSL), contains 90 per cent anacardic acid and 10 per cent cardol. The kernel is inside the shell wrapped up by brown skin known as testa.

5.2. Cashewnut processing

It can be defined as the recovery of edible kernel from conditioned raw nut by manual or mechanical means. In general, the processing is started as manual and it consists of steaming / roasting, shelling, kernel drying, peeling, grading and packing. Grading of raw cashewnuts before processing reduces broken kernel. Conditioning of raw cashewnuts is to make the shell brittle and to loosen the kernel from the shell. Three methods are being followed in India, they are: (i) Drum roasting; (ii) Oil bath roasting and (iii) Steam boiling.

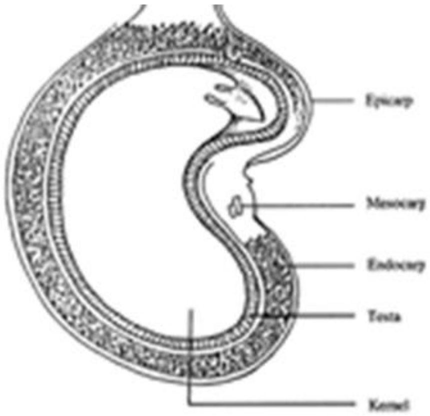


Fig 2. Cross sectional view of raw cashewnuts

5.3. Quality assessment of raw cashewnuts

Cashewnut is a seasonal crop, harvesting of nuts in India starts from March to June. While procuring raw cashewnuts, normally following quality tests are conducted to assess the quality and to fix up the price.

i)	Visual test (Indicative parameter)	Size and colour of the nuts to check the maturity
ii)	Floating test	A random sample (2kg) is put in a vessel containing water. After continuous stirring floaters are collected

	(Indicative parameter)	and counted. Mostly immature nuts, due to its lower density than water, improperly filled nuts and deteriorated nuts floats.
iii)	Counts (Nut count)	Number of nuts per kg and ratio of cashew kernels obtained by shelling a kilo of raw cashewnuts
iv)	Cutting test (Outturn)	A random sample of 2 kg is cut open using hand cutting tool. Based on the kernel appearance i.e. white, shrivelled dotted or rejects, the percentage of good kernel is calculated
v)	Moisture content	It may be determined by toluene distillation method or using commercially available moisture meter.

5.4. Stages of cashewnut processing

5.4.1. Drying and storage of raw cashewnuts

Harvested nuts are sun-dried for 2 to 3 days before processing. If nuts are not dried and stored, it leads to fungal spoilage, resulting in poor quality kernels. Fungi such as *Gonatobotryam*, Alternaria sp., *Verticuillium* sp., and many species of Aspergillus have been isolated from stored cashew nuts. Varietal variations with respect to colour and size of nuts do exist and the weight varies between 5 and 15g. Maximum permissible moisture content of raw cashew nuts is 8.7 to 9.1%. Gunny bag storage of 80 kg capacity is predominant in India and it has been shown that storage of raw nuts with a moisture content of 5 to 6 % for a period of 12 months at ambient temperature (25 to 30°C) did not affect either processing or biochemical quality. Studies on effect of maturity on the processing quality have clearly indicated that shelling percentage, peeling outturn, whole kernel recovery increases while kernel rejects decrease with maturity.

5.4.2. Calibration / Sorting of raw cashewnuts

Raw nut grading is the first step in mechanising the cashew processing system. The kernel yield is primarily a function of raw material, control over which is not much exerted prior to processing. Although many parameters represent quality of raw cashew nuts, moisture content, nut count representing size and outturn to assess quality and quantity of kernels, considered as quality indicators. Providing graded nuts can improve operator efficiency during manual shelling process. Grading nuts at preliminary level can ensure control over kernel drying cycle for better white whole kernel recovery and minimize workload at kernel grading stage. There are two types of calibration systems are available viz., Compartmental grader and Concentric drum type rotary sieve grader (Fig 3). Normally raw cashewnuts are grader in to A1, A2, B1, B2, C1, C2 and D depending on the minor axis dimension of the nuts.

Fig 3. Calibration of raw cashewnuts

5.4.3. Conditioning and curing of raw cashewnuts

In this process, the nuts are fed into an inclined rotary drum which is heated initially to such an extent that the exuding oil ignites and burns, thus charring the shell. The drum maintains its temperature because of the burning cashewnut shell liquid (CNSL) oozing out of the nuts. Roasting generally takes about 30-45 sec and the drum is rotated manually. The shell becomes brittle and rate of shelling and the outturn of whole kernels reported to be highest among the three methods of roasting (Fig 4).

Steam boiling mode of conditioning raw cashewnuts is considered to be the cost-effective system and gaining importance all over the world (Fig 4). As Cashew Nut Shell Liquid (CNSL) is preserved in the shell after conditioning, it can be extracted adding revenue to the processor, it is quite advantageous. During steaming process, nut expands and become soft due to infusion of moisture. Rate of moisture infusion should be controlled in order to prevent the transfer of pigment from testa to kernel surface. Therefore, steam pressure and duration of exposure are the decisive factors during steaming operation which are influenced by size, dryness and storage time. After steaming, the nuts are air-cured by spreading out on the floor in the ambient environment. These ultimately harden the shell and make it amenable for subsequent kernel extraction process.

Fig 4. Drum roasting and Steam conditioning process of raw cashewnuts

5.4.4. Deshelling of raw cashewnuts

The nuts after conditioning are shelled manually or mechanically using hand cum pedal operated shelling gadget. The manual shelling is an operation which requires high dexterity and hand cum pedal operated shelling machine is used for the purpose. Due to non-availability of work force, semi- mechanized and automated machines are used having more capacity and better efficiency (Fig 5). It is a standard practice to smear ash or clay or oil to prevent the contact of CNSL on their hands during operation.

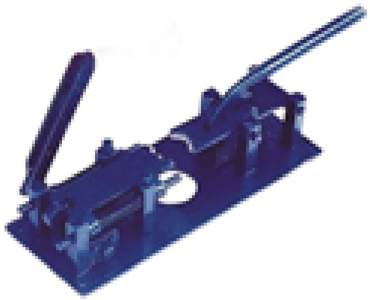
  

Fig 5. De-shelling machine for cashew

5.4.5. Drying of Unpeeled cashew kernels

Shelled kernels are exposed to controlled environment to facilitate the removal of skin adhering to edible kernel. Due to relatively faster diffusion of moisture from testa layer than kernel, it shrinks and become loose to ease the process of manual or mechanical removal of skin. In the commonly used ‘Borma’, drying chamber is indirectly heated by flue gases from the furnace wherein spent cashew shells or cashew shell cake are used as fuel. The conventional “Borma” is presently replaced by more efficient electrical/diesel/de-oiled shell cake or wood operated tray driers. This system reduces the heating time considerably and maintains uniform heat throughout the drier by forced air circulation. Steam assisted dryer deployed in processing line, utilises dry air converted from super-heated steam through radiator assembly. This type of dryer preserves the original color of the cashew kernel and quality consistency is achieved within a batch and in every batch dried.

5.4.6. Humidification of Unpeeled cashew kernels

Thermally treated cashew kernels are humidified i.e. moisturized by water-mist depending on the environment primarily to avoid breakage during peeling process. Duration of humidification depends on the atmospheric conditions and moisture level of cashew kernels. The brown skin i.e. testa of kernels, being hygroscopic in nature, absorb moisture during humidification and helps to dislodge easily the adhering skin from the kernel during mechanical process without damaging or breakage.

5.4.7. Peeling of Unpeeled cashew kernels

Peeling is the process of removing outer skin called testa. Specially designed stainless-steel knife is used to scrap adhering testa without damaging the edible kernel. Average peeling capacity ranges between 4-12 kg $head^{-1}$ day^{-1} and peeling efficiency or whole kernel recovery observed to be 65-72%. Wages are fixed on the basis of whole kernel recovery as it serves as a control for careful work. Pneumatically operated mechanized cashew kernel peeling machines are available and its capacity ranges from 60-1000 kg h^{-1} (Fig 6). Basic requirements for effective peeling depend on material parameters (Moisture content and size grade of unpeeled cashew kernels) and it is influenced by machine parameters such as feed rate, air velocity and residential time during peeling. Whole kernel recovery is in the range of 75-80% and demand human workforce to peel either partially or fully unpeeled cashew kernels.

Fig. 6. Mechanized abrasion and pneumatic based peeling machine

5.4.8. Grading of cashew kernels

Kernel grading is primarily based on wholesomeness, size and surface colour and manually segregated in majority of processing units. Mechanical graders with fluted rollers and colour sorters are also available for grading kernels based on size and surface colour respectively. Mechanical graders are utilized depending on availability of labour force and volume of production.

Fig 7. Size and colour-based cashew kernels graders

Grading standards developed in India refer to number of kernels in a pound weight, for example, WW320 indicates 320 numbers of white whole kernels in a pound (lbs) weight. Broken kernels are either butts or splits depending on whether they are broken across or along the cleavage and graded size grading is based on sieve through which it passes through. Presently 23 numbers of grade specifications are imposed for export of cashew kernels. Algorithm based electronically operating colour and size graders (Fig 7) are used for voluminous production and its capacity and grading efficiency is in the range of 100 to 1000 kg h^{-1} and 90 to 92 % respectively

5.4.9. Packaging of cashew kernels

Vita packing is the process of vacuumizing and flushing inert gas viz. CO_2 or N_2 into tins filled with cashew kernels. The gas infused tins are hand-soldered hermetically using lead free solder. This system is predominantly followed for domestic market as importing countries banned it due to difficulty in deposing off empty tin containers and inherent disadvantages. Moulded Vacuum Packaging (MVP) is encouraged to export cashew kernels and pouch packaging for less quantity.

Vita packing of cashew kernels

Moulded vacuum packaging of cashew kernels

5.5. Issues and Challenges in cashewnut processing in India

Procuring raw cashew is the largest component of the operating costs in cashew processing sector, a slight increase in cashew price adversely affects the entire economics of cashew processing. Traders and middlemen dominate the market for raw cashewnuts and kernels. The individual farmers are in a disadvantageous position as they are forced to sell the produce at a price determined by the traders / leaseholders. Farmers are not interested to use the regulated markets due to taxes/ cess and as such quality-based pricing system is not developed. Establishing supply chain for raw cashewnuts and developing quality standards could address this issue.

Working capital is required for purchasing raw cashewnut inventory. Small processors have constraints in accessing working capital limits from the banks. Access to working capital would induce entrepreneurs to invest in cashew processing facilities Awareness on quality and food safety standards need to be installed in the mind of small-scale processors. Machinery provider should be strengthened towards improving technical specifications. A low cost cashewnut shell liquid technique suiting to cooperative level to be developed and linked to the processor. Cost effective package technique for better shelf life of kernels and setting up common service centre or facility provider for small-scale processors in respect of value addition and packaging has to be encouraged.

5.6. Agri business incubation @ICAR-DCR

Agri Business Incubation (ABI) Centre is hosted at ICAR-Directorate of Cashew Research, Karnataka and supported by Intellectual Property and Technology Management, Indian Council of Agricultural Research (ICAR). This ABI Centre provide the effective platform to promote agribusiness and entrepreneurship developments in cashew eco system with the concept of growth through innovation, upgradation of technology and skill development. Technologies available for incubation are i) Nursery management and cashew grafting; ii) Value addition to cashew apples and iii) Cashewnut processing. It is designed to provide platform to Entrepreneurs/ Industries/ Students for business or research development under different incubation models. State-of-art facility is in place to facilitate incubatees for skill development or utilization. Hands on training (3-days) offered to incubatees to impart skill and enhance business knowledge to standup in the competitive world. Incubatees are permitted to use the facility for 180 days from the date of registration to be acquainted with technology and develop confidence. Potential entrepreneur will be provided work space, communication and computing, exhibition cum information, conference room and other incubation facilities. Details of ABI and its services are available at https://cashew.icar.gov.in/abi-guidelines/

5.7. Conclusion

Various modes of cashew processing are followed in cashew growing regions with varied degree of mechanization for effective utilization of man, machine and materials. The economic efficiency of the processing depends on the production of white whole kernels which fetches premium price at consumer's level. Therefore, pertinent technical parameters at all stages have to be optimized to recover maximum white whole kernels irrespective of the processing method followed. Further, various unit operations in cashewnut processing should be energy efficient, environment friendly and highly suitable for production catchments in order to promote rural economy. It is essential to build up internationally competitive business environments and promote enterprises to make the cashew processing sector an engine of the economic growth. It should particularly promote agricultural development-led industrialization to support successful implementation.

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Design and Development of Solar Thermal Energy Conversion Systems for the Seafood Industry

Dr. S. Murali,
Scientist, Engineering Section, ICAR- ICAR - Central Institute of Fisheries Technology (CIFT), Cochin, Kerala, India

Solar energy conversion systems

Solar energy conversion systems are thermal collectors and photovoltaic (PV) modules that absorb solar radiation and convert it to useful energy as thermal and electrical energy. Flat-plate solar thermal collectors, vacuum tube solar thermal collectors, compound parabolic concentrating solar collectors, Fresnel lenses, and parabolic trough concentrating collectors are typical devices that are mainly used to convert solar radiation into heat (Fig.1). PVs are the main type of solar devices that convert solar radiation directly into electricity. Typically, PVs are made from silicon-type modules, semiconductors based on polycrystalline silicon (pc-Si), monocrystalline silicon (c-Si), and thin films (Fig. 2).

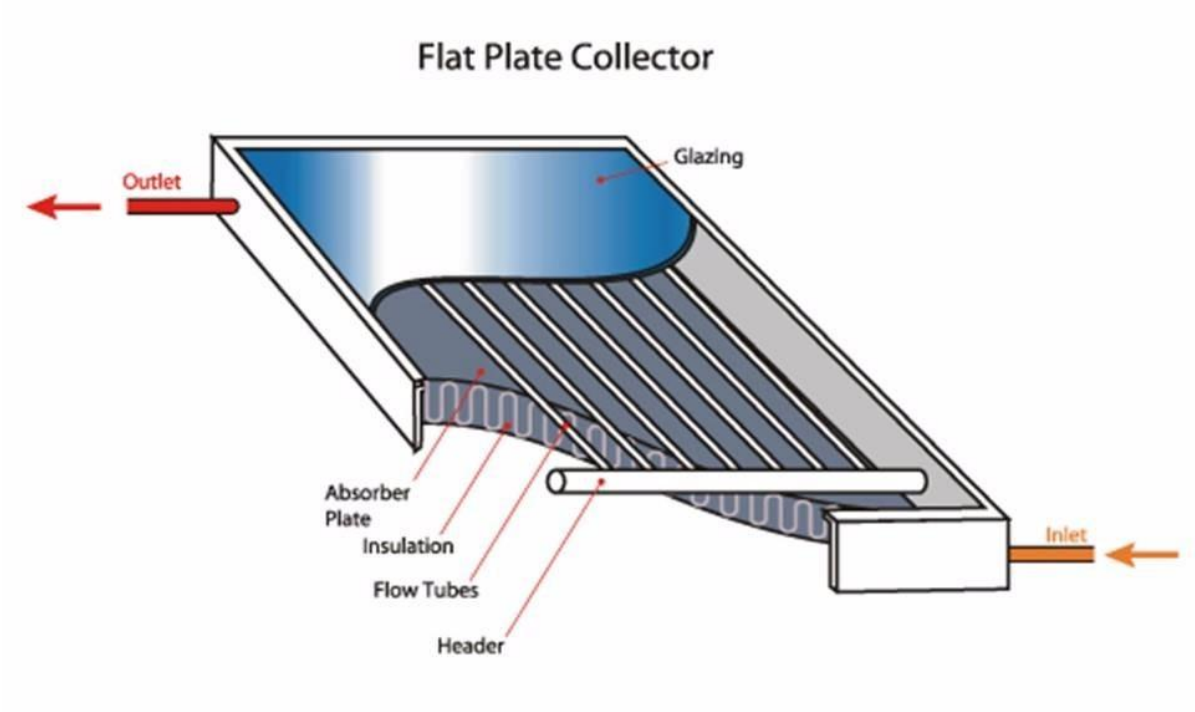

Fig 1. Cross-sectional view of a flat plate solar collector

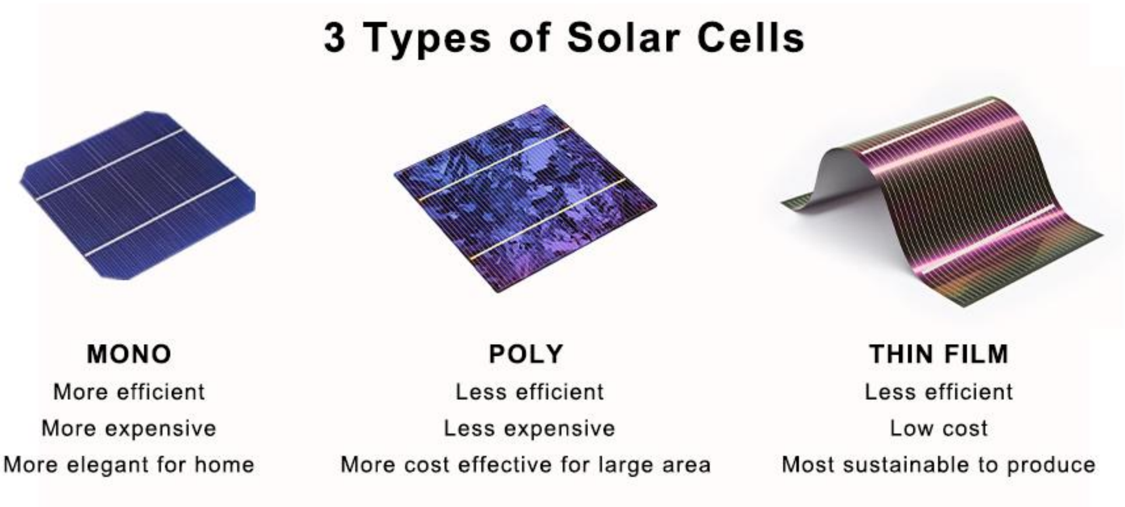

Fig 2. Types of solar PV modules

Solar Thermal Energy Conversion Systems

Solar thermal energy conversion systems capture sunlight using collectors, transforming it into usable heat for processes like water heating or for generating electricity via a thermodynamic cycle that uses steam to power turbines. These systems vary by temperature, application, and operational complexity, with active systems using pumps and passive systems relying on design for heat circulation. Components often include collectors, a heat-transfer fluid, and potentially thermal energy storage to provide power during cloudy periods or at night. Its applications are heating water for domestic or commercial use. Providing heat for buildings and large-scale power plants that use mirrors to focus sunlight and generate electricity. Also, purifying water by evaporating and condensing it using solar energy.

Photovoltaic-thermal (PVT) system

A method to reduce PV panel surface temperature and improve panel efficiency by incorporating a thermal absorber system was investigated by various researchers. The method was referred to as a photovoltaic-thermal (PVT) system, which combined both solar thermal and solar photovoltaic technology. A PVT system can be used to generate electricity and heat simultaneously. The heat absorbed by the PV panel through incident solar radiation is conducted to an aluminium absorber plate and then eliminated through forced convection using the cooling mediums. PVT panel temperature is reduced by the cooling mediums, including air, water, and nanofluid, and the absorbed heat can be utilized for domestic and industrial applications

Solar hybrid dryers for seafood applications

In a hybrid solar drying system (Fig. 3), drying can be continued during off-sunshine hours by utilizing a backup heat source and also by storing the energy in the form of sensible or latent heat during sunshine hours. In this way, drying becomes a continuous process, and the product is saved from possible deterioration by a microbial infestation. These types of hybrid solar dryers find useful applications in developing countries where the conventional energy sources are either scarce or expensive, and the heat-generating capacity of the solar system is not sufficient.

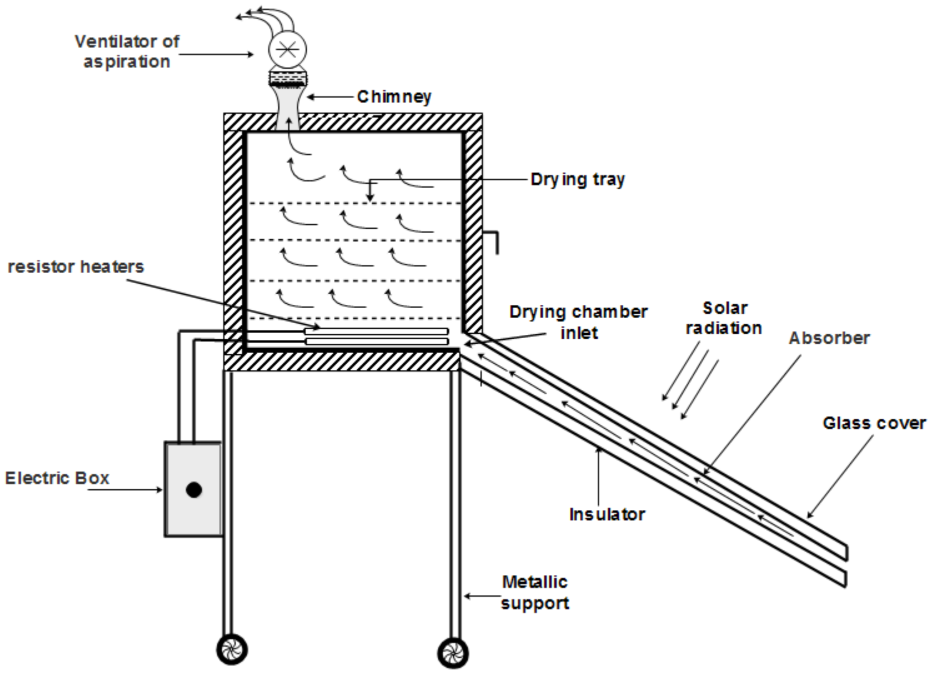

Fig. 3 Schematic of a hybrid solar dryer

Solar dryer with LPG backup

In this dryer during sunny days, fish will be dried using solar energy, and when solar radiation is not sufficient during cloudy/ rainy days, the LPG backup heating system will be automatically actuated to supplement the heat requirement. Water is heated with the help of solar vacuum tube collectors installed on the roof of the dryer and circulated through heat exchangers placed in the PUF-insulated stainless steel drying chamber. Thus, continuous drying is possible in this system without spoilage of the highly perishable commodity to obtain a good-quality dried product.

This dryer is ideal for drying fish, fruits, vegetables, spices, and other agricultural products. It helps to dry the products faster than open drying in the sun, by keeping the physicochemical qualities like colour, taste, and aroma of the dried food intact and with higher conservation of nutritional value. A programmable logical controller (PLC) system can be incorporated for automatic control of temperature, humidity, and drying time. Solar drying reduces fuel consumption and can have a significant impact on energy conservation.

Solar dryer with electrical backup

Effective solar drying can be achieved by harnessing solar energy with specially designed solar air heating panels and proper circulation of the hot air across the SS trays loaded with fish. Food-grade stainless steel is used for the fabrication of the chamber and perforated trays, which enable the drying of fish hygienically. Since the drying chamber is closed, there is less chance of material spoilage by external factors. An alternate electrical backup heating system under controlled temperature conditions enables the drying to continue even under unfavourable weather conditions like rain, cloud, non-sunny days, and at night, so that the bacterial spoilage due to partial drying will not occur. Improved shelf life and value addition of the product fetches higher income for the fisherfolk. The eco-friendly solar drying system reduces fuel consumption and can have a significant impact on energy conservation.

Solar tunnel dryer

The tunnel dryer can be used by fishermen or small-scale fish processing units for bulk drying during the seasonal higher catch/excess landing of fish. The materials of construction are UV-stabilized transparent polythene sheet or polycarbonate sheet for the roof cover, black absorber sheet for the floor, supporting frames of CPVC, and GI rod. Three ventilator fans of 0.5 hp were provided for air inlet and moisture removal. The trays with tray holders were placed inside the dryer for spreading and hooking the fish for drying. This tent dryer was designed as a stand-alone system, as it does not require any external power source/electricity. The fans were operated through a solar PV panel fitted on the rooftop of the dryer and an associated battery setup. It is also affordable and suitable for Indian fisherfolk.

Design and Development of Hybrid Dryers for Food Preservation

Dr. V. Arun Prasath
Assistant Professor, Department of Food Process Engineering, National Institute of Technology, Rourkela, Odisha, India

Abstract

Drying is one of the oldest and most effective preservation methods applied to agricultural and food products. However, conventional thermal drying techniques often compromise the nutritional, physical, and sensory quality of foods, while being energy intensive. Recent research in hybrid drying technologies—combinations of hot-air drying with non-thermal techniques such as ultrasound (US), pulsed electric fields (PEF), ultraviolet (UV), microwave (MW), and pulse combustion—has shown promising results in reducing drying time, saving energy, and improving product quality. This paper reviews the principles, mechanisms, and benefits of hybrid drying methods, with particular focus on ultrasound-assisted, pulsed electric field-assisted, ultraviolet-assisted, and microwave-assisted hot-air drying. Current challenges and future directions are also discussed, emphasizing the need for smart dryers, standardization of methodologies, and sustainable industrial adoption.

Keywords

Hybrid drying, ultrasound drying, pulsed electric fields, ultraviolet drying, microwave drying, non-thermal drying technologies.

Introduction

Food products such as fruits, vegetables, grains, and meat are highly perishable and require effective preservation methods to maintain their nutritional and sensory qualities. Drying remains a widely used method because it reduces moisture content, prolongs shelf life, and minimizes transport weight. However, conventional drying techniques often involve high energy consumption and long drying times, leading to undesirable quality changes such as shrinkage, discoloration, nutrient degradation, and poor rehydration capacity.

In response, researchers have developed hybrid drying technologies that combine traditional convective hot-air drying (CHAD) with innovative, non-thermal techniques. Hybrid drying methods have been shown to enhance drying efficiency, preserve bioactive compounds, and reduce operational costs. This paper explores the mechanisms, advantages, and limitations of various hybrid drying systems.

Drying and Quality Interaction

Drying significantly influences food quality attributes such as texture, color, aroma, nutritional value, and rehydration properties. Heat-sensitive products are particularly susceptible to degradation when exposed to high temperatures and oxygen during drying. Physical changes, including cracking, solute migration, and porosity alterations, further affect consumer acceptance.

Hybrid dryers aim to mitigate these problems by operating at lower temperatures, enhancing mass transfer, and maintaining desirable quality traits. However, the choice of dryer and process parameters must balance product quality, cost, and energy efficiency.

Conventional and Hybrid Dryers

Conventional dryers include tray dryers, rotary dryers, spray dryers, fluidized beds, and freeze dryers, among others. While these systems are well established, they are energy-intensive and may compromise product quality.

Hybrid dryers combine multiple drying modes—such as convection, radiation, vacuum, ultrasound, microwave, or UV—to overcome these limitations. Examples include:

- Flash + Fluid bed dryers
- Vacuum + Microwave dryers
- Convection dryer + Vacuum frying Such combinations yield higher efficiency, better control over product quality, and reduced environmental impact.

Ultrasound-Assisted Hot-Air Drying

Ultrasound (US) generates acoustic cavitation, causing cell disruption and enhancing mass transfer without significant heating. Low-frequency, high-intensity ultrasound is particularly effective in reducing drying time and improving diffusion.

Advantages:

- Significant reduction in drying time
- Enhanced heat and mass transfer
- Better quality at lower temperatures

Limitations:

- High equipment costs
- Industrial-scale challenges
- Safety concerns due to high frequencies

Pulsed Electric Field-Assisted Hot-Air Drying

Pulsed electric field (PEF) technology applies short, high-voltage pulses to food materials, inducing electroporation and pore formation in cell membranes. This process enhances water removal during hot-air drying.

Benefits:

- Increased effective moisture diffusivity
- Reduced drying time and energy consumption
- Improved color and rehydration properties

Challenges:

- High capital investment
- Limited industrial application
- Variability in results depending on crop type and process conditions

Ultraviolet-Assisted Hot-Air Drying

Ultraviolet (UV) radiation, particularly UV-C (254 nm), is effective for microbial inactivation and enhancing moisture transfer during drying. UV-assisted hot-air drying reduces microbial load, accelerates drying, and improves color.

Advantages:

- Eco-friendly and chemical-free
- Higher drying rates and energy savings
- Improved microbial safety

Limitations:

- Lack of standardized process conditions
- Still in early stages of research

Microwave and Pulse Combustion Hybrid Drying

Microwave-assisted drying offers rapid, volumetric heating, significantly accelerating drying and improving product quality compared to conventional methods. Pulse combustion drying, on the other hand, uses pulsating jets of hot gases to enhance mass transfer efficiency.

Both methods are promising for sensitive products like fruits and vegetables, offering better process control, energy savings, and high-quality products.

Smart Hybrid Dryers

Future developments focus on smart dryers that integrate mathematical modeling, sensors, and advanced control systems. These systems can optimize drying conditions, reduce carbon footprint, and ensure consistent product quality. Artificial intelligence approaches such as fuzzy logic and neural networks are being explored for real-time monitoring and control.

Current Challenges and Future Outlook

Despite the promise of hybrid dryers, several challenges remain:

- High cost of equipment and operation
- Lack of standardized methodologies for industrial-scale drying
- Limited research on long-term product quality and consumer acceptance

- Need for sustainable and eco-friendly drying technologies

Future research should emphasize pilot-scale testing, cost reduction, and sustainability assessments such as life cycle analysis (LCA). Incremental innovation with hybrid systems is preferred over radical changes to reduce risks and development costs.

Conclusion

Hybrid drying technologies represent a significant advancement in food preservation, offering solutions to the limitations of conventional drying. By combining hot-air drying with ultrasound, pulsed electric fields, ultraviolet light, microwaves, and pulse combustion, researchers have achieved improved drying efficiency, energy savings, and superior product quality. However, wider industrial adoption requires addressing cost, scalability, and standardization challenges. With continued research and the integration of smart technologies, hybrid dryers have the potential to revolutionize food drying and preservation in a sustainable manner.

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Chapter 7

Application of 3D Printing Technology in the Food Industry

Dr. Rajeev Kumar & Dr. Sukanya Barua
ICAR-Indian Agricultural Research Institute, Pusa, New Delhi, India

Introduction

3D food printing is a cutting-edge technology that employs digital designs to fabricate edible products with customized shapes, colours, flavours, textures, and nutritional profiles. As an extension of additive manufacturing, it constructs food layer by layer from printable materials such as purees, gels, doughs, or powders. This technological innovation is gradually reshaping the food industry by enabling greater personalization, efficiency, and sustainability compared to traditional production methods (Godoi et al., 2016; Sun et al., 2015).

Conceptual layout of 3D Food Printing

One of the most compelling features of 3D food printing is its ability to produce foods tailored to specific dietary requirements. It can support vegan, gluten-free, or dairy-free diets, and it is particularly beneficial for individuals with allergies and intolerances (Dankar et al., 2018). In healthcare, printed foods are being explored for patients with swallowing difficulties by customizing textures, while in sports nutrition, meals can be designed to deliver precise macronutrient compositions for performance and recovery (Pereira et al., 2021; Lipton, 2017). Furthermore, this technology can replicate the sensory attributes of conventional foods—including flavour, aroma, and texture—while simultaneously introducing new visual designs and creative culinary experiences (Liu et al., 2018).

Sustainability is another major driver behind the adoption of 3D food printing. By incorporating alternative protein sources such as edible insects, plant-based powders, or cultured cells, the technology reduces dependency on resource-intensive animal proteins (Brancolini & Spigno, 2021). It can also upcycle food by-products and surpluses into printable "food inks," thus minimizing waste and promoting circular food systems (Giannakas et al., 2023). Beyond reducing food loss, printing allows for precise portion control and on-demand preparation, helping to lower environmental impacts and align with global sustainability goals (Taneja et al., 2022). Moreover, its application in space missions and military operations demonstrates its value in closed or resource-limited environments, where efficient, nutrient-rich, and customizable meals are essential (Zhang et al., 2022).

However, despite its significant potential, 3D food printing faces several barriers to large-scale adoption. Technical challenges include slow printing speeds, limited ingredient compatibility, and the difficulty of ensuring the structural stability of printed foods (Çakmak & Gümüş, 2020). Food safety and regulatory frameworks remain critical concerns, as printed foods must comply with hygiene standards while maintaining nutritional integrity (Trends in Food Science & Technology, 2017). Equally important is consumer perception; some people still view printed foods as artificial or inferior to traditional counterparts (Liu et al., 2022). Scaling up from experimental kitchens to industrial production will therefore require advances in printer design, food formulations, and automation (Dai et al., 2022).

In summary, 3D food printing represents a disruptive innovation in modern gastronomy and food manufacturing. By enabling personalized nutrition, sustainable practices, and novel culinary experiences, it addresses many of the pressing challenges in today's food systems. At the same time, its integration into mainstream industry depends on overcoming technical, regulatory, and perceptual hurdles. This chapter will therefore explore the applications, benefits, challenges, and future prospects of 3D printing in the food sector.

What is 3D Food Printing and Its Types?

3D food printing is an emerging technology that applies the principles of additive manufacturing to the food sector. It uses a **layer-by-layer approach** to craft edible products with intricate shapes, customized textures, and innovative flavour combinations. The process combines **digital design software**, **specialized food-grade printers**, and **printable food materials** such as chocolate, dough, vegetable or fruit purees, protein gels, and hydrocolloids. Unlike conventional cooking or molding techniques, this method enables precise control of portion size, texture, and nutrition, making it highly relevant for personalized diets, healthcare, gastronomy, and sustainable food systems. The technology is versatile and encompasses several different approaches, each suited for specific ingredients and applications and its related image shown in below Figs.

1. Extrusion-Based Printing

This is the most widely used method, where semi-solid or paste-like materials are extruded through a nozzle and deposited layer by layer. It is ideal for chocolate, cheese, dough, mashed vegetables, or protein gels. By controlling the extrusion rate and nozzle movement, complex structures and multi-ingredient foods can be produced.

2. Inkjet Printing

Inkjet printers spray fine droplets of liquid food material—such as edible colours, flavour solutions, or nutrient suspensions—onto a surface with high precision. This method is often used for **decorative purposes** (e.g., personalized cake designs) or for adding nutrients and flavours to existing food substrates.

3. Selective Sintering or Binder Jetting

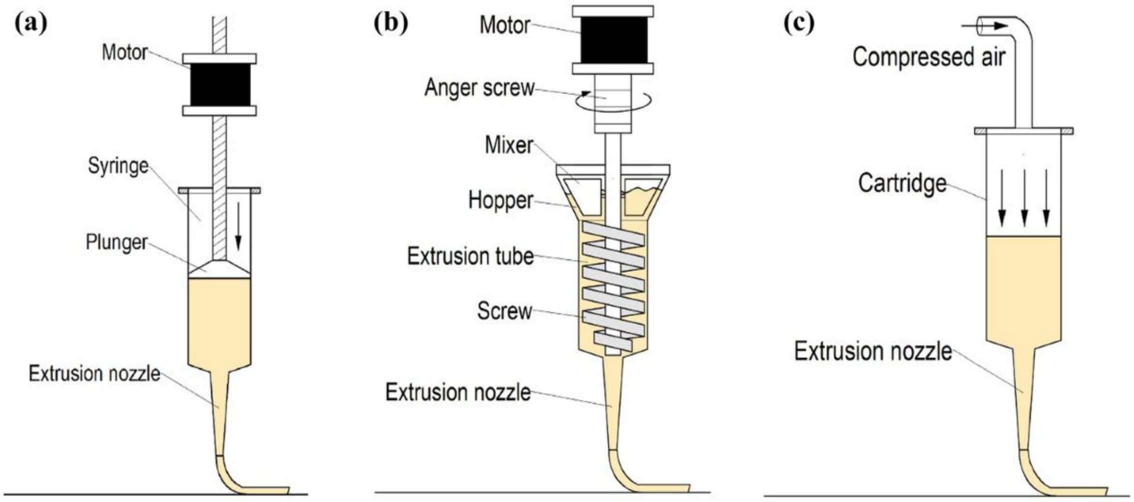
In this method, powdered ingredients (such as sugar or starch) are selectively bound together using heat, lasers, or edible binding agents. It enables the creation of highly detailed, complex shapes, but usually requires post-processing such as baking, frying, or drying to improve stability and taste.

4. Mold-Based Printing

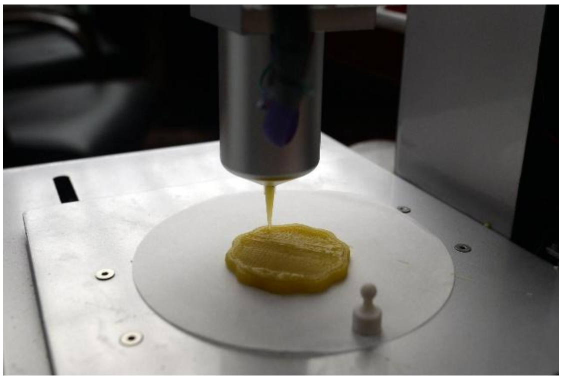
Here, 3D printers produce **custom edible molds** that can later be filled with chocolate, jelly, or other soft foods. This hybrid of additive and traditional molding techniques allows for intricate cavity designs that would be impossible with standard molds.

5. Cooking–Printing Combination

An emerging trend is the integration of **printing and cooking** into a single device. Such printers can bake, grill, or heat the food simultaneously while it is being printed. This improves efficiency, texture, and flavour by ensuring foods are not only shaped but also cooked and ready to eat immediately.

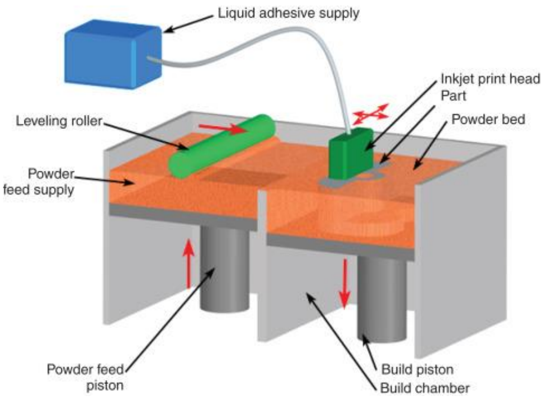


Extrusion-Based 3D Food Printing

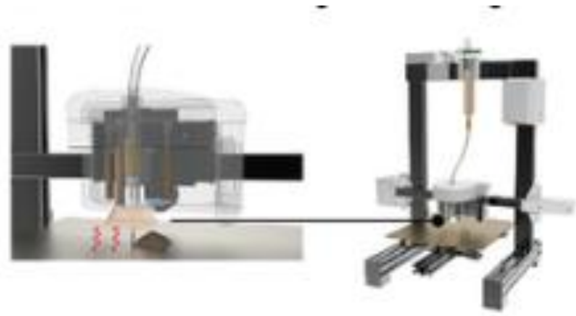


Inkjet Printing Based 3D Food Printing

Mold-Based Printing



Selective Sintering or Binder Jetting



Cooking–Printing Combination

Applications of 3D Printing

The food industry is constantly evolving, with technology playing a pivotal role in transforming the way we produce, design, and consume food. Among these innovations, **3D food printing** has emerged as a disruptive technology that blends culinary creativity with advanced engineering. It uses layer-by-layer deposition of edible ingredients to create customized meals, intricate designs, and sustainable alternatives that traditional methods cannot easily achieve. Below are the major applications of 3D printing in the food industry, explained under different themes.

1. Customized Nutrition

One of the most impactful applications of 3D food printing is its ability to create **personalized meals** tailored to individual nutritional requirements. In healthcare, this technology is already being explored to design meals for patients with unique dietary needs, such as those suffering from food allergies, diabetes, or swallowing disorders (dysphagia). By precisely controlling the ratio of carbohydrates, proteins, fats, vitamins, and minerals, food printers can deliver meals that meet exact caloric and nutrient specifications.

Athletes and fitness enthusiasts can also benefit from this level of personalization. For instance, a runner might require a protein-rich energy bar after training, while an elderly patient in a hospital may need soft-textured, easy-to-swallow food enriched with micronutrients. 3D printing ensures such dietary precision, which is often difficult to achieve with conventional food preparation methods.

Moreover, this application has the potential to integrate with digital health systems. For example, wearable devices tracking real-time health metrics could communicate with a food printer to create meals instantly adjusted to a person’s energy expenditure or blood sugar levels. This synergy positions 3D food printing as a key technology in the future of **personalized medicine and nutrition**.

2. Creating Customized Food Designs

In the culinary world, **appearance is as important as taste**. The dining experience is significantly influenced by presentation, and 3D food printing empowers chefs and food designers to push creative boundaries. Traditional cooking tools are limited when it comes to producing fine, detailed, and consistent shapes. However, with 3D printers, chefs can transform digital designs into edible masterpieces.

For example, pastry chefs use 3D printers to create intricate chocolate sculptures, delicate sugar lattices, and customized cake toppers. In high-end restaurants, artistic plating elements produced by printers enhance the overall dining experience, offering customers not only delicious flavors but also visually stunning dishes.

Beyond aesthetics, 3D printing can **modify textures and structures** in ways that alter the sensory experience of food. For instance, by adjusting the density of a printed dish, it can be made crispier, softer, or more aerated. This feature can also make food more accessible to people with chewing or swallowing difficulties while maintaining its visual appeal. Ultimately, this technology is redefining **gastronomy as an art form**, where creativity, precision, and innovation merge seamlessly.

3. Efficient Food Production and Automation

Efficiency is another area where 3D food printing is making significant contributions. Traditional food preparation often involves multiple steps, manual labor, and considerable time. By contrast, 3D printing automates much of the process, **reducing preparation time and minimizing human errors**.

Food manufacturers can use printers to produce uniform, complex products at scale. For instance, pasta with intricate shapes, geometrically designed confectionery, or pre-portioned ready-to-eat meals can be produced with consistent quality and minimal waste. This automation also improves **supply chain efficiency**, as products can be prepared on demand, reducing the need for excessive storage.

In addition, automation ensures that each product is identical, which is crucial for commercial food businesses where quality and consistency are key to customer satisfaction. As 3D food printers become faster and more cost-effective, they could play a major role in **industrial kitchens, airlines, and catering services** where large volumes of uniform meals are required daily.

4. Sustainability and Alternative Proteins

The global food industry faces pressing challenges such as **food waste, environmental sustainability, and the rising demand for protein**. 3D printing offers solutions by promoting resource efficiency and supporting the integration of alternative ingredients into mainstream diets.

For example, surplus vegetables, grains, or byproducts from food processing can be repurposed into printable pastes or powders. This not only reduces waste but also creates new edible products. Researchers estimate that 3D printing can reduce food waste by **10–30%**, a significant contribution to global sustainability goals.

Another exciting application lies in the use of **alternative proteins**. Plant-based proteins, insect flours, and even cultured meat can be incorporated into printable formulations. By controlling texture and flavor through printing, these sustainable protein sources can mimic traditional meat products, making them more appealing to consumers. For instance, a 3D-printed plant-based steak can replicate the fibrous texture of animal meat, providing a familiar sensory experience while reducing reliance on livestock farming.

This innovation aligns with the growing movement toward **eco-friendly diets** and has the potential to significantly lower the food industry's carbon footprint while ensuring global food security.

5. Educational and Experimental Use

Beyond commercial kitchens and factories, 3D food printing is finding applications in **education and research**. Culinary schools are beginning to integrate 3D printers into their programs, allowing students to experiment with design, fabrication, and presentation. This provides future chefs with exposure to cutting-edge tools that could shape tomorrow's food industry.

In research laboratories, 3D printing serves as a platform for **experimentation with recipes and processes**. For example, scientists can study how ingredient composition, printing speed, or cooking methods (like laser cooking during printing) affect the final product's texture, taste, and nutritional content. This opens opportunities for interdisciplinary collaboration between food scientists, engineers, and nutritionists.

Moreover, the ability to simulate and model printing conditions gives researchers a deeper understanding of process dynamics, which can be applied to optimize food safety, efficiency, and innovation. Educational applications also extend to public awareness, where workshops and demonstrations show consumers how technology can reshape everyday eating habits.

Challenges of 3D Printed Food in the Food Industry

3D food printing has been hailed as one of the most transformative innovations in the modern food sector, offering possibilities for customized nutrition, creative food design, and sustainable alternatives. However, despite its potential, the technology still faces several challenges that limit its scalability, efficiency, and acceptance in the commercial market. These challenges arise from technical, cultural, sensory, and economic factors that need to be addressed before 3D food printing can become mainstream. Below are the major challenges explained under different themes.

1. Slow Printing Speed and Limited Scalability

One of the most immediate challenges facing 3D food printing is **speed**. Unlike traditional food preparation or automated production lines, 3D printing relies on a **layer-by-layer deposition process**. This method is inherently slower, especially when producing complex or multi-layered dishes.

For example, in a fast-food restaurant setting, where speed and efficiency are critical, printing a burger from scratch could result in long wait times for customers during peak hours. The time-intensive nature of printing undermines its ability to compete with established high-volume production systems.

Moreover, current 3D printers often have limited **material processing volumes** and a restricted number of **printing heads**. This reduces their efficiency when handling large or intricate food items. Scaling the technology for commercial foodservice environments—such as airline catering, quick-service restaurants, or large-scale food manufacturing—remains a significant hurdle. Without breakthroughs in multi-head printing, high-speed extrusion, or batch processing, the technology risks being confined to niche or luxury applications.

2. Consumer Trust and Perception

Another barrier to widespread adoption is the issue of **novelty and trust**. Many consumers are still unfamiliar with the concept of 3D-printed food. Skepticism about its **safety, authenticity, and naturalness** often overshadows its benefits. Some consumers perceive 3D-printed meals as overly "synthetic" or "artificial," creating resistance to trying or purchasing them.

Trust can only be built through **transparent communication and education**. Companies and researchers need to emphasize that the raw materials used in 3D printers are safe, regulated, and often identical to traditional food ingredients—just presented in a different form. Clear labeling, safety assurances, and showcasing nutritional benefits can gradually improve public perception. Until then, the lack of familiarity may slow consumer acceptance, confining 3D food printing to experimental markets or high-end restaurants where novelty itself is the selling point.

3. Limitations in Sensory Experience

Food is not just about sustenance; it is a **multisensory experience** that involves taste, texture, aroma, and visual presentation. While 3D printers excel in creating visually intricate designs, they struggle to replicate the **aromas and textural complexities** of freshly cooked meals.

For instance, reproducing the marbling and flavor of a perfectly grilled steak is beyond the current capabilities of most 3D printers. Aroma development often requires chemical reactions such as the Maillard reaction (responsible for the savory flavors of cooked meat), which printing technology alone cannot replicate. Similarly, achieving crispy crusts, delicate flakiness, or layered textures—essential elements of many cuisines—remains technically challenging.

Until advancements in **post-printing cooking technologies** (such as integrated lasers, convection systems, or hybrid preparation methods) are more refined, 3D-printed food may fall short of providing a truly satisfying sensory experience. This limitation directly impacts customer satisfaction and slows broader adoption.

4. Nutritional Concerns

Nutritional quality is another area of concern. Many 3D-printed foods rely on **pureed or highly processed ingredients** to ensure that they can be extruded smoothly through printer nozzles. This often alters the food's natural structure and may reduce the availability of certain nutrients.

Nutrient degradation during processing, coupled with the limited diversity of printable "food inks," makes it difficult to create meals that are both nutritionally complete and appealing. For example, while proteins and carbohydrates can often be incorporated effectively, vitamins and delicate bioactive compounds may be lost or destabilized during printing.

Expanding the range of printable ingredients—while retaining their nutritional integrity—will be crucial for addressing these concerns. Without this, the promise of **customized nutrition** could remain limited to macronutrients rather than delivering comprehensive health benefits.

5. Difficulty in Achieving Textural Diversity

Texture plays a critical role in the enjoyment of food. The contrast between crispy, crunchy, and soft elements within a single dish enhances the eating experience. However, achieving this **textural diversity** is currently difficult with 3D food printers.

Most printers work with pastes, gels, or powders that are reconstituted into edible forms. These substrates naturally lack the complex structures found in whole foods, such as the fibrous texture of meat or the layered crispness of pastries. While researchers are experimenting with multi-material printing and advanced "food inks," progress is still in its early stages.

Overcoming this challenge will require **innovations in material science**, where ingredients are engineered not just for extrusion but also for replicating the tactile sensations of natural foods. This will help make printed meals more realistic, appealing, and satisfying for consumers.

6. High Costs and Limited Ingredient Availability

Cost remains one of the most practical obstacles. Current 3D food printers are expensive, and the specialized ingredients or **printable food inks** required are not yet widely available in mainstream markets. This raises both production and operational costs, making the technology economically unfeasible for most restaurants and households.

Moreover, sourcing these specialized ingredients often requires additional processing or modifications, which further drives up expenses. Until supply chains for printable ingredients are expanded and standardized, the cost barrier will continue to limit 3D food printing to **premium applications** rather than everyday use.

Conclusion

3D food printing represents a remarkable intersection of technology, creativity, and nutrition. Its applications range from personalized nutrition and artistic food design to efficient production, sustainability, and educational innovation, making it a promising tool for reshaping the global food industry. At the same time, the technology faces significant challenges such as slow printing speeds, scalability issues, sensory limitations, nutritional concerns, and high costs. Consumer trust and acceptance also remain key hurdles that must be overcome for widespread adoption.

Despite these obstacles, continuous advancements in material science, automation, and integrated cooking methods are steadily addressing current limitations. As awareness grows and costs decline, 3D food printing is likely to evolve from a niche innovation into a practical solution that supports healthcare, sustainable diets, and creative gastronomy. Ultimately, the future of 3D-printed food depends on how effectively the industry balances its innovative potential with technical feasibility and consumer acceptance, shaping a new era in the way we design, produce, and experience food.

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Innovative Thermal Processing Systems for Post-Harvest Value Addition: A Case of Frying Technologies

Dr. Praneeth Juvvi
Assistant Professor, College of Food Technology, Central Agricultural University, Imphal, Manipur, India

Abstract

Fruits and vegetables are highly perishable commodities that require efficient post-harvest processing to extend shelf life and retain quality. Frying remains one of the most popular methods for adding value, imparting desirable flavor, aroma, and crisp texture. However, conventional deep-fat frying at 150–200 °C causes high oil absorption, nutrient degradation, acrylamide formation, and deterioration of frying oil, leading to health and quality concerns. Growing consumer demand for healthier snack products has driven the development of advanced thermal processing systems that reduce fat content while preserving natural color and nutrients. Pretreatments such as blanching, edible coatings, osmotic dehydration, pre-drying, freezing, microwave heating, ultrasound, and high-pressure processing help limit oil uptake and improve texture. Among innovative techniques, vacuum frying offers the greatest promise by operating under reduced pressure and lower temperatures, thereby minimizing oil absorption and nutrient loss while maintaining fresh flavor and vibrant color. These emerging technologies provide the food industry with practical solutions to produce high-quality, health-oriented fried foods for modern markets.

Introduction

Fruits and vegetables are highly perishable, and their shelf life is often limited unless they undergo effective postharvest processing methods. Among the various techniques for extending their availability and enhancing sensory attributes, frying is one of the most commonly employed methods. The frying process involves a series of physical and chemical transformations that affect the texture, flavor, and nutritional quality of the food. These include water evaporation, protein denaturation, starch gelatinization, and the formation of a crispy exterior that consumers find so appealing.

Typically, frying is performed using edible oils heated between 150°C and 200°C, which induces significant changes in the food’s structure. For instance, when foods like potatoes are fried at temperatures ranging from 170°C to 180°C, water vapor is rapidly released, creating the signature crispy texture. This process is followed by oil penetration into the food's structure, triggering a range of chemical reactions, such as the Maillard reaction, caramelization, oxidation, and protein denaturation. These reactions not only contribute to the food’s taste and texture but also play a key role in the formation of desirable organoleptic qualities like color, aroma, and flavor.

However, while frying enhances the sensory appeal of food, it also introduces certain drawbacks. The primary concern is the high calorie content, as the food absorbs significant amounts of oil during frying. This leads to an increase in fat content and the creation of unhealthy trans fats, which have been associated with various health risks, including obesity, heart disease, and diabetes.

As consumers have become more health-conscious in recent years, there has been a growing demand for healthier food options that retain their nutritional value. This shift has spurred the exploration of alternative cooking methods aimed at preserving bioactive compounds while reducing the negative impacts of traditional frying. Among these alternatives, vacuum frying has emerged as a promising technique. Unlike conventional frying, vacuum frying is carried out under reduced atmospheric pressure, which lowers the boiling point of water and allows for lower frying temperatures. This process significantly reduces oil absorption, helping to maintain the food's natural flavor, color, and nutritional content, while also minimizing the degradation of essential vitamins and minerals.

In addition to vacuum frying, other innovative frying techniques such as high-pressure processing, electric field frying, and two-stage frying are gaining attention for their ability to reduce oil uptake without compromising the taste and quality of fried foods. These alternative methods offer a promising future for the food industry, allowing manufacturers to meet the growing demand for healthier, low-fat fried foods that do not sacrifice flavor or texture. This manual will delve into these alternative frying technologies, their benefits, and their potential to revolutionize the production of healthier fried food options for today's health-conscious consumers.

Frying Mechanism

Frying is a complex process that involves both physical and chemical changes, which transform raw food into its final crispy, golden-brown form.

Initial Heat Transfer

When raw food is immersed in hot oil, the temperature of the food increases rapidly. Heat is transferred from the oil to the surface of the food, causing the water inside to start evaporating. The rapid loss of water from the food surface forms bubbles, which are visible as steam escaping from the product. This is the first visible indication of the frying process.

Water Evaporation & Oil Penetration

As the moisture in the food evaporates, the interior temperature begins to rise, but at a slower rate than the exterior. Initially, water loss occurs at the surface, but as the frying continues, the rate of evaporation from the food's interior increases. The formation of a porous structure allows for oil to penetrate the food, replacing the water that has evaporated. This stage is critical because it leads to the formation of the food's texture, with the oil filling the capillaries and contributing to a crispy, golden crust.

Changes in food and oil during frying

The food product itself experiences profound structural and compositional changes during frying. As surface moisture rapidly evaporates, a dry crust forms, while the core undergoes key textural transformations. The intense heat causes starch granules to gelatinize and subsequently degrade, while proteins denature and set, contributing to the characteristic crispness of fried foods. Non-enzymatic browning reactions, particularly the Maillard reaction between amino acids and reducing sugars, produce the appealing golden-brown color and distinctive flavor but also lead to the formation of acrylamide, a potential carcinogen. Nutritional quality is further impacted as heat-sensitive vitamins and bioactive molecules degrade, resulting in a loss of essential nutrients and antioxidants. The simultaneous oil uptake increases the caloric content and modifies the lipid profile of the product. Overall, frying is a complex process in which both the medium and the product interact dynamically: the oil absorbs water and food particles that accelerate its degradation, while the food gains oil and undergoes transformations that define its final texture, flavor, and nutritional characteristics. Understanding these changes is crucial for optimizing frying conditions, selecting appropriate oils, and implementing practices that minimize the formation of undesirable compounds, ensuring the production of high-quality and safer fried foods.

During deep-fat frying, the cooking oil undergoes significant physical and chemical transformations that directly affect both the quality of the oil and the fried food. At the high temperature of approximately 175 °C, the oil is subjected to intense heat that promotes thermal degradation, hydrolysis, oxidation, and polymerization. Moisture from the food sample escapes as steam, leading to dehydration, while some oil is simultaneously absorbed into the food matrix. Water released from the food reacts with triglycerides in the oil, causing hydrolysis and producing free fatty acids, mono- and diglycerides. Oxygen present in the air triggers oxidation, generating hydroperoxides that further break down into aldehydes and ketones, compounds responsible for rancid flavors and off-odors. These reactions collectively lead to the formation of polar compounds, a key indicator of oil deterioration. Additionally, the high temperature induces isomerization of fatty acids, forming trans fats, and promotes polymerization, creating larger molecules such as dimers and cyclic compounds. These chemical changes not only reduce the frying oil's quality and stability but also have implications for human health, as excessive intake of degraded oil components is associated with cardiovascular and other chronic diseases.

Pretreatments for Lower-Fat Fried Foods

Reducing oil uptake during frying is a key goal in modern food processing, both to improve nutritional quality and to enhance the stability of the final product. Applying specific steps to the raw material before it enters the fryer known collectively as pretreatments can remove part of the natural moisture, alter surface characteristics, or add protective layers. These changes help limit the contact between hot oil and the food's internal water, so less fat is absorbed and texture remains crisp. Techniques commonly used for this purpose include blanching, edible coatings, osmotic dehydration, pre-drying, freezing, microwave heating, ultrasound treatment, and high-pressure methods.

Blanching is among the most familiar of these techniques. In this process, vegetables or fruits are briefly heated with steam or in boiling water. The short burst of heat halts enzymatic activity that would otherwise darken the color or soften the texture during storage and frying. It also helps wash away dirt and microorganisms, brightens natural pigments, and can retain certain vitamins when properly timed. Because too much heat leads to flavor and nutrient losses, careful control of time and temperature is essential. Blanching also deactivates the polyphenol oxidase enzyme, which is largely responsible for unwanted browning. When followed by other steps such as osmotic dehydration, it can give fried foods a more uniform color, a firmer bite, and noticeably less oil.

Edible coatings act as thin, invisible shields between the food surface and the frying oil. These coatings are usually less than a third of a millimeter thick and can be formulated from plant-based polysaccharides, starches, pectins, cellulose derivatives, or proteins. Applied as a dip or batter, they slow the escape of moisture and at the same time prevent excess oil from seeping in. Beyond lowering fat content, these films help protect the product from oxygen, moisture fluctuations, and even ultraviolet light, extending shelf life and preserving flavor without changing appearance.

Osmotic dehydration, which relies on natural concentration gradients. Raw food pieces are soaked in a dense solution often sugar, salt, or a combination so that water moves out of the cells while some solutes move in. This partial removal of water lowers the initial moisture level and gently modifies the internal structure. When the treated food is later fried, the reduced water content and compact tissue slow down oil absorption. Studies have shown, for example, that immersing cassava slices in strong salt or sucrose solutions can remove more than two-thirds of their water, resulting in lighter, less greasy fried chips.

Several other pretreatments provide additional ways to manage moisture and structure before frying. Pre-drying, whether by hot air or under vacuum, creates a thin dry layer at the surface that acts as a barrier to oil. Freezing forms small ice crystals inside plant tissues; as these crystals vaporize rapidly during frying, escaping steam limits oil penetration. Microwave heating offers fast, even removal of water while preserving color and nutrients, thereby shortening frying time. Ultrasound treatment generates microscopic bubbles that collapse violently, loosening cell walls and helping water escape. More recently, high-pressure processing has been explored for its ability to modify cell structure and reduce subsequent oil uptake while keeping the texture appealing.

Vacuum Frying: An Advanced Innovative Technology

Vacuussm frying is an emerging technology that transforms the traditional deep-frying process by operating under low pressure and reduced temperature. Instead of frying foods at the high heat of atmospheric oil baths, this method lowers the boiling point of water inside the food, allowing moisture to evaporate and cooking to occur at much gentler temperatures. This controlled environment prevents the excessive breakdown of natural pigments, flavors, and nutrients, giving finished products a fresh taste and vibrant color that closely resemble the raw ingredients. It also limits the formation of acrylamide, a compound of growing health concern in high-temperature frying.

The equipment for vacuum frying is designed as a closed system that typically includes a sealed frying chamber, a powerful vacuum pump to maintain low pressure, and a vapor-cooling condenser to capture released steam and oil vapors. Food materials are placed inside the chamber, hot oil circulates at the lower temperature, and the vacuum environment quickly removes internal moisture without harsh heat. As a result, the product absorbs less oil and retains a light, crisp texture.

Although the technology requires higher initial investment than conventional fryers, it offers distinct advantages for manufacturers aiming to create premium, health-oriented snacks. Fruits, vegetables, and delicate herbs benefit greatly, as their natural colors and aromas remain intact and the nutritional profile stays closer to that of fresh produce. For small-scale entrepreneurs, the cost and limited availability of compact vacuum units remain challenges, but growing consumer demand for low-oil, nutrient-rich fried foods is encouraging wider adoption.

Vacuum frying stands as a modern, innovative solution that bridges consumer expectations for indulgent flavor with the need for healthier options. By combining efficiency with superior product quality, it represents a forward-looking approach to snack production and a promising alternative to conventional deep fat frying methods.

Conclusion

Frying continues to be one of the most versatile and popular methods of post-harvest value addition, transforming highly perishable fruits and vegetables into products with longer shelf life and enhanced sensory appeal. Yet, traditional deep-fat frying brings unavoidable challenges such as excessive oil uptake, nutrient loss, formation of acrylamide, and rapid deterioration of frying oil. The growing demand for healthier snack options has therefore encouraged the food industry to move beyond conventional practices and adopt innovative thermal processing systems.

Modern pretreatments ranging from blanching and osmotic dehydration to edible coatings, pre-drying, freezing, microwave heating, ultrasound, and high-pressure processing—play a pivotal role in reducing oil absorption and maintaining the natural qualities of the raw material. Each technique, whether by partially removing moisture or creating protective barriers, helps limit fat content while preserving color, texture, and flavor.

Among the emerging technologies, vacuum frying stands out as a major advancement. Operating under reduced pressure and lower temperatures, it minimizes thermal degradation, retains delicate bioactive compounds, and significantly lowers acrylamide formation. Although the equipment requires higher capital investment and remains less accessible to small-scale processors, its ability to produce premium, nutrient-rich fried products positions it as a key solution for the future of healthy snack manufacturing.

Future Trends of Automation & Sensor Integration in Agricultural Equipment

Dr. S. Syed Imran,
Scientist, ICAR-Central Institute of Agricultural Engineering (CIAE)-Regional Centre, Coimbatore, Tamil Nadu, India

Introduction:

The agricultural sector is experiencing a transformative shift, largely driven by the integration of automation and advanced sensor technologies into farming equipment. Traditional farming methods, which often rely heavily on manual labor and experience-based decision-making, are being supplemented—or in many cases replaced—by intelligent machinery capable of performing complex tasks with minimal human intervention. Autonomous tractors, robotic harvesters, drones, and precision irrigation systems are just a few examples of the innovations reshaping modern agriculture.

Sensors embedded in these machines continuously collect data on a wide range of parameters, including soil moisture, nutrient levels, crop health, and environmental conditions such as temperature and humidity. This real-time monitoring allows farmers to make data-driven decisions, optimizing the application of water, fertilizers, and pesticides to ensure maximum efficiency while minimizing resource wastage. The combination of automation and sensor technology also enables early detection of plant diseases and stress factors, improving crop management and yield outcomes.

Beyond increasing productivity, these technologies address pressing challenges in the agricultural sector. Labor shortages, escalating operational costs, and the need for sustainable farming practices have historically limited the growth potential of many farms. Automation mitigates labor dependency, while sensor-driven insights promote environmentally responsible practices by reducing excessive chemical usage and conserving water resources.

Moreover, the integration of Artificial Intelligence (AI) and Machine Learning (ML) into automated agricultural equipment enhances decision-making capabilities. AI algorithms analyse vast amounts of data collected by sensors and drones to provide predictive insights, such as identifying optimal planting times, forecasting crop yields, and detecting potential threats from pests or unfavourable weather conditions. This convergence of robotics, sensors, and AI is paving the way for a new era of precision agriculture—one that is more efficient, sustainable, and capable of meeting the growing global food demand.

In essence, the recent advances in automation and sensor integration are not merely incremental improvements; they represent a paradigm shift in how farming is conducted. By combining intelligent machinery with real-time data analytics, farmers can achieve higher productivity, reduce operational costs, and promote sustainable practices, ensuring that agriculture remains resilient and capable of feeding the world's growing population.

1. SENSOR INTEGRATION IN AGRICULTURE

Agriculture is rapidly evolving through the adoption of modern technologies, and one of the most transformative developments is sensor integration. Sensors in agriculture provide farmers with real-time data on soil, crops, and environmental conditions, enabling precision farming practices that optimize productivity, reduce waste, and promote sustainability. By combining sensor technology with automation, data analytics, and Artificial Intelligence (AI), farmers can make informed decisions that improve crop yields and resource management.

1.1 Types of Sensors in Agriculture:

- **Soil Sensors**
  Soil sensors measure moisture content, pH, nutrient levels, and temperature. By monitoring these parameters, farmers can optimize irrigation schedules, fertilization, and soil management practices, preventing overuse of water and chemicals while enhancing crop health.
- **Crop Health Sensors**
  These sensors detect plant stress, nutrient deficiencies, and diseases. Multispectral and hyperspectral imaging sensors, often mounted on drones or robots, provide detailed insights into plant health, enabling timely interventions.
- **Environmental Sensors**
  Sensors that track temperature, humidity, rainfall, wind speed, and light intensity

allow farmers to understand environmental conditions affecting crop growth. This information supports weather-adaptive strategies, reducing losses caused by adverse conditions.

- **RFID and IoT Sensors**
  Radio-frequency identification (RFID) and IoT-enabled sensors track machinery, livestock, and crop movement. These sensors facilitate efficient farm management and logistics, while also integrating with centralized platforms for data analysis.

1.2 Benefits of Sensor Integration:

- **Precision Agriculture**: Sensors allow precise application of water, fertilizers, and pesticides, minimizing waste and environmental impact.
- **Increased Productivity**: Real-time monitoring helps detect issues early, reducing crop losses and improving yields.
- **Resource Efficiency**: Optimized use of water, nutrients, and energy lowers operational costs and conserves natural resources.
- **Data-Driven Decisions**: Continuous data collection supports predictive analytics, helping farmers plan crop cycles, irrigation, and pest control more effectively.
- **Sustainability**: By reducing chemical overuse and conserving water, sensor integration promotes environmentally friendly farming practices.

1.3 Emerging Trends:

- **Wireless and Battery less Sensors**: New energy-efficient sensors powered by solar or RF energy reduce maintenance requirements.
- **Integration with Drones and Robots**: Sensors mounted on drones or robotic platforms enable large-scale, autonomous monitoring of fields.
- **AI and Machine Learning**: Algorithms analyse sensor data to predict crop stress, disease outbreaks, and yield outcomes.
- **Cloud-Based Platforms**: Sensor data is increasingly stored and analysed in the cloud, allowing remote monitoring and decision-making.

1.4 Challenges

Despite the advantages, sensor integration faces challenges such as high initial costs, data management complexity, and the need for technical expertise. Ensuring sensor accuracy, durability in harsh agricultural conditions, and interoperability with existing farm equipment are also critical considerations.

2. Robotics and Artificial Intelligence (AI) In Agriculture

The agriculture sector is experiencing a technological revolution with the adoption of robotics and Artificial Intelligence (AI). These innovations are transforming traditional farming by automating labour-intensive tasks, optimizing crop management, and enhancing overall farm efficiency. Robotics and AI enable precision agriculture, where data-driven insights guide decision-making, reduce resource wastage, and improve crop yields. From autonomous tractors to AI-powered crop monitoring systems, these technologies are reshaping how modern farms operate.

2.1 Robotics in Agriculture

- **Autonomous Machinery**
  Autonomous tractors, harvesters, and planters are capable of performing tasks such as ploughing, seeding, and harvesting without human intervention. These machines rely on GPS, sensors, and advanced navigation algorithms to operate efficiently, reducing labor dependency and increasing productivity.
- **Robotic Harvesters and Pickers**
  Robots equipped with machine vision can identify ripe fruits and vegetables and harvest them with precision. This reduces damage to crops, ensures uniform quality, and addresses labor shortages during peak harvesting seasons.
- **Drones and Aerial Robots**
  Agricultural drones are used for field monitoring, crop spraying, and data collection. Equipped with multispectral and thermal sensors, drones provide real-time insights into plant health, soil conditions, and pest infestations, allowing farmers to act proactively.

- **Weeding and Pest Control Robots**
  Specialized robots can remove weeds mechanically or apply targeted pesticides with minimal environmental impact. These autonomous systems reduce chemical use, improve crop health, and lower operational costs.

2.2 Artificial Intelligence in Agriculture

- **AI-Powered Crop Monitoring**
  AI systems analyse data collected by sensors, drones, and satellites to detect plant stress, nutrient deficiencies, and disease outbreaks. Early detection enables timely interventions, reducing crop losses and improving yields.
- **Predictive Analytics**
  Machine learning algorithms process historical and real-time data to forecast crop growth, yield, and potential risks from pests or adverse weather. This predictive capability helps farmers plan irrigation, fertilization, and harvest schedules more efficiently.
- **Decision Support Systems**
  AI-based platforms integrate data from multiple sources, including soil sensors, weather stations, and farm machinery. These systems provide actionable recommendations for irrigation, fertilization, pest control, and resource management, optimizing farm operations.

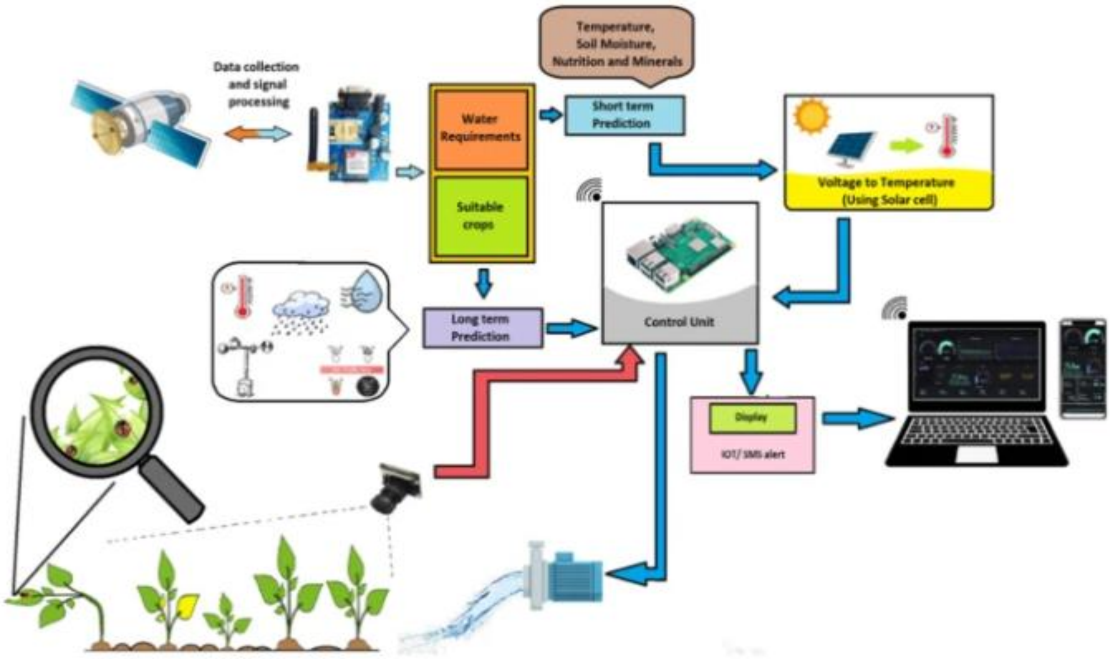
2.3 Benefits of Robotics and AI

- **Labor Efficiency**: Reduces dependency on manual labor, particularly for repetitive or strenuous tasks.
- **Precision Farming**: Enables accurate application of water, fertilizers, and pesticides.
- **Resource Optimization**: Conserves water, reduces chemical use, and lowers energy consumption.
- **Higher Yields**: Early detection of plant stress and disease improves crop quality and quantity.
- **Sustainability**: Minimizes environmental impact through targeted interventions and reduced waste.

2.4 Challenges

Despite their advantages, robotics and AI in agriculture face challenges, including high initial costs, complex maintenance, and the need for technical expertise. Integration with existing farm equipment and ensuring reliability under harsh environmental conditions are also key considerations.

3. MICROCONTROLLER SYSTEMS IN AGRICULTURE



The integration of microcontroller systems in agriculture is revolutionizing traditional farming methods by enabling automation, precision, and real-time monitoring. Microcontrollers—compact computers embedded within agricultural devices—control sensors, actuators, and other electronic components, allowing smart management of crops, soil, water, and machinery. By facilitating data collection, analysis, and automated responses, microcontroller-based systems improve productivity, reduce resource wastage, and support sustainable farming practices.

3.1 Applications of Microcontroller Systems in Agriculture

- **Irrigation Automation**
  Microcontroller systems are widely used to automate irrigation based on soil moisture, temperature, and weather data. Soil moisture sensors connected to microcontrollers can trigger water pumps only when needed, ensuring optimal water usage, preventing over-irrigation, and conserving water resources.
- **Greenhouse Monitoring and Control**
  In greenhouses, microcontrollers manage temperature, humidity, and lighting. Sensors detect environmental conditions, and microcontrollers adjust fans, heaters, or grow lights automatically. This precise control ensures optimal crop growth, reduces human intervention, and increases yield quality.
- **Crop Monitoring Systems**
  Microcontrollers interface with sensors that monitor soil pH, nutrient levels, and crop health. Real-time data collected is processed by the microcontroller to alert farmers or trigger automated actions, such as nutrient supplementation or pest control.

- **Automated Fertilization Systems**
  Microcontroller-based systems can regulate fertilizer application by monitoring soil nutrient levels and crop requirements. This targeted fertilization reduces chemical usage, prevents over-fertilization, and promotes sustainable farming.
- **Livestock Monitoring**
  Microcontrollers are used in smart livestock systems to track animal health, movement, and feeding patterns. Wearable sensors on animals communicate with microcontroller units to alert farmers about irregularities in behavior or vital signs, enhancing animal welfare and farm efficiency.
- **Pest and Disease Management**
  Microcontroller systems can integrate with environmental and crop sensors to detect conditions conducive to pest attacks or disease outbreaks. Automated sprayers or alerts can then be activated, ensuring timely intervention and minimizing crop losses.

3.2 Advantages of Using Microcontroller Systems

- **Automation**: Reduces manual labor by automating irrigation, fertilization, and monitoring tasks.
- **Precision Agriculture**: Enables accurate resource application based on real-time data.
- **Cost Efficiency**: Optimizes water, fertilizers, and energy usage, reducing operational costs.
- **Sustainability**: Promotes eco-friendly practices by minimizing wastage of water and chemicals.
- **Data-Driven Decisions**: Provides farmers with actionable insights for better crop management.

3.3 Challenges

Despite their advantages, microcontroller-based systems face challenges, such as initial installation costs, requirement for technical knowledge, and susceptibility to environmental factors like dust, humidity, and temperature extremes. Additionally, integrating these systems with legacy farm equipment can be complex.

Future Trends of Automation & Sensor Integration in Agricultural Equipment

- **Advanced Autonomous Machinery** – Multi-tasking tractors, harvesters, and drones performing operations with minimal human intervention.
- **Swarm Robotics** – Multiple autonomous machines working collaboratively to increase efficiency and reduce soil compaction.
- **Smart Sensors** – Multispectral, hyperspectral, and environmental sensors providing detailed crop and soil data in real-time.
- **Wireless & Batteryless Sensors** – Energy-harvesting sensors reducing maintenance and enabling long-term deployment.

- **AI & Predictive Analytics** – Machine learning for yield forecasting, disease detection, and resource optimization.
- **Decision Support Systems** – AI platforms guiding irrigation, fertilization, pest control, and harvesting decisions.
- **IoT & Cloud Integration** – Remote monitoring, data centralization, and interconnected farm equipment for seamless operations.
- **Sustainability Focus** – Precision application of water, fertilizers, and pesticides, plus renewable energy-powered machinery.
- **Human-Machine Collaboration** – Augmented Reality interfaces and collaborative robots (cobots) assisting farmers in complex tasks.
- **Environmentally Aware Systems** – Sensors monitoring soil health, water usage, and carbon footprint to reduce ecological impact.

Conclusion:

The integration of automation and advanced sensors in agricultural equipment is transforming modern farming into a more efficient, precise, and sustainable practice. These technologies enable real-time monitoring, data-driven decision-making, and optimized resource use, while addressing challenges like labor shortages and environmental impact. As AI, IoT, and robotics continue to evolve, the future of agriculture will increasingly rely on intelligent machinery and smart systems, ensuring higher productivity, reduced waste, and the capacity to meet the growing global food demand.

Chapter 10

Engineering Precision: Tools and Technologies for Smart Agriculture

Dr. Subeesh
Scientist, Centre of Excellence on Agri-Electronics and Automation in Agriculture, ICAR – Central Institute of Agricultural Engineering (CIAE), Bhopal, Madhya Pradesh, India

Introduction

Agriculture remains the backbone of global food security, yet it is under increasing pressure due to climate change, resource constraints, labor shortages, and a rapidly expanding population projected to surpass 9 billion by 2050. Meeting future food demands while ensuring sustainability requires effective approaches that go beyond traditional farming (Jha et al., 2019). Precision engineering supported by advanced technologies such as the Internet of Things, big data analytics, cloud computing, artificial intelligence, and machine learning provides an opportunity to enhance productivity, reduce input costs, and minimize environmental impacts. The convergence of these tools marks the era of smart agriculture where data-driven solutions enable informed decision-making across the agricultural value chain. Modern agriculture faces the challenge of producing more with fewer resources. Increasing water scarcity, soil degradation, loss of arable land, and the variability introduced by climate change have made conventional practices insufficient. Technology intervention becomes essential to optimize the use of inputs such as water, fertilizers, and pesticides while maintaining quality and sustainability (Houetohossou et al., 2023). Precision agriculture ensures that the right quantity of inputs is delivered at the right time and place, thereby increasing efficiency and protecting the environment. In the context of post-harvest systems, technology-driven interventions are critical to reducing losses, which currently account for nearly one-third of global agricultural output. Smart technologies provide real-time monitoring, predictive insights, and automated controls to reduce wastage and improve the resilience of supply chains.

Internet of Things and Bigdata in Agriculture

The Internet of Things has emerged as the cornerstone of smart farming. IoT in agriculture refers to interconnected physical objects embedded with sensors, actuators, and communication devices that collect and transmit data about field conditions, crop health, and storage environments. A layered architecture enables acquisition, transmission, processing, and application of data. Low-cost devices such as Arduino, Raspberry Pi, and Jetson Nano can be integrated with sensors for temperature, humidity, soil moisture, pH, and gas concentrations. In the post-harvest domain, IoT sensors deployed in storage systems continuously monitor microclimatic parameters to ensure optimal preservation. Automated alerts help farmers and warehouse managers prevent spoilage and maintain quality. Beyond storage, IoT supports irrigation automation, livestock monitoring, greenhouse management, and precision application of inputs. By creating a connected agricultural ecosystem, IoT lays the foundation for data-driven farming (Xu et al., 2022).

The exponential growth of agricultural data from sensors, satellites, drones, and markets has introduced the era of big data in farming. Unlike traditional datasets, agricultural big data is characterized by high volume, velocity, variety, veracity, and value. Every IoT sensor generates continuous streams of data, which, when aggregated, provide powerful insights into crop growth, soil health, climate patterns, and supply chain dynamics. In post-harvest engineering, big data enables prediction of shelf life, detection of spoilage risks, and optimization of storage conditions. For example, gas sensors integrated with data analytics can identify ethylene accumulation and forecast ripening rates of fruits. Similarly, big data supports yield estimation, disease prediction, and market forecasting. By refining large, complex datasets into actionable knowledge, big data analytics empowers farmers and stakeholders to make precise and timely interventions. The convergence of IoT and big data also creates opportunities for advanced integration with artificial intelligence and cloud platforms, making agricultural systems more intelligent, adaptive, and resilient. By combining continuous sensor data with predictive analytics, farmers can move from reactive to proactive decision-making. In the post-harvest chain, this means anticipating storage failures before they occur, dynamically adjusting supply chain logistics based on demand forecasts, and ensuring that perishable goods reach markets at peak quality. Such integration not only improves productivity and profitability but also strengthens sustainability by reducing waste, conserving resources, and enhancing food security on a global scale.

Cloud Computing for Scalable Agricultural Solutions

The deployment of IoT and big data analytics requires scalable computing resources that are often unavailable at the farm level. Cloud computing provides an on-demand infrastructure where storage, processing, and analytical tasks are hosted remotely and accessed via the internet. Platforms such as Amazon Web Services, Microsoft Azure, and Google Cloud enable rapid data processing, integration of advanced models, and real-time access to insights. For post-harvest systems, cloud computing facilitates centralized management of storage facilities distributed across regions, ensuring quality control and traceability. In addition, cloud-based platforms integrate data from multiple stakeholders including farmers, distributors, and retailers to streamline supply chains. The elasticity of cloud resources allows agriculture to transition from localized experiments to large-scale deployments without the limitations of local infrastructure (Kalyani & Collier, 2021).

In agriculture, cloud computing also enables the creation of shared data ecosystems where diverse datasets such as weather forecasts, soil profiles, market information, and sensor readings can be integrated and analyzed collectively. This collective intelligence improves predictive accuracy and supports real-time decision-making at multiple stages of the agricultural value chain. For example, in post-harvest logistics, cloud platforms can dynamically adjust transportation schedules based on predicted shelf life and market demand, reducing waste of perishable goods. Farmers and cooperatives can also access software-as-a-service applications hosted in the cloud for tasks such as crop planning, pest monitoring, and financial management, eliminating the need for local installation or technical expertise. Furthermore, cloud computing enhances data security and disaster recovery by ensuring that valuable agricultural data is stored redundantly across multiple servers, protecting it from local hardware failures. By offering scalability, accessibility, and resilience, cloud computing provides the digital backbone for precision and smart agriculture, ensuring that innovations in IoT, AI, and machine learning can be deployed effectively even in resource-constrained environments.

Blockchain for security and transparency

Blockchain in agriculture is emerging as a powerful tool to enhance transparency, trust, and efficiency across the entire agri-food value chain. At its core, blockchain is a decentralized and immutable digital ledger that records transactions in a secure, verifiable, and tamper-proof manner. Each entry in the blockchain, known as a block, is linked chronologically to previous blocks, creating a continuous chain that cannot be altered without consensus from the entire network. This architecture ensures accountability and prevents manipulation of records, which is especially important in agriculture where multiple stakeholders are involved and data integrity directly influences food safety, quality, and market trust. In post-harvest engineering, blockchain integration with IoT devices and sensors has proven to be particularly transformative. As harvested crops move through different stages of storage, transportation, processing, and retail, IoT sensors monitor critical parameters such as temperature, humidity, and gas composition. These data points, when uploaded to the blockchain, create an immutable record of the conditions under which produce was handled. This real-time traceability allows every actor in the supply chain, from farmers to consumers, to verify not only the origin of food products but also the quality assurance measures taken during storage and transit. For example, blockchain can confirm that cold chain conditions were consistently maintained for perishable fruits during long-distance export, thereby reducing disputes and enhancing consumer trust. Beyond ensuring quality and safety, blockchain also plays a role in enabling fairer and more efficient trade. Traditionally, farmers and cooperatives rely heavily on intermediaries to reach markets, which often reduces their profit margins and introduces inefficiencies. Blockchain-based smart contracts allow farmers to establish direct, verifiable agreements with buyers, ensuring secure payments once pre-agreed conditions are met. This reduces dependence on middlemen, minimizes delays, and fosters equitable participation in markets. For international trade, blockchain traceability systems help producers comply with stringent import regulations and certifications related to food safety, organic standards, and sustainability (Xu et al., 2020).

Artificial Intelligence and Machine Learning in Agriculture

Artificial intelligence has emerged as one of the most powerful drivers of innovation in modern agriculture, transforming the sector from intuition-driven practices into a knowledge-intensive and adaptive enterprise. At its core, artificial intelligence enables machines to learn from data, recognize patterns, and make intelligent decisions, often surpassing the capabilities of traditional rule-based systems. This ability is particularly critical in agriculture, where the complexity of biological processes, climate variability, and market fluctuations creates a highly dynamic environment that demands rapid and informed decision-making. Machine learning, a subset of AI, has become central to predictive analytics in agriculture. Unlike traditional statistical models, machine learning algorithms improve their performance as they are exposed to more data, making them highly suitable for agricultural systems where conditions change continuously across seasons and regions. Supervised learning techniques such as regression, support vector machines, and decision trees are widely applied for predicting crop yields, estimating water requirements, and forecasting disease outbreaks. For instance, yield prediction models integrate historical yield records with weather parameters, soil fertility data, and remote sensing imagery to provide accurate forecasts that help farmers plan harvest and storage requirements. Unsupervised learning, on the other hand, is used for clustering soil types, identifying hidden patterns in crop performance, or detecting anomalies in sensor data (Oliveira & Silva, 2023). Reinforcement learning has also begun to find applications in resource optimization, where algorithms learn to balance irrigation and nutrient supply over time to maximize productivity with minimal inputs.

Deep learning, a more advanced branch of machine learning inspired by neural networks, has shown remarkable promise in handling complex, unstructured agricultural data such as images and videos. Convolutional neural networks (CNNs) in particular have transformed agricultural computer vision tasks by providing high accuracy in image classification and object detection (Kamilaris & Prenafeta-Boldú, 2018). One of the most impactful applications lies in post-harvest engineering, where deep learning-based grading systems analyze fruits and vegetables for parameters such as size, shape, texture, and color. Unlike manual grading, which is often subjective and labor-intensive, these automated systems ensure uniformity, efficiency, and consistency at industrial scale. Grading accuracy is crucial for market acceptance and pricing, and CNNs provide the precision necessary to meet both domestic and export standards. Beyond classification, deep learning also supports object detection models such as Faster R-CNN, YOLO, and SSD, which identify not only the class of an object but also its location within an image. These models have been employed for detecting pest infestations, mapping weed populations, and identifying diseased crop regions in both field and storage environments. In post-harvest systems, object detection algorithms can rapidly identify damaged or diseased produce on conveyor belts, ensuring that only high-quality products enter storage or packaging. This real-time detection significantly reduces spoilage and prevents contamination from spreading to healthy stock. The integration of AI is not limited to prediction and classification; it also extends into decision-support and advisory systems. AI-driven chatbots have been developed to interact with farmers in regional languages, offering recommendations on nutrient management, weather risks, and government schemes. These digital assistants democratize access to agricultural expertise, particularly in rural areas where extension services are limited. Predictive models hosted on cloud platforms provide guidance on optimal planting windows, irrigation scheduling, and logistics planning, ensuring that decisions are not only based on local conditions but also aligned with broader market and climatic trends.

Advances in Deep Learning, Federated Learning, and TinyML

Deep learning has enabled precise object detection, disease identification, and quality grading with levels of accuracy that surpass traditional approaches, making it a cornerstone of digital agriculture. Yet as agriculture becomes more digital, new challenges emerge, particularly those related to data privacy, limited connectivity, and constrained computing resources at the farm level (Žalik & Žalik, 2023). Farmers, cooperatives, and agribusinesses generate vast amounts of sensitive data through IoT devices, drones, satellites, and supply chain systems. Centralizing all this data for model training raises concerns about ownership, confidentiality, and trust. At the same time, many farms are located in rural regions with limited bandwidth, making continuous cloud connectivity impractical. Moreover, the cost and energy requirements of running advanced machine learning models often exceed the capabilities of local devices. To overcome these barriers, innovative approaches such as federated learning and TinyML are being introduced, allowing agricultural intelligence to expand in an inclusive, scalable, and resilient manner (Gookyi et al., 2024). Federated learning provides a new paradigm for building collaborative intelligence without centralizing data. Instead of transferring raw data to a central server, federated learning enables local devices to train models on their own datasets and only share the learned parameters or model updates with a global aggregator. This global model then incorporates knowledge from many distributed sources while keeping the underlying data private. In agriculture, this approach has significant potential. For example, storage warehouses equipped with IoT sensors generate large datasets on temperature, humidity, and gas concentrations. These datasets are often sensitive, especially when linked to trade information, ownership, or contracts. Using federated learning, each warehouse can train local models to predict spoilage risks or shelf life, and then contribute model updates to a global network that learns patterns across multiple facilities. The resulting global model becomes more robust, capable of predicting deterioration under a wide range of conditions, yet no single warehouse needs to expose its raw data. Such systems strengthen trust among stakeholders and promote broader participation in digital agriculture. TinyML, on the other hand, addresses the challenge of resource limitations by bringing machine learning capabilities directly to ultra-low-power devices at the edge. Conventional machine learning often relies on cloud servers for processing, which requires continuous internet connectivity and high bandwidth. TinyML eliminates this dependence by embedding lightweight machine learning models into small, energy-efficient microcontrollers that can operate for months on minimal power. In agriculture, this is particularly beneficial for rural and resource-constrained environments where internet connectivity may be intermittent or completely absent.

Applications in Post-Harvest Engineering

Post-harvest engineering plays a critical role in preserving agricultural produce after harvest, ensuring quality, safety, and marketability until it reaches consumers. With nearly one-third of global agricultural output lost post-harvest due to spoilage, inefficiencies, and lack of infrastructure, technological innovations have become essential. Smart solutions powered by IoT, artificial intelligence, big data, and blockchain are transforming post-harvest management into an intelligent, data-driven, and automated system. These technologies address the challenges of storage, grading, logistics, and loss reduction, ultimately enhancing food security and farmer profitability.

i) <u>Smart Storage Systems</u>

Smart storage systems represent one of the most important applications of digital technologies in post-harvest engineering. Agricultural commodities are highly sensitive to environmental conditions such as temperature, humidity, and gas composition, which directly influence shelf life and quality. IoT-enabled sensors continuously monitor these parameters inside cold storage units, warehouses, or silos and transmit real-time data to analytical platforms. Predictive analytics applied to this data can estimate the likelihood of spoilage and classify commodities according to their storage needs. For example, in fruit storage, ethylene gas levels provide an indication of ripening. Gas sensors integrated with smart systems detect rising ethylene levels, and predictive models can then estimate how long the fruit will remain in marketable condition. What makes smart storage systems transformative is the automation of control responses. Environmental control devices such as cooling fans, dehumidifiers, and ventilation units can be connected directly to IoT platforms, enabling automatic adjustment when conditions deviate from the ideal range. This reduces reliance on manual monitoring and minimizes the risk of human error. Cloud integration allows multiple storage facilities distributed across different regions to be monitored centrally, ensuring consistency in quality standards. Beyond preservation, smart storage systems also contribute to sustainability by optimizing energy use. By maintaining stable conditions only when required, energy consumption is reduced, leading to cost savings and lower environmental footprints. Collectively, IoT-enabled smart storage systems help reduce post-harvest losses, extend shelf life, and preserve the nutritional quality of produce, directly addressing one of the most critical challenges in food systems.

ii) <u>Automated Grading and Sorting</u>

Grading and sorting are fundamental steps in post-harvest processing, determining not only the market value of commodities but also consumer trust in product quality. Traditionally, grading has been performed manually, which is labor-intensive, time-consuming, and prone to inconsistency. Deep learning-based vision systems now provide a more accurate, efficient, and standardized alternative. These systems are integrated into conveyor belt setups where cameras capture high-resolution images of fruits, vegetables, or grains. Convolutional neural networks (CNNs) analyze these images in real time to classify commodities based on attributes such as size, shape, color, and surface texture. Automated grading systems offer several advantages. First, they ensure uniformity in grading, which is critical for meeting domestic and international quality standards. Second, automation reduces the need for manual labor, which is particularly important in contexts of labor shortages. Third, these systems operate at much higher speeds than human graders, making them suitable for industrial-scale operations. For example, apple grading lines equipped with computer vision systems can inspect thousands of fruits per hour with consistent accuracy. Moreover, the integration of AI allows grading systems to go beyond surface appearance. Hyperspectral imaging combined with deep learning can detect internal defects such as bruising or fungal infection that are not visible to the naked eye. This ensures that only high-quality produce enters the supply chain while damaged commodities can be diverted for processing, reducing waste (Singh et al., 2022). The consistency and efficiency provided by automated grading systems build consumer confidence, enhance profitability for farmers, and improve competitiveness in export markets. In this way, deep learning-powered grading has become a cornerstone of precision post-harvest engineering.

iii) <u>Yield Estimation and Planning</u>

Accurate yield estimation before harvest is essential for effective planning of post-harvest operations such as storage, processing, and logistics. Traditionally, yield forecasts were based on farmer experience or simple sampling methods, which often resulted in inaccuracies. Machine learning has introduced more reliable methods by integrating diverse datasets, including historical yield records, real-time weather data, soil conditions, and remote sensing imagery from satellites or drones. These models apply regression techniques, time-series analysis, and deep learning approaches to generate precise predictions of crop output. For post-harvest management, yield estimation provides critical insights into how much storage capacity will be required, what level of logistics support is necessary, and how contractual agreements with buyers should be structured. For example, if predictive models indicate a bumper harvest of grains, storage systems can be prepared in advance to handle the increased volume, while buyers and processors can align their procurement strategies accordingly. Conversely, if yields are predicted to be lower than average, contracts and market prices can be adjusted early to prevent losses. In fruit and vegetable production, yield estimation models often combine drone imagery with computer vision algorithms to count fruits on trees or assess canopy health. These predictions guide not only storage planning but also labor scheduling and distribution logistics. By aligning production data with post-harvest capacity and market demand, yield estimation reduces inefficiencies and prevents bottlenecks in the supply chain.

iv) <u>Supply Chain Traceability</u>

In an increasingly globalized food system, supply chain traceability has become essential to ensure transparency, safety, and trust. Consumers and regulators demand clear information about where food comes from, how it has been handled, and whether it complies with quality standards. Blockchain technology integrated with IoT and AI provides a secure and transparent solution for achieving end-to-end traceability in agricultural supply chains. Every stage, from harvest through processing, distribution, and retail, is recorded on an immutable blockchain ledger. This ensures that data cannot be altered or manipulated, creating trust among all stakeholders. In practice, IoT devices such as RFID tags and QR codes are attached to consignments of produce, enabling data on temperature, humidity, handling conditions, and transport routes to be uploaded in real time. This information is stored securely in the blockchain, allowing each actor in the supply chain, including distributors, retailers, and consumers, to verify the journey of a product. For exporters, blockchain traceability is especially valuable for meeting international regulations and certifications related to food safety and sustainability. AI further enhances traceability by analyzing large datasets to detect inefficiencies or risks in supply chains. Predictive models can identify delays, recommend optimal transport routes, and estimate arrival times with high accuracy.

v) <u>Post-Harvest Loss Reduction</u>

Post-harvest loss reduction is one of the most critical applications of smart technologies, as food wastage continues to undermine both economic viability and food security. Losses occur at multiple stages, including sorting, storage, transport, and retail, often due to inefficiencies in monitoring and decision-making. Artificial intelligence, particularly computer vision and predictive analytics, provides powerful solutions for minimizing these losses. AI-based image recognition systems integrated into sorting lines can identify damaged, diseased, or underdeveloped produce early in the process. By removing compromised items before they reach storage or packaging, the risk of contamination spreading to healthy stock is reduced significantly. Deep learning models can also detect subtle signs of deterioration that may not be visible to human inspectors, ensuring higher accuracy in identifying compromised produce. Predictive analytics plays an equally important role by helping farmers and managers decide whether to store, process, or immediately market harvested commodities. For example, if models predict that a certain batch of vegetables has a short shelf life, it can be directed toward immediate sale or processing rather than storage, thereby reducing wastage. Combined with IoT sensors in storage facilities, these predictive systems create a feedback loop where real-time data continuously informs management decisions. Loss reduction is not only about preventing spoilage but also about enhancing economic efficiency and sustainability. By reducing waste, farmers can maximize returns from their harvests, while the food system as a whole becomes more resource-efficient.

Conclusion

Smart agriculture uses modern tools like sensors, cloud computing, artificial intelligence, and blockchain to make farming and storage more efficient and reliable. These tools help farmers and managers see what is happening in the field or storage in real time, understand risks early, and take action before serious problems occur. This kind of support is very important after harvest, where a large part of food is often lost due to poor storage or weak handling systems. With the help of smart storage, automated grading, yield prediction, and supply chain monitoring, food can be kept safe for longer, quality can be maintained, and farmers can earn better prices. New technologies like federated learning and TinyML make it possible to use artificial intelligence even where internet is weak or equipment is very simple. These systems allow farmers to get useful results without sending all their data to one place. This protects privacy and makes advanced tools available even to small farmers. Blockchain also adds trust by keeping a record of every step of the food journey that cannot be changed. This helps consumers know the origin of their food and also supports fair trade. The future of farming depends on combining careful engineering with smart digital systems. By using these tools, farmers can grow more with fewer resources, reduce food waste, protect the soil and water, and make sure safe and good quality food reaches people.

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Cold Plasma System Design Applications in Food Processing

Dr. Sellam Perinban & Dr. Anamika Thakur
Scientist, Division of Food Science and Post-Harvest Technology, ICAR- Indian Agricultural Research Institute (IARI), New Delhi, India

1. Introduction

With the growing emphasis on clean label technologies in food processing, cold plasma applications have gained significant attention. The conventional thermal disinfection methods of havingsignificant impact on the food products nutritional quality while the chemical-baseddisinfection methods are less preferred due to residual effects in foods. The novelnon-thermal method, cold plasma on the other hand has proven to be a clean label technology which not only preserves the nutritional quality of the food product but also does not leave any residues on the food material. Hence this technology has been extensively researched for its microbial decontamination properties, degradation of pesticide residues, allergens, antibiotic residues and to modify the functional properties of the food.

Apart from food processing, cold plasma and plasma activated liquids are widely researched in medicine and dentistry for wound healing, disinfection anddisintegration of cancer cells. Further, the recent reports also suggest the application of cold plasma activated water (PAW) in agriculture for seed germination and disease control. The mechanism behind these applications of cold plasma is mainly due to the reactive species and its oxidative properties. Even though this leads to the disinfection and other beneficial changes in the food material, due to the high susceptibility of food materials to the oxidative stress, there are undesirablechanges in the quality of food materials implicated by this oxidation mechanism. Hence it is important to optimize the reactive species generation and its interaction to achieve the desirable function of cold plasma without affecting the quality of the food materials. Furthermore, the underlying reaction mechanisms and the specific effects of these reactive species on various food components are not yet completely explored, necessitating further in-depth research on these aspects.

The characteristics and concentration of these reactive species are influenced by various operational parameters, including the applied voltage, system configuration, gas composition, treatment time, and method of application. As an emerging technology, cold plasma currently faces a significant hurdle: unlike established methods such as ozone or UV processing, it has not yet received Generally Recognized As Safe (GRAS) status from the FDA for food applications. Overcoming this regulatory roadblock will be essential for the widespread commercial adoption and integration of cold plasma technology within the food industry.

2. Classification of Plasma

Plasma is a fourth state of matter which is produced by the ionization of gases. Plasma is abundantly present in the universe, and it is broadly classified into thermal and non-thermal plasma based on the thermal equilibrium of free electrons (Te) withneutral gas molecules

(Tg), and negative ions (Ti). Further based on the operating pressure conditions NTP's further classified as atmospheric pressure plasmas and low-pressure plasma (Figure 1).

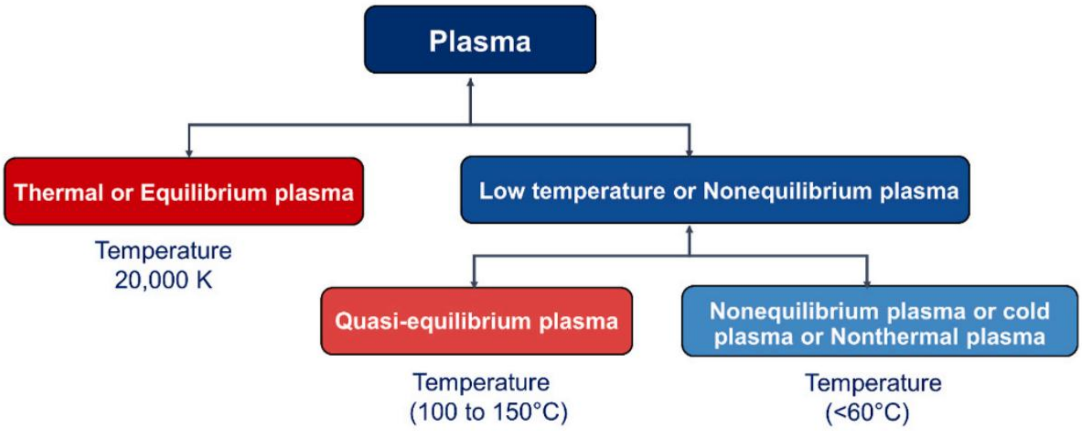

Figure 1: Classification of Plasma(Subrahmanyam et al., 2024)

2.1 High-Temperature Plasma (Thermally Equilibrium Plasma)

This category, also known as thermally equilibrium plasma, is characterized by all particle species existing in thermodynamic temperature equilibrium at the same very high temperature (Te≈Ti≈Tg) (Afshari & Hosseini, 2012). The gas temperature (Tp) of these plasmas typically ranges from 10^6 to 10^8 K(Huang & Tang, 2007).

- Examples: The most prominent examples are fusion plasmas found in the core of stars and in experimental fusion reactors (like tokamaks). These plasmas are fully ionized and require extreme temperatures to sustain nuclear fusion reactions, necessitating powerful magnetic confinement.

2.2 Low-Temperature Plasma (Thermally Non-Equilibrium Plasma)

This broader category is known as thermally non-equilibrium plasma because not all particle species are at the same temperature. It is further subdivided based on the degree of thermal equilibrium:

- Thermal Plasma (Quasi-Equilibrium Plasma): In this subcategory, particle species are in a local thermal equilibrium (LTE) state. While the heavy particles (ions and neutrals) reach very high temperatures, there can be slight deviations from full equilibrium, where Te might be slightly higher than Tg. The gas temperature (Tg) for quasi-equilibrium plasma is about 2×10^4 K (Afshari and Hosseini 2012).
    - Examples: Common applications include plasma torches and arc welding plasmas. These are widely used in industrial processes for cutting, welding, and material spraying, leveraging their high gas temperatures for effective material processing.

- Non-Thermal Plasma (Non-Equilibrium Plasma / Cold Plasma): This type is also known as cold plasma due to its significantly lower gas temperature, typically ranging from 300 K to 1000 K ((Fridman, 2008). In these plasmas, the electron temperature (Te) is much higher than the ion and neutral gas temperatures (Te≫Ti≈Tg). This allows energetic electrons to drive chemical reactions while the bulk gas remains relatively cool. This plasma can further be classified as atmospheric pressure cold plasma and low pressure cold plasma based on the operating pressure conditions.
    - Examples: Fluorescent lamps, dielectric barrier discharges (DBDs), and atmospheric pressure plasma jets are prime examples. Their low gas temperature makes them suitable for sensitive applications like medical sterilization, wound healing, food disinfection, surface modification of heat-sensitive materials, and environmental remediation.

This chapter focuses exclusively on the applications of cold plasma. Other plasma types fall outside the scope of this discussion.

3. Generation of cold plasma

Plasma is produced by the ionization of gas molecules by applying energy in the form of nuclear energy, electrical energy, mechanical energy or thermal energy(H Conrads & M Schmidt, 2000). Generating low-temperature plasma for technical uses commonly involves applying an electric field to a neutral gas. A few free electrons and ions, naturally present due to background radiation, are accelerated by this field. As they speed up, they collide with gas atoms, molecules, or electrode surfaces. These collisions are energetic enough to liberate more charged particles, creating an avalanche. This process continues until the rate at which new charged particles are formed equals the rate at which they are lost, establishing a stable, steady-state plasma(H Conrads & M Schmidt, 2000).

In cold plasma, partially ionized gas is produced by relatively low lower power input as compared to the thermal plasmas. This weakly ionized cold plasmahas less than 0.1% ionization and the temperature will be less than 100°C(Adesina et al., 2024). Further, based on the energy source and the working gas, cold plasma can be produces at atmospheric pressure or at low pressure (0-100 kPa) conditions. The commonly used discharge methods in food applications are dielectric barrier discharges, corona discharges, gliding arc discharges, plasma jets, and glow discharges using energy sources like AC, DC, pulsed DC power supply, microwave and radio frequency. Further, the plasma activated medium such as plasma activated water in which the water is activated by coldplasma first and then used for treating food materials. The major CP generation methods are discussed in detail below (figure 2).

3.1 Dielectric barrier discharge (DBD)

Dielectric barrier discharges (DBD) are also known as silent discharges, and it is one of the versatileand widely used methods of generating cold plasma at atmospheric pressure. This system consists of two electrodes with at least one electrode covered with the dielectricbarrier material such as glass, quartz or acrylic, PET, polypropylene etc. The distance between the electrodes is limited to few millimeters to ensure stable discharge of CP. The dielectric material on the electrodes or in between the electrodes limits the discharge current and prevents the formation of streamer discharge/ arching thereby enabling the continuous or pulsed CP discharge. Further it also distributes streamers created by the electron accumulation to ensure homogenous discharge. Generally, DBD discharges are generated with ac voltages or pulsed power ranging from 1 to 100 kV, with frequencies spanning through line frequency to several kilohertz.

As the voltage rises, the electric field in the gas gap increases, accelerating any free electrons (naturally present from background radiation or pre-ionization). These electrons collide with gas molecules, leading to ionization, excitation, and dissociation, forming a multitude of reactive species and creating localized plasma filaments known as microdischarges. Crucially, when these microdischarges strike the dielectric surface, charge accumulates on it. This accumulated charge then rapidly creates an opposing electric field that quenches the microdischarge within nanoseconds, preventing the full breakdown into a hot arc. This self-limiting characteristic of the dielectric barrier is key to maintaining the non-thermal nature of the plasma, ensuring that the heavy particles (ions and neutrals) remain near ambient temperature while electrons possess high energy. The rapid switching of the AC field continuously re-ignites new microdischarges across the surface, leading to a sustained, spatially distributed cold plasma rich in reactive species.

Due to its simpler construction, various configurations of DBD discharges are available such as symmetric, asymmetric, planar, co-planar, DBD brushes, cylindrical, coaxial, microarray DBDs etc. Detailed information on the DBD discharge and the system configurations can be found at (Bardos & Barankova, 2010; Brandenburg, 2017; H. Conrads & M. Schmidt, 2000; Flores-Fuentes et al., 2009)

While Dielectric Barrier Discharge (DBD) cold plasma systems offer significant promise for various applications, their utility in food processing faces two key limitations:

(1) DBD systems, particularly those using parallel plate or coaxial cylinder configurations, typically operate with a very narrow gap (often a few millimeters) between the dielectric surface and the opposing electrode. This narrow gap is crucial for maintaining the non-thermal nature of the plasma and preventing arcing.A narrow discharge gap makes it difficult to uniformly treat large or irregularly shaped products, leading to inefficient or incomplete decontamination.

(2) DBD plasma characteristics are highly sensitive to even minor fluctuations in operating parameters. These parameters include the applied voltage and frequency, the type and flow rate of the process gas, the humidity and temperature of the ambient air (if using air), and even the surface properties of the dielectric material and the treated food product. A slight change in any of these can significantly alter the intensity, homogeneity, and reactive species composition of the plasma.If the plasma properties vary, the efficacy of microbial inactivation, enzyme deactivation, or surface modification can become inconsistent. For example, a minor change in humidity could alter the

generation of key reactive oxygen and nitrogen species (RONS), affecting decontamination effectiveness.

3.2 Corona Discharge

Corona discharges are another commonly used method for cold plasma (CP) generation, employed in both direct and indirect applications in food processing.This system typically employs an electrode configuration with a sharp point, wire, or edge (the high-voltage electrode) positioned at a significant distance from a larger, often grounded, counter-electrode or surface. When a high voltage (either DC or AC) is applied, the electric field becomes highly concentrated around the sharp features of the energized electrode. If this localized electric field exceeds the dielectric strength of the surrounding gas, a partial electrical breakdown occurs, forming a region of ionized gas around the pointed electrode. This creates a characteristic bluish or purplish glowwhich is the visual indicator of the “corona”. The mechanism involves the acceleration of initial free electrons in this strong field, leading to inelastic collisions with gas molecules that cause ionization and excitation, primarily at the point of highest field strength. While these collisions generate reactive species and energetic electrons, the discharge does not fully bridge the gap to form a hot arc, as the electric field rapidly weakens away from the sharp electrodeand the dischargeextinguishes before it becomes too conductive at the end of each pulse. This localized and self-limiting nature allows the heavy gas particles to remain near ambient temperature. The main draw back of corona discharge is the thin plasma volume posing limitations in the applications. Furthermore, as the cold plasma is directly formed on a metal electrode, concerns regarding metal etching and subsequent deposition onto food material also present a significant challenge(Lukes et al., 2012).

3.3 Gliding arc discharge

In gliding arc discharge is another type of cold plasma discharge in which the discharge “glides” between the electrodes under high voltage. Typically, this system consists of a set of two to four electrodes operating the voltage range of 100 v to 20 kV.The core mechanism involves an arc forming at the point of shortest inter-electrode distance. This arc is then dynamically stretched and "blown" along the electrodes by the gas flow, often combined with magnetic fields, until it breaks into a plasma plume. Immediately, a new arc reforms, initiating a new cycle. This irregular arc development is influenced by several critical parameters, including the gas flow rate, the type of process gas, the electrode material and geometry, and even surface micro-corrosion (Pawłat et al., 2019).

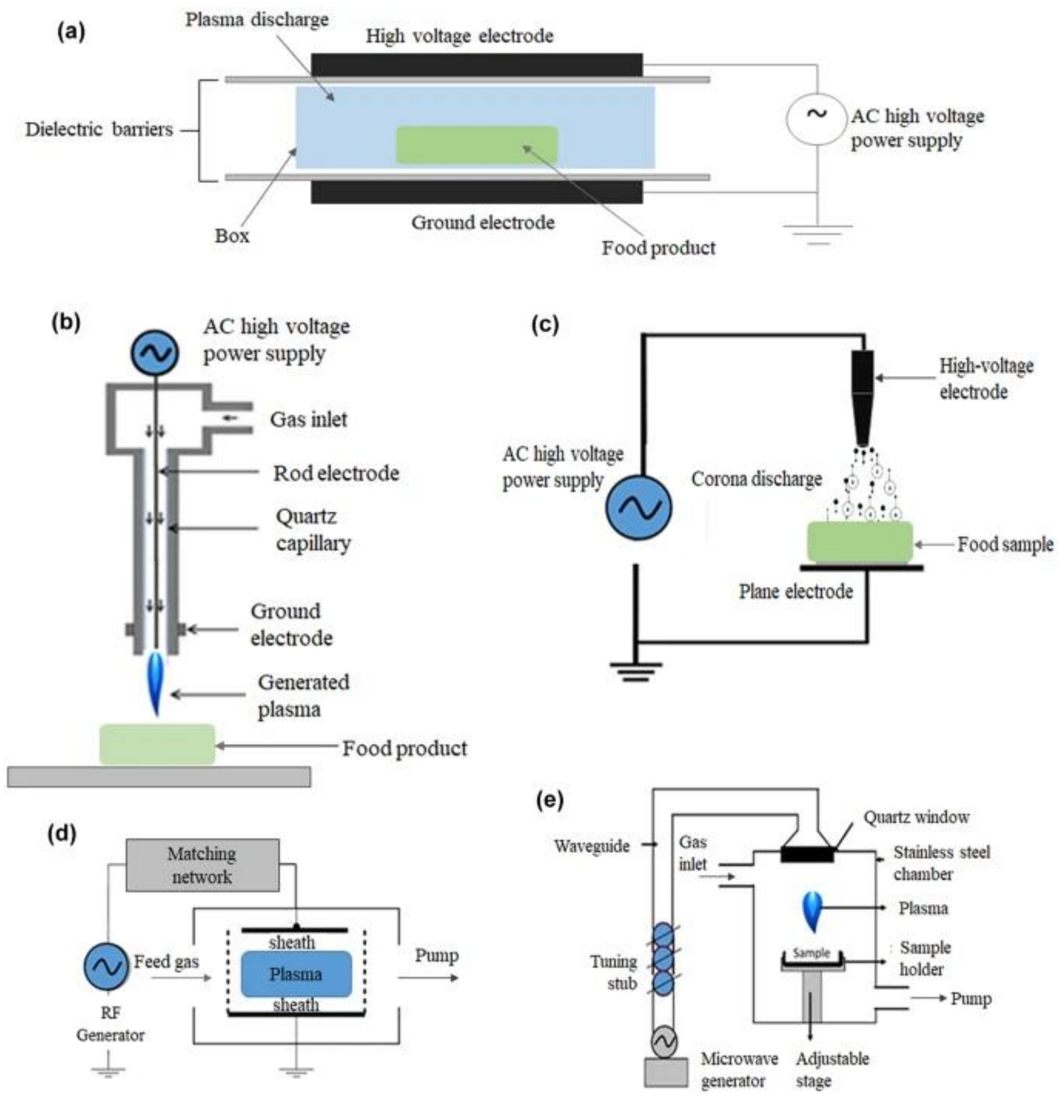

Figure: Schematics of Cold plasma generation systems (a) dielectric barrier discharge, (b) plasma jet, (c) corona discharge, (d) radiofrequency, and (e) microwave plasma system (Nwabor et al., 2022)

3.4 Plasma jets

Plasma jet devices offer a distinct advantage in plasma applications, particularly in food processing, due to their ability to project a stable plasma discharge onto a target surface without requiring the target to be an integral part of the electrical circuit.According to (Lu et al., 2012), the noble gas plasma jets are classified into four types viz.,

1. Dielectric Barrier Discharge (DBD) jets: Where at least one electrode is covered by a dielectric material, controlling the discharge and preventing arc formation.
2. Dielectric-free electrode jets: Lacking a dielectric barrier, often relying on specific gas flow dynamics or pulsed power to maintain non-thermal conditions.
3. DBD-like jets: Configurations that share characteristics with DBD systems but may have variations in electrode arrangement or dielectric placement.

4 Single-electrode jets: Utilizing only one active electrode, with the surrounding air or the treated material acting as the implicit ground.

The sustained, uniform discharge of noble gas plasma jets at higher frequencies are highly favored in biomedical applications as it avoids the possibility of arcing and enables the precise application of plasma. However, the air plasma jets are difficult to sustain at atmospheric pressures due to the presence of oxygen. (Hong et al., 2009) reported a device using a porous alumina dielectric to separate a high-voltage electrode from a ground electrode, producing a 2 cm plasma jet at 60 Hz, but with a relatively high gas temperature (60°C at 10mm). Additionally, "floating" electrode air plasma jets have been developed, which are notably safe and generate room-temperature plasma, suitable for both large surface and localized 3D treatments respectively(Lu et al., 2012). These plasma jets, including those that can also operate with N_2, vary in plasma plume length and specific operating parameters.

3.5 Radiofrequency discharge

These discharges are made utilizing radio frequency energy to ionize the gas. RF discharges can be capacitively coupled (between parallel electrodes) or inductively coupled (using an electromagnetic field). In an RF discharge, an alternating voltage is applied to a gas at low pressure, typically in the range of 1-100 MHz. This oscillating electric field accelerates electrons, causing them to collide with neutral gas molecules, leading to ionization and the formation of plasma.

3.6 Microwave discharges

Microwave cold plasma discharges, also known as microwave-induced plasma, are a type of electrodeless discharge created by using electromagnetic waves, typically at a frequency of 2.45 GHz, to ionize a gas(Lebedev, 2010). These discharges are characterized by a high electron density and relatively low electron temperatures, making them ideal for various applications, including food safety, materials science, and chemical processing.

3.7 Plasma activated media (PAM)

Another important, indirect method of utilizing cold plasma in food processing. As the optimization and control of reactive species exposure of the food material is difficult under direct coldplasma applications, the plasma activated media such as Plasma activated water(PAW)are being evaluated. In PAM, the liquid media is exposed to cold plasma so thatthe reactive species generated in the plasma penetrate the medium and remain stable for varying periods. This also enables the storage and transportation of PAM as opposed to on-the-spot treatment of cold plasma. Detailed information on plasma activated liquid media can be found in (Kaushik et al., 2018; Perinban, Orsat, & Raghavan, 2019)

4.1 Applications in Microbial Disinfection

Cold plasma is increasingly used for microbial control in foods because it operates at low temperatures and preserves quality while inactivating pathogens. Its antimicrobial activity is mainly due to reactive oxygen and nitrogen species (RONS), UV photons, and charged particles. The efficiency of treatment depends on the type of microorganism, food surface properties, treatment time, and gas composition. Gram-negative bacteria are generally more sensitive than gram-positive bacteria and spores, and food matrices with smooth, moist surfaces allow greater penetration of reactive species (Kaur et al., 2024).

Cold plasma has been successfully applied to liquids, fresh produce, dried foods, seafood, and packaged products. For instance, *E. coli* in apple juice was reduced by >4 log CFU/mL in 30 seconds (Liao et al., 2018), while strawberries treated in continuous mode showed up to 3.8 log reductions in *E. coli* and *Listeria innocua* (Ziuzina et al., 2020). Dried squid treated with corona discharge plasma showed 1–2 log reductions in bacteria with minimal sensory changes (Choi et al., 2017). Packaged beef jerky exposed to plasma achieved 2–3 log reductions of *E. coli O157:H7*, *Listeria monocytogenes*, and *Salmonella* within 10 minutes (Yong et al., 2017). These examples highlight cold plasma's versatility across different food systems.

4.1.1 Mechanism of Microbial Inactivation

Plasma-generated RONS interact with microbial membranes, proteins, and DNA, leading to oxidative and nitrosative stress. Lipid peroxidation disrupts cell membranes, causing leakage and lysis. Proteins are oxidized and denatured, impairing enzymatic activity. DNA damage occurs through UV-induced thymine dimers and oxidative base modifications, preventing replication (Perinban, Orsat, Raghavan et al., 2019). Reactive nitrogen species such as peroxynitrite further acidify the cytoplasm and disrupt metabolic pathways (Bourke et al., 2017). Together, these mechanisms overwhelm microbial defenses and ensure effective inactivation, even for resistant biofilms and spores (Zhu et al., 2020).

In fruit juices, plasma reduced *Zygosaccharomyces rouxii* by 5.6 log (Wang et al., 2020) and achieved 5 log reductions of *E. coli*, *Listeria*, and *Salmonella* in tender coconut water within 2 minutes (Mahnot et al., 2019). Fresh-cut apples and strawberries treated with atmospheric DBD

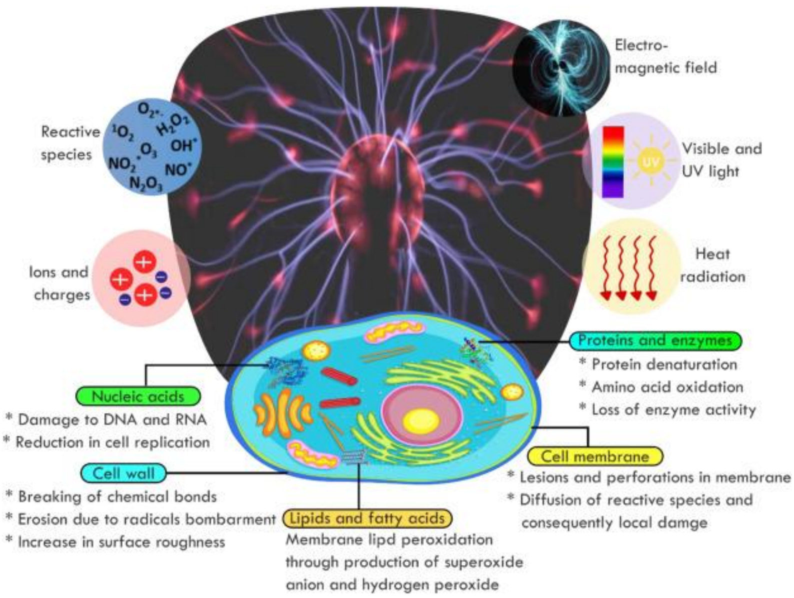

Figure 3: Cold plasma microbial inactivation mechanism (Kaur et al., 2024)

4.2 Removal of Allergens and Enzymes

Cold plasma can reduce the allergenicity of food proteins by altering their structures through oxidation, nitration, peptide bond cleavage, and crosslinking. These changes disrupt conformational and linear epitopes, lowering IgE binding and immune recognition.

Peanut allergens have been widely studied. Plasma exposure decreased solubility and antigenicity of Ara h 1 and Ara h 2 in whole peanuts and defatted flour, with reductions of up to 66% (Venkataratnam et al., 2020). Ultrasound-assisted plasma enhanced these effects, shifting secondary structures and reducing IgG binding by 74%, with in vivo tests confirming improved immune balance (Wang et al., 2025). In dairy proteins, plasma reduced antigenicity of casein and α-lactalbumin, though β-lactoglobulin was resistant (Ng et al., 2021). Shrimp tropomyosin also showed a 96% drop in IgE binding after dielectric barrier discharge treatment, along with reduced inflammatory responses (Cheng et al., 2023). Cashew allergens, however, were largely unaffected (Alves Filho et al., 2019). Overall, plasma's ability to selectively reduce allergenicity highlights its promise for developing hypoallergenic foods.

4.3 Modification of Food Functional Properties

Plasma treatment also modifies protein functionality, which is critical for food, pharmaceutical, and biomaterial applications. By introducing reactive groups and inducing crosslinking, plasma can alter solubility, hydrophobicity, film strength, and emulsifying properties.

For example, whey and gluten protein films treated with glow plasma showed increased tensile strength and surface modifications without major losses in permeability (Moosavi et al., 2020). In whey protein isolate, vacuum plasma with different gases altered oxidation levels, hydrophobicity, and interfacial behavior depending on gas type (Mohammadi et al., 2023). Similar improvements have been observed in plant proteins, where plasma enhanced solubility, foaming, and emulsifying capacity, though overexposure can impair functionality (Basak & Annapure, 2022). Combined pH-shifting and plasma treatment of chickpea protein significantly improved solubility and reduced aggregation, demonstrating potential for tailored protein modifications (Wang et al., 2024).

4.4 Applications in Food Packaging

Cold plasma has emerged as a sustainable method for improving packaging materials. Initially used to increase polymer surface energy, it is now applied for in-package decontamination and enhancing the performance of bio-based films. Plasma treatment can increase surface roughness, adhesion, and printability, while maintaining barrier properties.

For example, plasma combined with carnauba wax coating improved fish protein films by raising tensile strength 175% and reducing water vapor permeability by 65% (Romani et al., 2020). Plasma-treated edible films also show enhanced antimicrobial activity, as the process preserves bioactive compounds due to its non-thermal nature. Thus, plasma represents a green alternative to chemical modification in food packaging.

4.5 Removal of Pesticide Residues

Consumer concern over pesticide residues has increased interest in cold plasma as a non-thermal degradation method. Its diverse reactive species enable faster breakdown of pesticides compared to ozonation or pulsed electric fields.

Plasma treatments have achieved up to 91% reduction of imidacloprid (Ni et al., 2024), >70% removal of chlorpyrifos and carbaryl from grapes and strawberries using plasma-activated water (Sarangapani et al., 2020), and nearly complete degradation (>99%) of carbamate pesticides in water via dielectric barrier discharge. Reductions of 90% in abamectin and fenpyroximate residues on dates and effective degradation of diazinon and chlorpyrifos on apples and cucumbers have also been reported (Mahbubeh Mousavi et al., 2017). These findings confirm plasma’s potential as a versatile tool for safer, residue-free foods.

Table 1: Cold plasma disinfection of microoragnisms in food products

Food	Microorganism	Treatment conditions	Findings	Reference
Apple Juice	Zygosaccharomyces rouxii	Voltage: 21 kV, Treatment time: 30 min, gas flow rate: 150 L/h	5.6 log CFU/g reduction	(Wang et al., 2020)
Tender coconut water	*E.coli*, L. *monocyotogenes* and *S.enterica*	Voltage:90 kV; Gas: Air & M65 (65% O_2, 30% CO_2, 5%N_2); Treatment: 120 s	-5 $\log_{10}$ reduction in population of *E. coli* L. *monocyotogenes* and *S.enterica* -	(Mahnot et al., 2019)
Fresh-Cut Apple (Granny Smith) Skin	E. coli, L. innocua	Low pressure cold plasma: Treatment time: 20 min; Gas: Ar, N2, O2 and Ar–O2; Power: 29.6 W; Flowrate:40 L/min	20 min treatment effectively inactivated ($p < 0.05$) E. coli (1.68 log CFU/cm2) with O2, and L. innocua (0.88 log CFU/cm2) with N2.	(Segura-Ponce et al., 2018)
cherry tomatoes and strawberries	Escherichia coli, S. enterica serovar Typhimurium and Listeria monocytogenes	DBD, 70 kVRMS for 30 s – 300 s in air and at atmospheric pressure	reducing by 3.5, 3.8, and 4.2 log10 CFU/sample, respectively within 300 s of treatment	(Ziuzina et al., 2014)
Chicken breast	Campylobacter jejuni	Ar/5 lpm 2–3 kV 1 MHz, 3 min	2.5 log reduction	(Rossow et al., 2018)
Egg	Salmonella typhimurium	N2/100 SCCM 600 W, for 2 min	2.6 log reduction	(Lin et al., 2020)
Egg	Salmonella enteritidis	DBD Air 100 kV 60 kHz 1 min	More than 5 log reduction	(Illera et al., 2023)
Beef jerky	Aspergillus flavus	Flexible thin-layer plasma DBD, AIR, 15 kHZ, 10 min	3.18 log reduction	(Yong et al., 2017)
Asian sea bass	Enterobacteriaceae	DBD, (Ar:O2 (10:90) 80 kVRMS	1.5 log reduction	(Olatunde et al.,

slice		50 Hz 5 min		2020)
Fresh strawberries and spinach	E. coli and L. innocua	In-package DBD in PET containers	Strawberry: 2.0 and 1.3 log10 CFU/mL reductions of E. coli and L. innocua respectively Spinach: 2.2 and 1.7 log10 CFU/mL reductions for E. coli and L. innocua, respectively	(Ziuzina et al., 2020)

Table 2: Applications of cold plasma on food pesticide residues

Food material	Type of pesticide	Processing conditions	Percentage reduction	Reference
Tomato	Chlorpyrifos	5 W for 6 min.	89	(Ranjitha Gracy et al., 2019)
Mango	Chorpyrifos	8 kV for 5 min.	74	(Phan et al., 2017)
	Cypermetrin		63	
Lyciumbarbarum	Dichlorovos	10 kV for 30 min.	96.8	(Zhou et al., 2018)
	Omethoate		99.5	
Blueberry	Boscalid	80 kV for 5 min.	75	(Sarangapani et al., 2017)
	Imidacloprid		80	
Apple	Chlorpyrifos	13 Kv for 10 min	86	(Mahbubeh Mousavi et al., 2017)
	Diazinon		87	
Cucumber	Chlorpyrifos		58	
	Diazinon		82	
Cucumber	Diazinon	0.75 W for 15 min.	88	(Dorraki et al., 2016)
Strawberry	Azoxystrobin	80 kV for 5 min.	69	(Misra et al., 2014)
	Cyprodinil		45	
	Fludioxonil		71	
	Pyriproxyfen		46	
Black Grapes	Chlorpyrifos	120 V for 15 min	65.25	(Rakesh et al., 2024)
Lettuce	Malathion Chlorpyrifos	80 kV for 120 s	53.1 51.4	(Cong et al., 2021)
Corn	Chlorpyrifos Carbaryl	20 W for 60 s	86.2 66.6	(Liu et al., 2021)

5. Conclusion

The growing demand for minimally processed, nutritious, and preservative-free foods has propelled research into non-thermal preservation methods like cold plasma (CP). This innovative technology offers a promising alternative to conventional thermal treatments, capable of preserving the nutritional integrity and extending the shelf life of various food products. CP demonstrates significant potential for commercial applications in ensuring microbial safety of foods, inactivation of enzymes, modification of functional properties of foods, eliminating reducing chemical and biological contaminants such as pesticides and allergens, thereby enhancing consumer safety while maintaining the desired organoleptic and nutritional qualities. Furthermore, its integration into packaging materials could revolutionize shelf-life extension, delivering substantial benefits across the food industry by ensuring prolonged product freshness and minimizing waste.

However, optimizing CP's performance, economic viability, and environmental sustainability hinges on precise control of key parameters including gas composition, pressure, electric field strength, frequency, and temperature. Achieving optimal outcomes also necessitates a profound understanding of microbial diversity, substrate characteristics, and the synergistic effects of UV radiation, reactive species, and free radicals. While CP represents a notable advancement in food safety and quality assurance, it is crucial to acknowledge its limitations. It is not a universal solution, and its judicious application often requires a hybrid approach, combining CP with other preservation techniques, to maximize food safety and nutritional integrity effectively within complex food systems.

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Automation in Paneer Processing

Dr. N. Karpoora Sundara Pandian, Dr. S. Sivaranjani & Dr. C. V. Vithun
Department of Food Plant Operations, College of Food and Dairy Technology, Tamil Nadu Veterinary and Animal Sciences University, Chennai, Tamil Nadu, India.

Paneer, a fresh, non-fermented, non-renneted cheese, holds a special place in the Indian dairy industry as one of the most popular and widely consumed indigenous milk products. Its mild flavor, soft texture, and high nutritional value make it a staple ingredient in a wide range of culinary preparations. Traditionally, paneer production has been carried out on a small scale using conventional methods involving manual labor, which often results in variations in quality, low efficiency, and higher production costs. With the increasing demand for standardized, hygienic, and large-scale paneer production, the need for technological advancements has become inevitable.

The conventional process involves heating milk to around 85–90°C, followed by coagulation using food-grade acids like citric acid or vinegar, straining of whey, pressing of coagulated mass, and cooling to obtain the final product. While this process has remained largely unchanged for decades, it is highly labor-intensive and susceptible to inconsistencies in product texture, moisture content, and yield. Furthermore, factors such as pressing time, coagulation temperature, and pressure application significantly influence the quality attributes of paneer, including firmness, chewiness, and sensory properties.

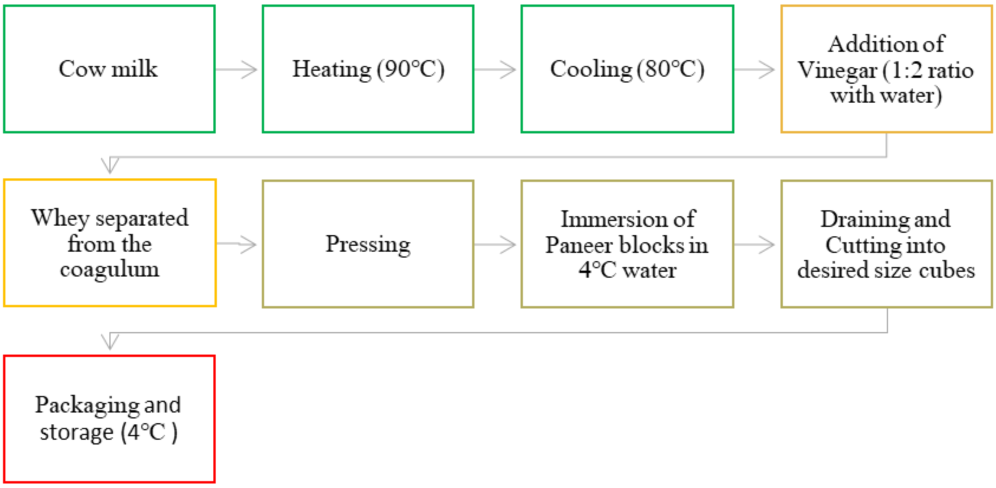
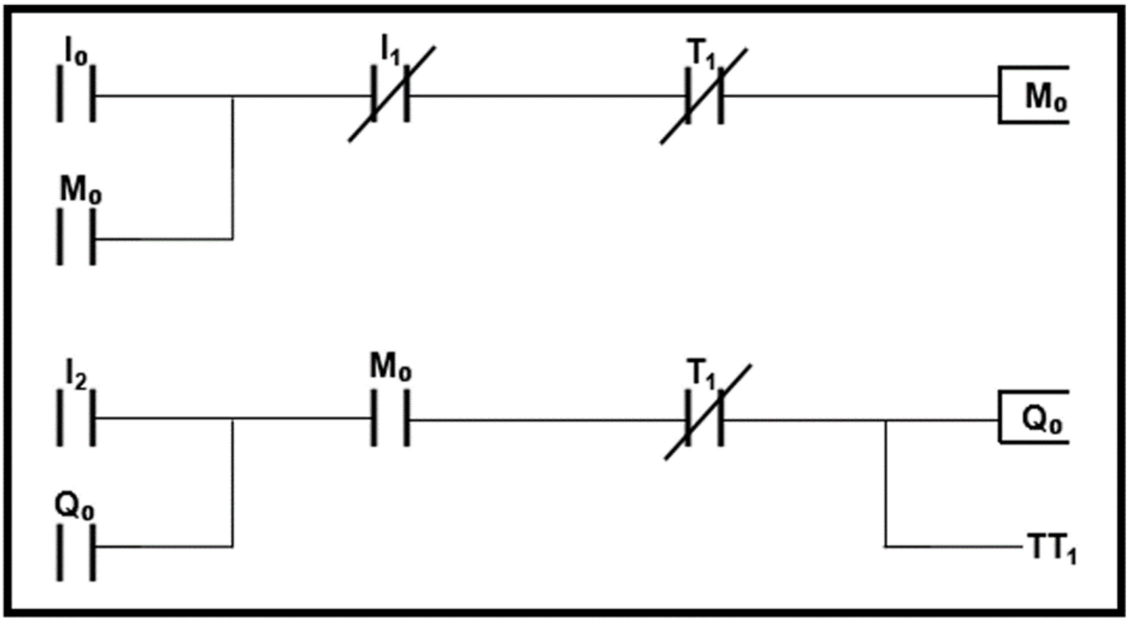


Fig 1: Flow Chart for Paneer preparation

In recent years, automation in paneer processing has emerged as a transformative solution aimed at overcoming these limitations. By replacing manual steps with mechanized and computer-controlled systems, automation ensures precision, repeatability, and better hygiene while reducing operational costs and human intervention. This technological shift aligns with the modern dairy industry's focus on quality, efficiency, and food safety.



PLC I/O	Address	Function
Input	I_0	Push to on switch (S1)
	I_1	Push to on switch (S2) emergency switch
	I_2	Pressure switch
Output	Q_0	Flow control valve

Model	10C1DR- D-V2
Programming language	Ladder diagram
Input	6 inputs
Output	4 outputs
Inbuilt power supply	5 A

Fig 2: Ladder diagram showing the automation control logic for paneer processing

One of the earliest advancements in automation was the development of mechanized pressing systems. Raghavendra's advanced curd pressing mechanism (2010) introduced the concept of pneumatic pressure application, ensuring uniformity in paneer blocks while reducing whey losses. Later, Chitranayak et al. (2017) designed a microprocessor-controlled paneer press that allowed precise control over pressure and pressing time, enhancing product texture and consistency. Similarly, Sherawat's integrated paneer-making device (2008) combined coagulation, pressing, and cooling operations into a single automated system, paving the way for continuous production units.

Modern automated paneer-making systems now incorporate PLC (Programmable Logic Controller)-based control units, temperature-regulated coagulation tanks, pneumatic pressing mechanisms, and automated whey drainage systems. For instance, Sivaranjani et al. (2022) developed a semi-automatic paneer-making machine with a 40 L capacity, enabling accurate regulation of coagulation temperature, pressing pressure, and processing duration. By optimizing parameters such as coagulation temperature at 80°C and pressing pressure at 0.5 MPa using citric acid or vinegar as coagulants, the system consistently produced paneer with desirable yield, moisture retention, and textural attributes.

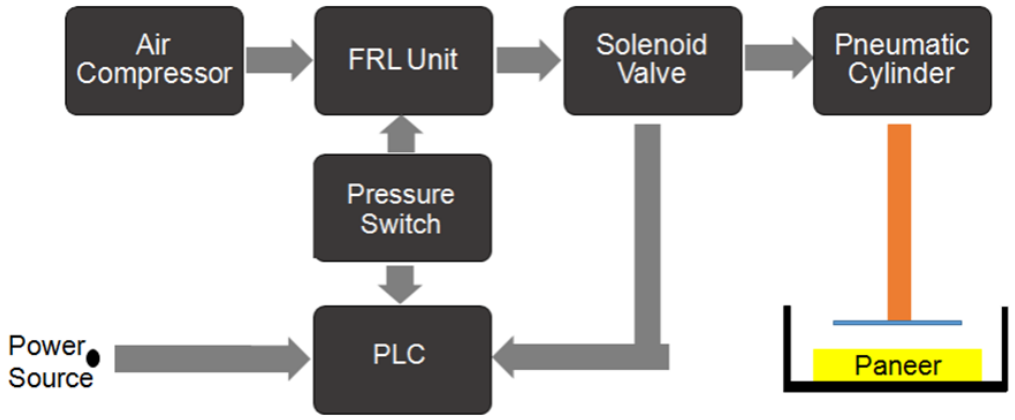
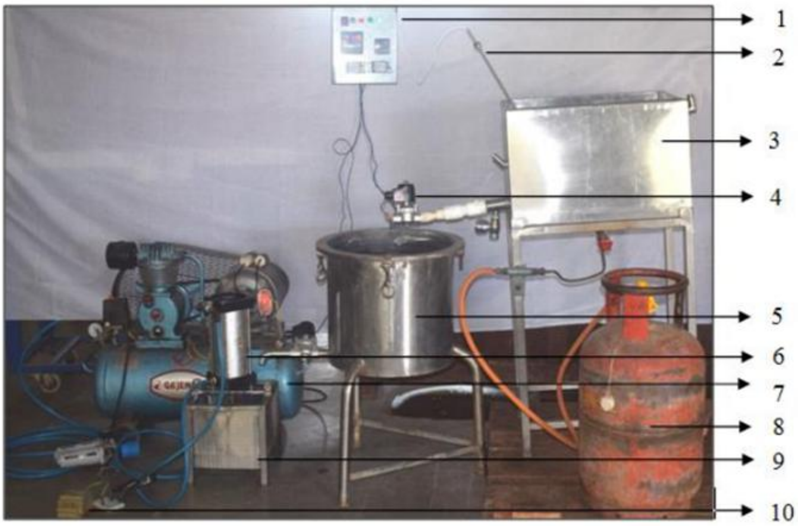


Fig 3: Schematic diagram of the automated paneer-making unit

Continuous paneer-making systems have further revolutionized the industry by integrating helical coil heat exchangers for rapid heating, vacuum-assisted whey removal for reduced moisture variability, and conveyor-based pressing units for uninterrupted production. These advancements minimize manual handling, thereby improving hygiene standards and reducing microbial contamination risks. Studies have demonstrated that machine-controlled systems maintain consistent moisture content, minimize fat losses in whey, and produce paneer with extended shelf life compared to conventional methods.



1 – Controller unit, 2 – thermocouple, 3 – milk heating tank, 4 – solenoid valve, 5 – coagulation tank, 6 – pneumatic press, 7 – compressor, 8 – LPG cylinder, 9 – pressing unit, 10 - PLC

Fig 4: Automated Paneer Unit

In addition to improving efficiency and product quality, automation significantly reduces production costs by lowering labor requirements and energy consumption. With the dairy industry moving towards large-scale, value-added production, automated systems provide a foundation for integrating advanced preservation technologies such as modified atmosphere packaging (MAP) and refrigeration to further enhance product stability and marketability.

The adoption of automation in paneer processing not only modernizes traditional practices but also ensures alignment with international dairy quality standards. As consumer demand for hygienic, high-quality paneer continues to grow, the integration of automation with digital monitoring tools, IoT-based sensors, and AI-enabled quality control systems holds immense potential for the future. These innovations can facilitate real-time process optimization, predictive maintenance, and data-driven decision-making, leading to fully automated, smart dairy processing facilities.

In conclusion, automation in paneer processing represents a paradigm shift from manual, labor-intensive methods to sophisticated, technology-driven systems. By ensuring consistency, efficiency, and economic viability, automation not only enhances product quality but also strengthens the dairy industry's ability to meet evolving consumer preferences and global quality benchmarks.

Unlocking the Potential of Spectroscopy and Hyperspectral Imaging in Food Industry: Ensuring Quality and Safety Standards

Dr. M. Naveen Kumar,

Scientist, Post Harvest Technology Research Station, Dr. Y.S.R. Horticultural University

Venkataramannagudem, West Godavari, Andhra Pradesh, India

Abstract

The food industry faces unprecedented challenges in ensuring quality and safety standards while meeting increasing consumer demands. Spectroscopy and hyperspectral imaging have emerged as transformative technologies that combine the power of spectroscopic analysis with advanced imaging capabilities. This comprehensive review examines the fundamental principles of image processing, spectroscopy techniques, and hyperspectral imaging applications in food quality assessment. The integration of machine learning algorithms with these optical sensing technologies has revolutionized non-destructive food analysis, enabling rapid, accurate, and real-time monitoring of food properties from farm to fork.

1. Introduction

The global food industry is undergoing a technological transformation with the growing need to ensure quality, authenticity, and safety of products. Conventional inspection methods, though accurate, are often destructive, time-consuming, labor-intensive, and unable to provide rapid results for large-scale operations. To overcome these challenges, non-destructive approaches such as digital image processing, spectroscopy, and hyperspectral imaging (HSI) are increasingly being employed. These techniques, supported by advances in sensors, computational power, and artificial intelligence, provide rapid and reliable tools for monitoring food quality and safety while enabling real-time and automated decision-making.

Digital image processing is one of the most widely used techniques for food inspection, particularly for visual quality assessment and grading. By utilizing conventional RGB or multispectral cameras, it captures spatial attributes such as size, shape, texture, and color, making it highly effective in sorting, grading, and detecting surface defects in fruits, vegetables, grains, and meat. Its advantages include high speed, cost-effectiveness, repeatability, and suitability for automation in industrial food lines. However, digital image processing is largely limited to visible features, which restricts its ability to detect internal defects, compositional variations, or hidden contaminants. It is also sensitive to external conditions such as illumination and background, which can reduce reliability under variable environments.

Spectroscopy, on the other hand, offers detailed chemical information by analyzing the interaction of electromagnetic radiation with food components. Techniques such as near-infrared (NIR), mid-infrared (MIR), Raman, and fluorescence spectroscopy are widely applied for detecting adulterants, profiling nutrients, monitoring spoilage, and assessing product authenticity. The primary advantages of spectroscopy are its rapid, non-destructive nature and its ability to detect molecular-level compositional changes with high sensitivity. Nonetheless, its lack of spatial resolution poses a significant limitation, as spectra are usually collected from a bulk sample or a specific point, potentially overlooking localized variations within heterogeneous food products. Moreover, the accuracy of spectroscopic analysis depends heavily on sample presentation and calibration models.

Hyperspectral imaging has emerged as a powerful technique that bridges the gap between digital imaging and spectroscopy by combining spatial and spectral information. Unlike traditional methods, HSI acquires a full spectrum at each pixel, enabling simultaneous evaluation of both physical and chemical characteristics of food items. This capability allows precise detection of contaminants, quality defects, authenticity issues, and processing inconsistencies. Applications of HSI in the food sector range from identifying pesticide residues on fruits and fungal infections in grains to distinguishing between adulterated and authentic products, as well as monitoring freshness and storage stability. By offering a non-invasive, real-time inspection method, HSI addresses the shortcomings of conventional imaging and spectroscopy, thereby enhancing food quality monitoring and safety assurance.

Overall, while digital image processing and spectroscopy have individually contributed significantly to quality evaluation, hyperspectral imaging stands out as a comprehensive tool that integrates their strengths while overcoming their limitations. With increasing global emphasis on food safety regulations and consumer demands for transparency, HSI is poised to play a central role in ensuring traceability, quality assurance, and safety standards in modern food supply chains.

2. Image Processing

Digital image processing has become an indispensable tool in the food industry, providing rapid, non-destructive, and objective methods for quality assessment [1]. The technology converts visual data into computer-readable formats, enabling detailed analysis of food characteristics through pixel grids [2]. Modern food analysis relies on sophisticated image acquisition systems that capture and interpret visual information to assess various quality parameters.

2.1 Fundamental Principles of Digital Image Processing

Digital image processing encompasses image acquisition, storage, analysis, and pattern recognition techniques [1]. A digital image represents real-world objects composed of pixels that store information in binary format [2]. The processing involves algorithms that extract or measure various visual features of objects, performing task-relevant analysis and interpretation with precision, objectivity, and speed [1].

In food applications, digital image analysis enables the conversion of visual data into quantitative measurements. The technology utilizes advanced imaging techniques and sophisticated algorithms to evaluate properties such as color, texture, composition, and surface defects [2]. From detecting surface defects in fruits and vegetables to assessing color uniformity in processed foods, digital image processing enhances precision in quality control [2].

2.2 Types of Camera Systems in Food Analysis

The selection of appropriate camera systems is crucial for effective food quality assessment. Two primary sensor technologies dominate the field: Charge-Coupled Device CCD) and Complementary Metal-Oxide Semiconductor CMOS) sensors [2].

CCD sensors are preferred for quality checks in the food industry due to their high image quality, low noise characteristics, and superior performance in low-light conditions [2]. These sensors provide excellent sensitivity and produce images with minimal electronic interference, making them ideal for precise food analysis applications. In contrast, CMOS sensors, while more cost-effective, tend to exhibit higher noise levels and rolling shutter effects that can compromise image quality [2].

Advanced imaging systems in food analysis also incorporate specialized cameras designed for specific wavelength ranges. Near-infrared (NIR) cameras excel in penetrating food surfaces to assess internal quality parameters, while visible spectrum cameras provide detailed surface characterization [3]. Multi-spectral and hyperspectral cameras extend imaging capabilities across broader wavelength ranges, enabling comprehensive chemical and physical property assessment [3].

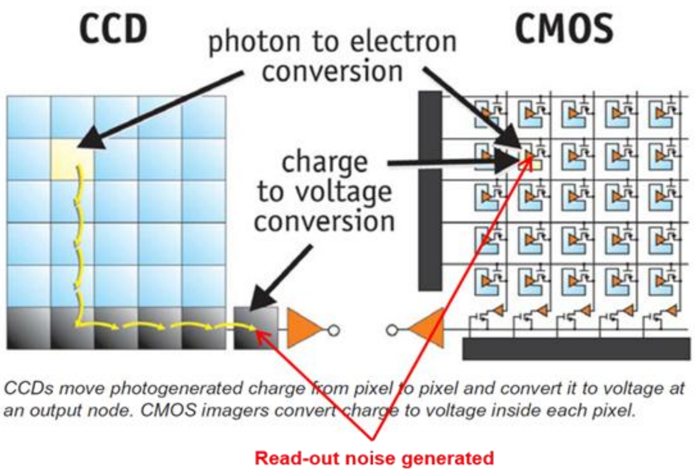


Figure: Working mechanism of CCD and CMOS cameras.

2.3 Limitations of Digital Image Processing

Despite its advantages, digital image processing faces several significant limitations that impact its implementation in food analysis [4, 5]. High-resolution imaging requires substantial computational resources and memory capacity, demanding powerful processors to handle large datasets effectively [5]. The cost of specialized instrumentation remains a significant barrier, particularly for smaller food producers with limited budgets [6].

Data complexity presents another major challenge, especially when analyzing multiple contaminants or variables simultaneously. Spectroscopic data can be intricate and difficult to interpret, requiring standardized analysis methods and user-friendly software platforms [6]. The development of comprehensive spectral libraries remains incomplete, with new or emerging substances often lacking well-characterized spectra, limiting detection capabilities [6].

Environmental factors significantly influence image quality and processing accuracy. Fluctuating lighting conditions, shadows, reflections, and varying backgrounds can distort captured data and impact analysis reliability [3]. Food products exhibit natural variability in size, shape, color, and texture, making algorithm design challenging and requiring extensive data collection and model training [3].

The transition from laboratory conditions to industrial environments introduces additional noise and variability, complicating real-world applications [7]. Processing speed limitations can hinder real-time applications, particularly when dealing with high-resolution images or complex analysis algorithms [4].

3. Spectroscopy

Spectroscopy has revolutionized food analysis by providing rapid, non-destructive methods for determining composition, quality, and safety parameters [8]. The technique exploits the interaction between electromagnetic radiation and food components to reveal detailed information about molecular structure and chemical properties [9].

3.1 Working Principles of Spectroscopy

At its core, spectroscopy is based on the fundamental principle that materials interact uniquely with electromagnetic radiation across different wavelengths [8]. When light strikes a food sample, various phenomena occur including absorption, emission, reflection, scattering, or resonance 8. Each spectroscopic technique exploits one or more of these interactions to provide specific information about the sample.

The electromagnetic spectrum spans from radio waves with long wavelengths to gamma rays with short wavelengths [8]. Different regions interact with food components in unique ways: ultraviolet and visible light interact with electronic transitions in molecules, while infrared radiation interacts with molecular vibrations [8]. This wavelength-dependent interaction forms the basis for identifying and quantifying specific compounds within food matrices.

Spectroscopic measurements follow the Beer-Lambert law, which relates the absorption of light to the properties of the material through which light travels [10]. This fundamental relationship enables quantitative analysis by correlating absorption intensity with concentration levels of specific compounds [10].

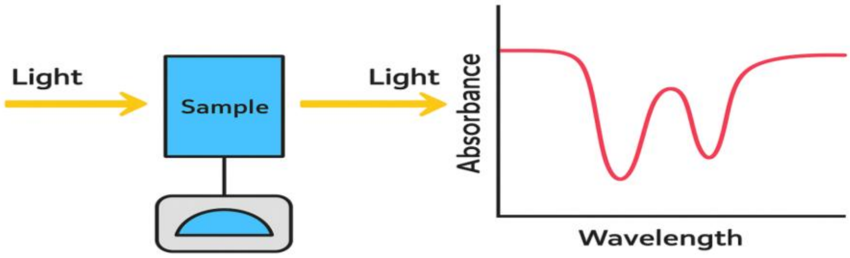


Figure: Working mechanism of absorption spectroscopy

3.2 Types of Spectroscopy Techniques

3.2.1 Ultraviolet-Visible UV Vis Spectroscopy

UV-visible spectroscopy measures light absorption in the ultraviolet (200-400 nm) and visible 400 800 nm) regions [10, 8]. This technique proves particularly useful for analyzing compounds with chromophores-chemical groups capable of absorbing light in this range [8]. In food analysis, UV-VIS spectroscopy finds extensive applications in vitamin quantification, colorant detection, antioxidant capacity evaluation, and food adulteration detection [8].

3.2.2 Near-Infrared NIR Spectroscopy

NIR spectroscopy operates in the 700-2500 nm wavelength range and excels in analyzing organic compounds through overtone and combination vibrations [11, 12]. This technique has become the workhorse of food analysis due to its ability to penetrate food surfaces and provide information about moisture, protein, fat, and carbohydrate content [13]. NIR spectroscopy requires minimal sample preparation and enables rapid analysis of both solid and liquid foods [14].

3.2.3 Mid-Infrared MIR) and Fourier Transform Infrared FTIR Spectroscopy

FTIR spectroscopy operates in the mid-infrared region (4000-400 cm^{-1}) and identifies chemical bonds and functional groups within molecules [11, 9]. This technique provides detailed molecular fingerprints, making it valuable for identifying adulterants, characterizing food components, and monitoring processing-induced changes [11]. FTIR spectroscopy has demonstrated effectiveness in detecting honey adulteration and assessing physicochemical characteristics of wheat species [11].

3.2.4 Raman Spectroscopy

Raman spectroscopy analyzes molecular vibrations through inelastic light scattering, providing complementary information to infrared techniques [11, 15]. The technique excels in aqueous environments and offers molecular fingerprinting capabilities for food authentication and contaminant detection [11]. Surface-Enhanced Raman Spectroscopy (SERS) significantly improves sensitivity, enabling detection of trace toxic substances and pathogens in foods [11, 15].

3.2.5 Nuclear Magnetic Resonance NMR Spectroscopy

NMR spectroscopy provides detailed information about molecular structure and conformational properties through nuclear spin interactions in magnetic fields [11, 8]. This technique offers unparalleled capability for food authentication, quality assessment, and metabolomic profiling [11]. NMR has proven particularly valuable in analyzing milk quality, spice authentication, and detecting food fraud [11].

3.3 Limitations of Spectroscopy Techniques

Despite their numerous advantages, spectroscopic techniques face several limitations that impact their effectiveness in food analysis [7, 6]. The complexity of food matrices presents significant challenges, as multiple components can interfere with spectral measurements and complicate data interpretation [7]. Matrix effects often require sophisticated chemometric approaches to extract meaningful information from spectral data [6].

Sample preparation requirements vary among techniques, with some methods requiring extensive preprocessing that can alter food properties [15]. The Raman effect, for instance, produces very weak signals, requiring sensitive instrumentation and longer acquisition times [15]. Fluorescence interference can mask Raman signals, particularly in highly fluorescent food samples [6].

Instrument costs remain prohibitive for many applications, especially for high-resolution spectrometers required for detailed analysis [6]. Calibration complexity increases with sample diversity, requiring extensive reference databases and regular model updates to maintain accuracy [7]. Environmental sensitivity affects measurement reproducibility, with factors such as temperature, humidity, and vibrations influencing spectral quality [6].

The lack of standardized protocols across different instruments and laboratories leads to variability in results and limits inter-laboratory comparisons [6]. Data interpretation requires specialized expertise, and the integration of artificial intelligence approaches, while promising, introduces additional complexity in model validation and implementation [7].

4. Hyperspectral Imaging

Hyperspectral imaging represents a revolutionary advancement in food analysis, combining the spatial information of digital imaging with the spectral resolution of spectroscopy [16 17]. This technology captures detailed spectral information for every pixel in an image, creating comprehensive datasets that enable unprecedented insight into food quality and safety parameters [17].

Hyperspectral imaging is defined as a technique that collects and processes information across the electromagnetic spectrum to obtain complete spectral profiles for each pixel in an image [17]. Unlike conventional RGB imaging that captures three broad spectral bands, hyperspectral systems acquire hundreds of narrow, contiguous spectral bands spanning wavelengths from 250 nm to 15,000 nm and beyond [17].

The technology creates a three-dimensional data structure known as a hyperspectral cube or hypercube, containing two spatial dimensions (x, y) and one spectral dimension (λ) [18 19]. Each wavelength channel provides a monochromatic two- dimensional image, while each pixel contains a complete optical spectrum that serves as a unique spectral fingerprint [16 17].

The fundamental principle underlying hyperspectral imaging is that different materials reflect, scatter, or absorb electromagnetic energy differently based on their chemical composition and physical structure [20]. When food samples are exposed to electromagnetic radiation, their molecular-level interactions with light photons create characteristic spectral signatures that enable material identification and quantification [20].

4.1 System Components and Architecture

A typical hyperspectral imaging system comprises four core components that work synergistically to capture and process spectral information [21]:

(a) Light Source

The illumination system provides uniform, stable illumination across the spectral range of interest. Halogen and LED based light sources are commonly employed, with LED technology offering superior efficiency, sustainability, and configurability [22]. The light source must deliver consistent intensity across all wavelengths to ensure accurate spectral measurements [21].

(b) Hyperspectral Camera

The camera system captures incoming light and separates it into constituent wavelengths. Modern hyperspectral cameras utilize advanced sensor technologies including InGaAs Indium Gallium Arsenide) for near-infrared applications and silicon-based sensors for visible wavelengths [17]. Camera selection depends on the target wavelength range and required spectral resolution [23].

(c) Spectrograph

The spectrograph disperses incoming light into its spectral components, enabling wavelength-specific detection. This component determines the spectral resolution and range of the imaging system [21]. Advanced spectrographs provide high spectral resolution while maintaining good light throughput efficiency [17].

(d) Processing Software

Sophisticated software platforms process and classify hyperspectral data in real-time, implementing advanced algorithms for calibration, preprocessing, feature extraction, and classification [21]. Modern systems integrate machine learning capabilities for automated analysis and decision-making [24].

4.2 Working Mechanism and Data Acquisition

Hyperspectral imaging systems operate through several acquisition modes, each optimized for specific applications and constraints [18]. The three primary imaging modes are:

(a) Spatial Scanning (Push-broom and Whisk-broom)

Push-broom scanners acquire complete spectra for each pixel along a line perpendicular to the scanning direction [18]. As the sample moves past the scanner (typically on a conveyor belt), successive line scans build up the complete hyperspectral image [25]. This mode is ideal for industrial applications where products move along production lines [26].

Whisk-broom scanners capture spectra pixel by pixel across the scene, requiring both spatial and spectral scanning [18]. While providing high spatial resolution, this mode requires longer acquisition times [18].

(b) Spectral Scanning (Band Sequential)

Band sequential scanners acquire complete spatial images at different wavelengths sequentially [18]. This approach provides excellent spectral resolution but requires stationary samples and longer acquisition times [18].

(c) Snapshot Imaging

Snapshot hyperspectral imagers capture complete spatial and spectral information simultaneously using specialized sensor arrays [18]. This mode enables rapid data acquisition but typically offers lower spectral resolution compared to scanning systems [18].

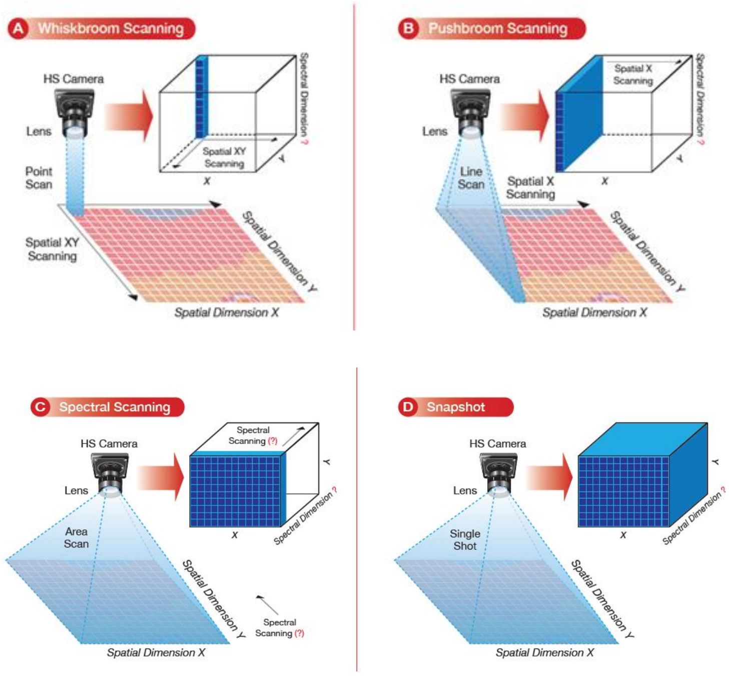


Figure: Working mechanism of different HSI acquisition techniques.

Table: Comparison of various imaging techniques.

Feature	**Point scan**	**Line scan**	**Area scan**
Common name	Whisk broom	Push broom	Band sequential
Method of scanning	Spatial scanning	Spatial scanning	Spectral scanning
Wavelength dispersion technology	Prism/diffraction grating	Prism/diffraction grating	Tunable filters or filter wheels
Real-time application	Not possible	Possible	Not possible
Time consumption	More	Less	More
Object exposed time	High	Low	High
Relative motion between object and camera	Present	Present	Not present

4.3 Types of Imaging Modes for Food Analysis

Food quality assessment utilizes three primary measurement modes, each offering distinct advantages for specific applications [24]

(a) Reflectance Mode

Reflectance measurements analyze light reflected from food surfaces, providing information about surface properties, color characteristics, and shallow subsurface features [24]. This mode excels in detecting surface defects, contamination, and color variations in fruits, vegetables, and processed foods [27].

(b) Transmittance Mode

Transmittance mode analyzes light passing through translucent food samples, enabling assessment of internal quality parameters [24]. This approach proves particularly valuable for evaluating fruit ripeness, detecting internal defects, and assessing liquid food properties [28].

(c) Interactance Mode

Interactance measurements combine reflectance and transmittance principles, analyzing light that enters the sample and exits at a different location [24]. This mode provides information about subsurface properties and internal structure, making it suitable for analyzing thick or opaque food products [24].

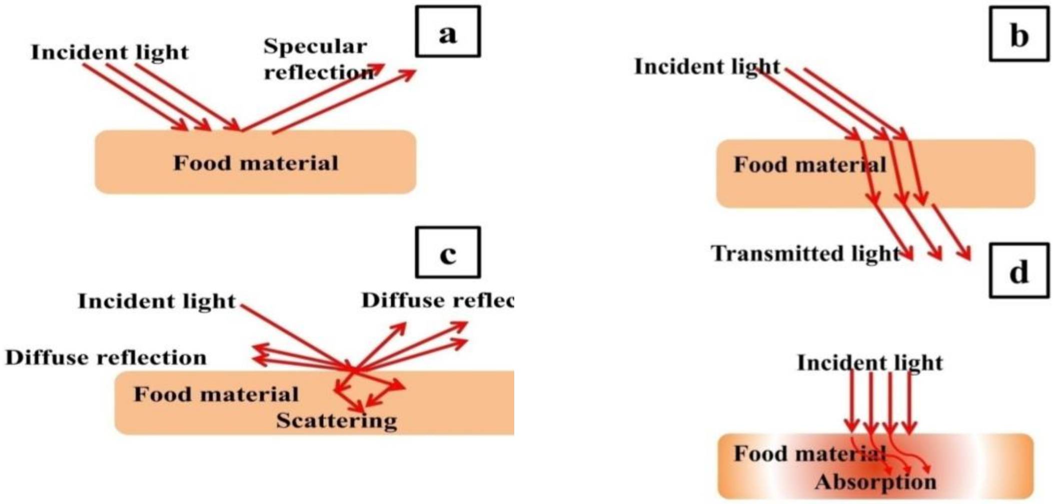


Figure: Various imaging modes for food analysis.

4.4 Applications in Food Industry

Hyperspectral imaging has found extensive applications across the food industry, revolutionizing quality control, safety assessment, and process optimization [27 29]. Key application areas include:

4.4.1 Quality Control and Inspection

Hyperspectral systems enable rapid identification of foreign materials such as glass, plastic, metal, wood, and rubber that may contaminate food products during processing or packaging [22 27]. The technology can detect contaminants like molds, fungi, and other unwanted agents that compromise food safety [22].

Quality assessment capabilities extend to evaluating freshness and ripeness of fruits and vegetables by analyzing subtle changes in spectral profiles [22]. Meat, fish, and poultry applications include detecting foreign objects like bone and cartilage, measuring chemical composition including fat and protein content, and assessing tenderness parameters [27].

4.4.2 Food Safety and Traceability

Hyperspectral imaging detects bacterial contamination on food surfaces, helping prevent food borne illnesses [22]. The technology identifies fungal infections in grain crops during growth and storage, addressing yield decline and health risks [22]. Regulatory compliance applications ensure food products meet required quality and safety standards while facilitating supply chain transparency [22].

4.4.3 Composition Analysis

The technology provides unique capabilities for measuring distribution of moisture, fat, protein, and other components in complex food samples [25]. Unlike traditional spectroscopy that provides average composition data, hyperspectral imaging maps component distribution across the entire sample area [25]. This spatial information proves invaluable for analyzing multi-component products and ensuring composition uniformity [25].

4.5 Processing Steps in Hyperspectral Image Analysis

Hyperspectral image processing involves multiple sequential steps designed to extract meaningful information from complex multidimensional datasets [30 31]. The processing workflow typically includes:

4.5.1 Image Acquisition and Preprocessing

The initial phase focuses on obtaining high-quality hyperspectral images that meet research objectives [30]. Proper sensor selection, spatial and spectral resolution settings, lighting schemes, scan rates, and exposure times are prerequisites for accurate results [30].

Preprocessing encompasses calibration and spectrum correction procedures [30]. Standard reflectance calibration utilizes black and white reference images to standardize spectral and spatial axes, evaluate accuracy, and eliminate curvature effects and instrumental errors [30]. The corrected hyperspectral image R is calculated using:

R = IS-ID / IW-ID

Where IS represents the raw hyperspectral image, ID is the dark reference image, and IW is the white reference image [30].

4.5.2 Spatial Preprocessing Techniques

(a) Cropping and Region of Interest ROI Selection

Background removal through thresholding or ROI selection eliminates irrelevant target regions and focuses analysis on food samples [32]. Proper cropping reduces computational load and improves processing efficiency while ensuring relevant information retention [30].

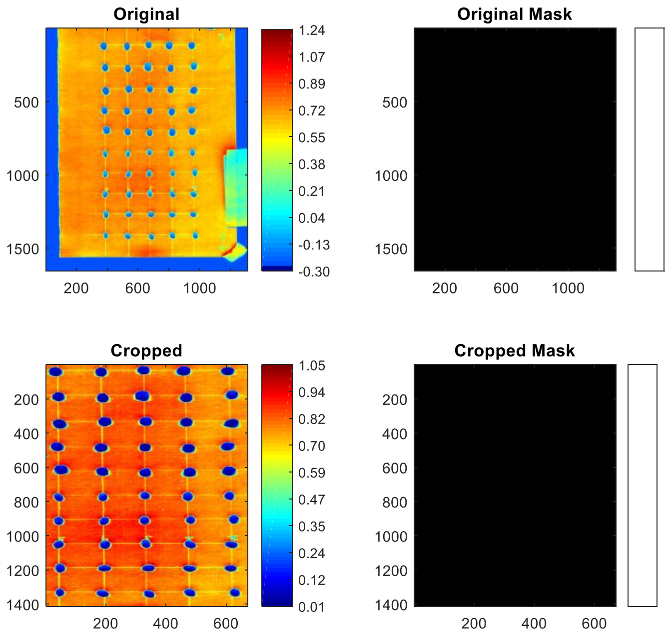


Figure: Spatial processing (cropping) of hyperspectral image.

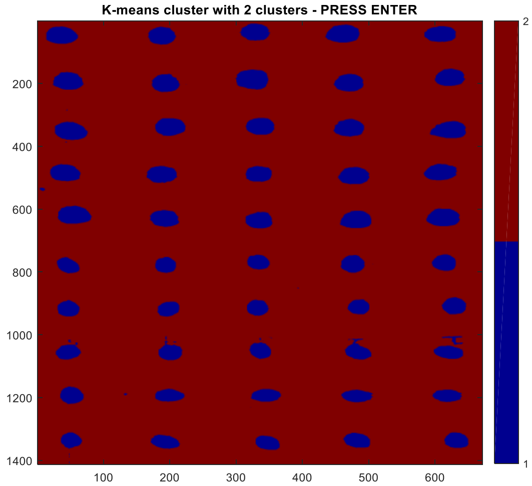


Figure: K-means clustering for removal of background.

(b) Masking and Segmentation

Image segmentation extracts target objects from backgrounds and forms masks for ROI definition [30]. Common segmentation methods include threshold-based approaches, K-means clustering, watershed algorithms, and edge detection techniques [30]. These methods separate food samples from backgrounds and identify different tissue types within samples [31].

(c) Geometric Correction

Spatial distortions arising from optical system imperfections require geometric correction to ensure accurate spatial registration [30]. These corrections account for lens distortions, sensor alignment issues, and platform movement effects [33].

(d) Illumination Correction

Uneven illumination across the field of view necessitates correction procedures to ensure uniform spectral measurements [33]. Correction algorithms compensate for illumination gradients and variations in light source intensity [30].

4.5.3 Dead Pixel and Spike Identification

(a) Dead Pixel Detection

Non-responsive sensor elements create data gaps that require identification and correction [34 23]. Dead pixels are detected through statistical analysis of sensor response patterns and comparison with neighboring pixels [35]. Automated detection algorithms analyze intensity variations and identify consistently non-responsive elements [23].

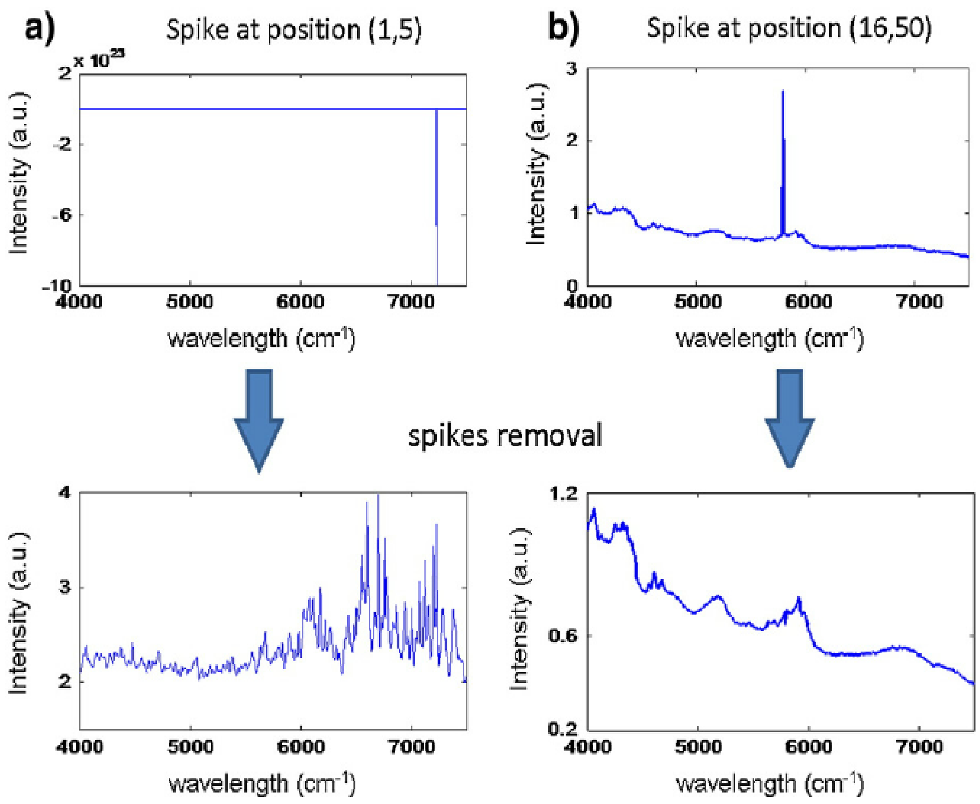


Figure: Detection of spikes in hyperspectral imaging data.

(b) Spike Removal

Random noise spikes in spectral data are identified through statistical analysis and removed using interpolation techniques [30]. Spike detection algorithms compare spectral values with expected ranges and flag anomalous measurements for correction [36].

Correction Algorithms

Dead pixel correction utilizes spatial and spectral interpolation to estimate missing values [34, 35]. Advanced algorithms consider both spatial proximity and spectral similarity to generate accurate replacement values [35].

4.5.4 Spectral Preprocessing Techniques

(a) Noise Reduction

Smoothing algorithms including moving average, Savitzky-Golay filtering, median filtering, and Gaussian filtering reduce spectral noise [30, 36]. These techniques improve signal-to-noise ratios while preserving important spectral features [36].

(b) Baseline Correction

First and second derivatives correct spectrum baseline shifts caused by instrumental drift and sample variation [30]. Derivative preprocessing enhances spectral features and reduces the impact of additive and multiplicative effects [37].

(c) Scattering Correction

Multiplicative Scatter Correction MSC) and Standard Normal Variate SNV) preprocessing reduce spectral variability due to light scattering effects [30, 36]. These techniques normalize spectra to account for physical differences in sample presentation and optical properties [37].

(d) Spectral Normalization

Normalization techniques including unit vector scaling and range normalization ensure comparable spectral intensities across samples [38]. These methods account for variations in illumination intensity and sample thickness [30].

5. Machine Learning Models for Classification

The integration of machine learning algorithms with hyperspectral imaging has revolutionized food quality assessment, enabling automated analysis with high accuracy and reliability [39, 40]. Different machine learning approaches offer distinct advantages for various food analysis applications.

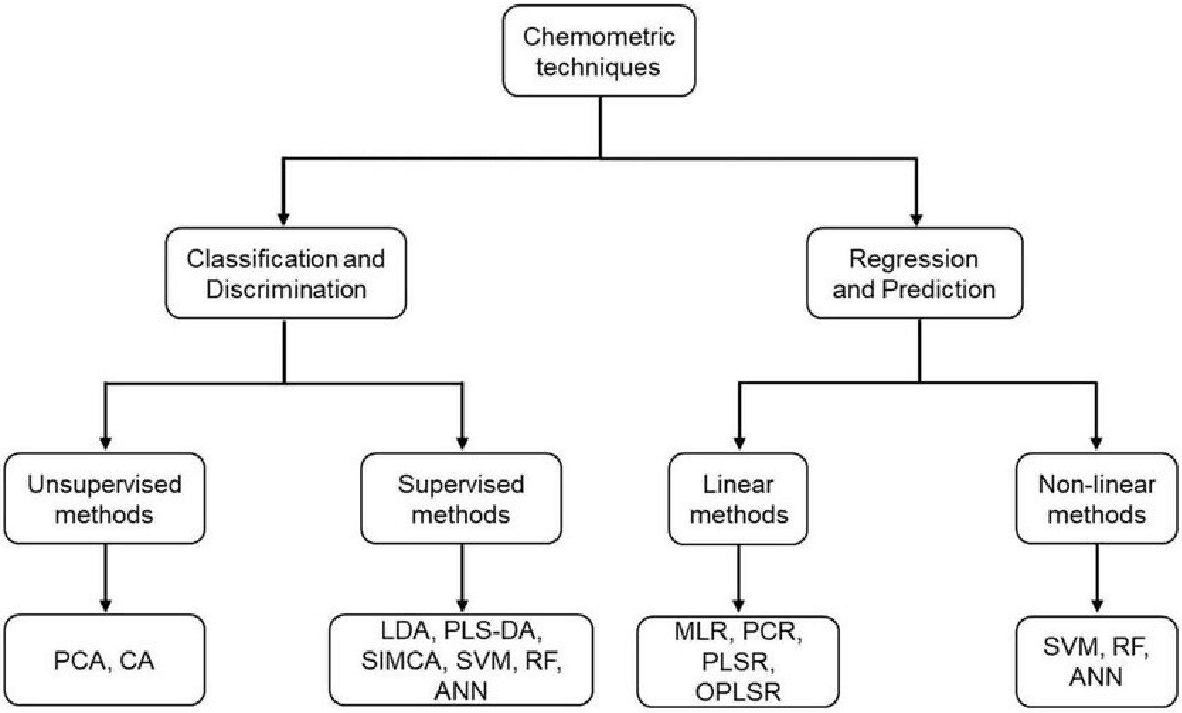


Figure: Various chemometrics techniques used for classification and regression analysis.

5.1 Traditional Machine Learning Approaches

5.1.1 Support Vector Machines SVM

SVM algorithms excel in handling high-dimensional hyperspectral data and demonstrate superior performance with limited sample sizes [36, 39]. The technique creates optimal decision boundaries in high-dimensional feature spaces, making it particularly effective for food classification tasks [41]. SVM applications include wheat flour grade classification, vegetable oil identification, and meat quality assessment [36, 41].

5.1.2 Random Forest RF

Random Forest combines multiple decision trees to create robust classification models [41 42]. The ensemble approach reduces overfitting and provides reliable performance across diverse food applications [39]. RF demonstrates particular effectiveness in vegetable oil adulteration detection and multi-class food classification problems [41].

5.1.3 Partial Least Squares PLS Models

PLS regression and PLS Discriminant Analysis (PLS-DA) provide linear modeling approaches that handle collinear spectral data effectively [32, 42]. These methods extract latent variables that maximize covariance between spectral features and target properties [39]. PLS applications span fruit ripeness assessment, chemical composition prediction, and contaminant detection [32].

5.2 Deep Learning Architectures

5.2.1 Convolutional Neural Networks CNN

CNNs automatically extract hierarchical features from hyperspectral data, eliminating the need for manual feature engineering [40, 43]. One-dimensional CNNs process spectral information efficiently, while three-dimensional CNNs exploit both spatial and spectral relationships [32]. CNN applications include food classification, defect detection, and quality prediction with accuracies exceeding 95% [40, 43].

5.2.2 Autoencoder Networks

Stacked Autoencoders (SAE) and Stacked Weighted Autoencoders (SWAE) perform unsupervised feature extraction and dimensionality reduction [32]. These architectures learn compressed representations of hyperspectral data while preserving essential information [32]. Applications include fruit quality prediction and food authenticity verification [32].

5.2.3 Advanced Architectures

Recent developments include Fully Convolutional Networks (FCN) for semantic segmentation, enabling pixel-level classification of food defects and tissue types [32, 43]. Spinal Networks offer improved classification performance for crop identification tasks [44].

5.2.4 Ensemble Methods and Hybrid Approaches

Ensemble learning combines multiple algorithms to achieve superior performance compared to individual models [39 41]. Hybrid approaches integrate traditional machine learning with deep learning architectures, leveraging the strengths of both methodologies [40]. These advanced techniques demonstrate particular effectiveness in complex food analysis scenarios with multiple quality parameters [45].

6. Case Studies

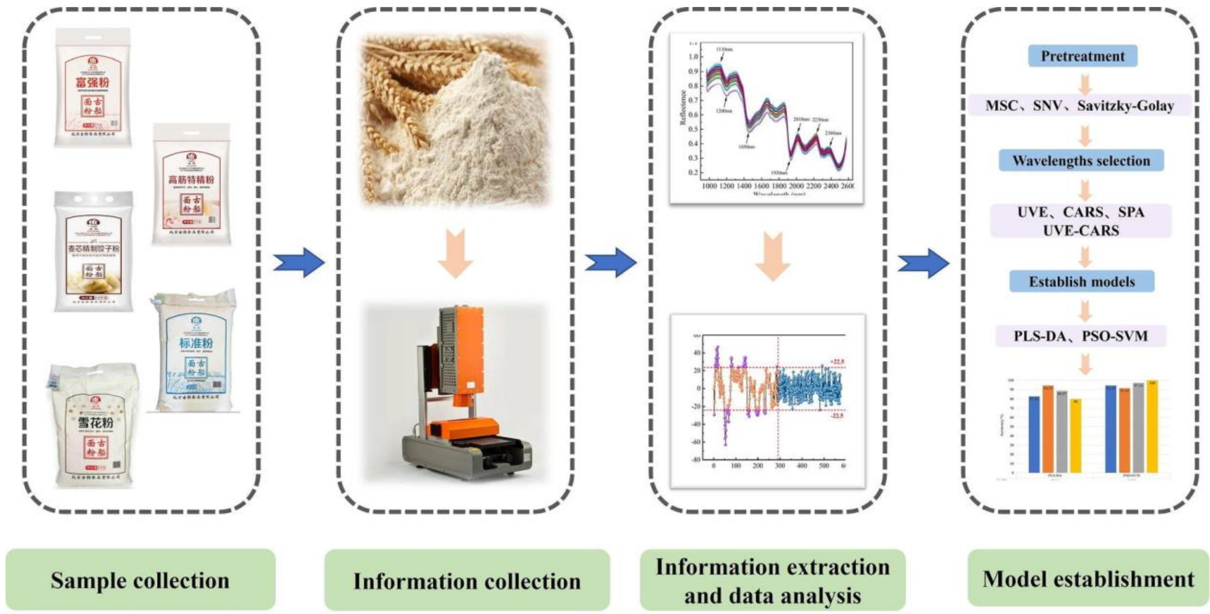


Figure: Application of HSI for wheat flour quality analysis.

6.1 Wheat Flour Quality Assessment

Researchers developed hyperspectral imaging systems for discriminating wheat flour grades using wavelengths from 968 to 2576 nm [36]. The study implemented Particle Swarm Optimization (PSO) combined with SVM for classification, achieving high accuracy in grade discrimination. Preprocessing techniques including MSC, SNV, and Savitzky-Golay smoothing enhanced model performance by reducing noise and improving spectral feature extraction [36].

6.2 Vegetable Oil Authentication

Hyperspectral imaging combined with machine learning successfully identified eight different vegetable oils and detected adulteration levels [41]. Random Forest models achieved the highest classification accuracy 98.9%) and demonstrated superior performance in quantifying adulteration in binary oil blends $R^2 > 0.992$, RMSE 2.75 [41]. The study highlighted hyperspectral imaging's potential as an alternative to traditional chemical analysis methods [41].

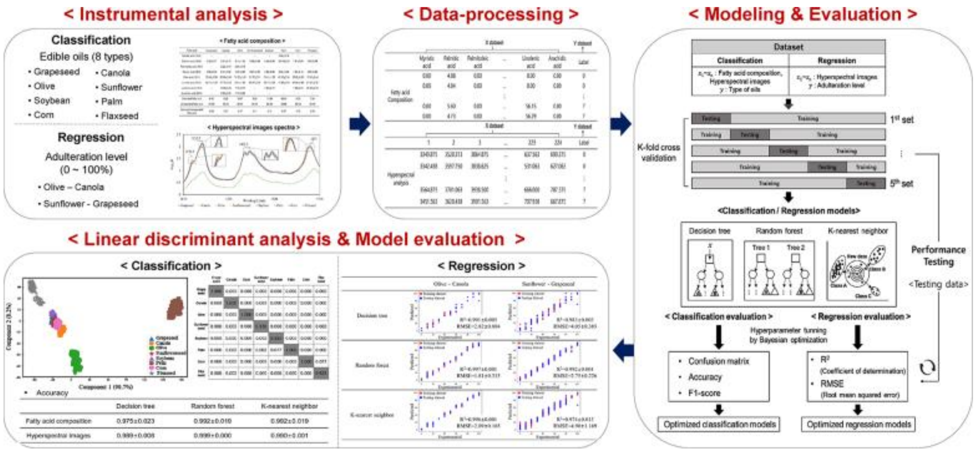


Figure: Application of HSI for detection of adulteration in edible oils.

6.3 Fruit Quality Evaluation

Near-infrared hyperspectral imaging (NIR-HSI) has been effectively employed to investigate the internal heterogeneity of apple fruit. In this study, NIR-HSI images were acquired from six transverse slices of each apple, with systematic sampling of 5–6 cylinders per slice. Principal Component Analysis (PCA) was used to select 141 representative samples from an initial dataset of 1056, which were further analyzed for dry matter content (DMC), total soluble sugars (TSC), fructose, glucose, sucrose, malic acid, and polyphenols through spectrophotometry and chromatography. Subsequently, leave-one-out Partial Least Squares (PLS) models were developed to predict spatial distribution of DMC ($Rcv^2 = 0.83$, RPD = 2.39) and TSC ($Rcv^2 = 0.81$, RPD = 2.20). Results highlighted pronounced within-fruit heterogeneity of both DMC and TSC. This approach demonstrated the potential of NIR-HSI as a rapid, non-destructive alternative to extensive chemical analysis for assessing spatial variation of key quality traits in apples, thereby improving fruit quality evaluation and management.

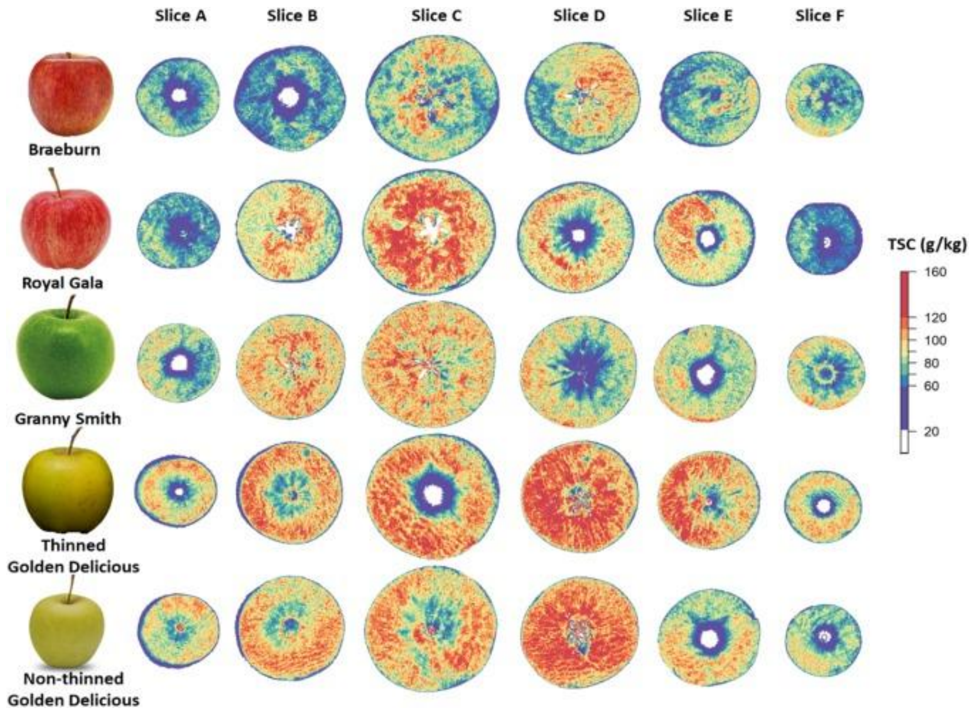


Figure: The distribution of total sugars content (TSC) in apple slices predicted by the LOO- PLS models developed based on the ROI averaged spectra.

6.4 Meat Safety and Quality

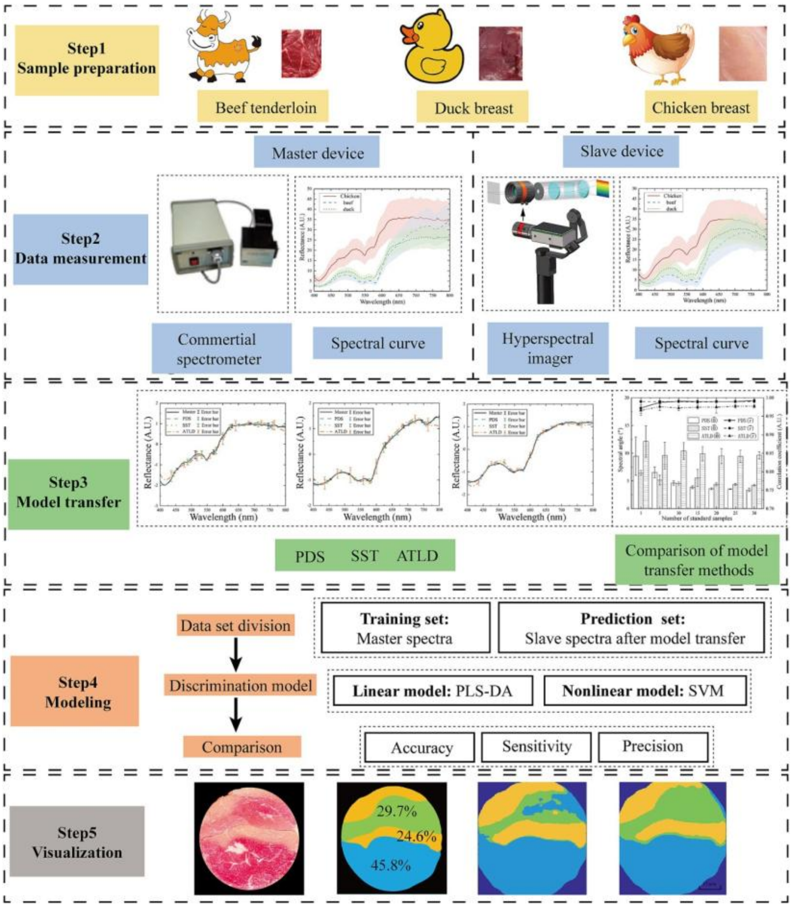


Figure: Application of HSI for authentication of meat.

Hyperspectral imaging systems successfully detected bacterial contamination, predicted total viable count TVC, and assessed chemical composition in various meat products [32]. Meat species adulteration poses significant risks to consumer interests and food safety. To address this, a portable push-broom hyperspectral imaging (HSI) system was developed, featuring a spectral resolution of 5 nm and a spatial resolution of 0.1 mm, with Raspberry Pi control for on-site rapid detection. A model transfer method was introduced to enhance generalization across instruments, ensuring robust application in diverse settings. Using spectral space transformation (SST) combined with support vector machine (SVM) classification, the system achieved an accuracy of 94.91% in detecting meat adulteration. Furthermore, visualization maps provided spatial distribution insights of adulterants. This portable HSI platform demonstrates strong potential as a reliable, non-destructive tool for real-time meat authentication and food quality control.

6.5 Food Residue Detection

Advanced applications include detecting liquid food residues (apple juice, coffee, cola, milk, tea) on textile surfaces using hyperspectral imaging [46]. Machine learning algorithms successfully classified different residue types, demonstrating the technology's versatility beyond direct food analysis [46]. In a study a filter-array-based hyperspectral imaging (HSI) system enhanced with a dynamic filtering demosaicking algorithm was developed to address these challenges. The method significantly improved spatial and spectral resolution, enabling image acquisition within 20 ms and demonstrating robust performance under high noise conditions. Tested on synthetic and real agricultural samples, the system achieved high precision in spectral reconstruction, particularly at critical color edges. By integrating a hyperspectral microfilter array with a smartphone imaging sensor, this approach highlights the feasibility of portable, low-cost, and rapid on-site monitoring of pesticide residues [47].

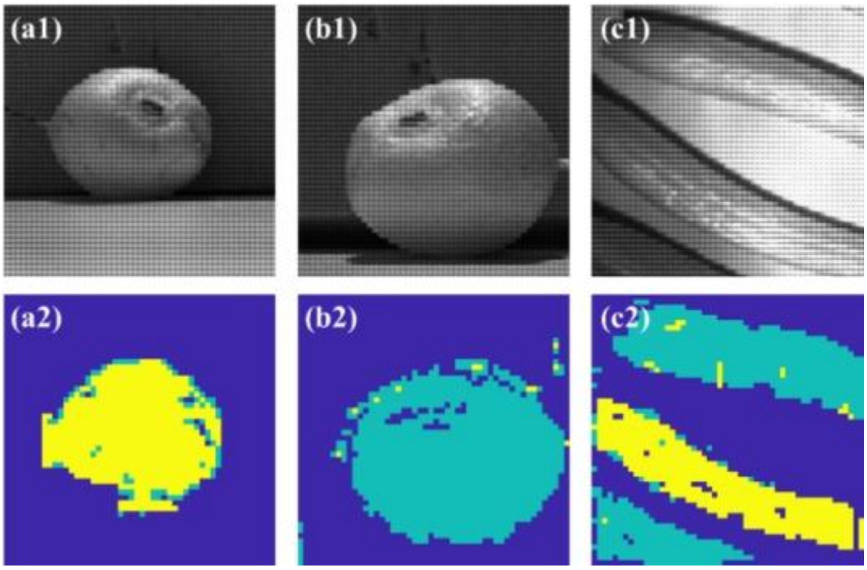


Figure: Visualization of pesticide residue detection via SVM classification. Original hyperspectral images (a1), (b1), and (c1) contrast with their classification counterparts (a2), (b2), and (c2), where classification colors purple for background, cyan for no pesticide, and yellow for pesticide presence. The setups show (a) a pesticide-treated sample, (b) an untreated sample, and (c) a mixed arrangement.

7. Conclusion

The integration of spectroscopy and hyperspectral imaging technologies represents a paradigm shift in food quality and safety assessment. These advanced optical sensing techniques provide rapid, non-destructive, and comprehensive analytical capabilities that surpass traditional methods in speed, accuracy, and objectivity. The synergy between spectroscopic technologies and machine learning algorithms has created unprecedented opportunities for real-time food monitoring throughout the supply chain.

Current applications span the entire spectrum of food analysis, from raw material assessment to finished product quality control. The technology's ability to simultaneously capture spatial distribution and spectral signatures enables detailed characterization of food properties that were previously unattainable. Machine learning integration has further enhanced these capabilities, providing automated analysis with human-level or superior accuracy.

Despite significant advances, challenges remain in terms of instrument costs, data complexity, and standardization across different platforms and applications. The transition from laboratory research to industrial implementation requires continued development of robust, cost-effective systems that can operate reliably in demanding production environments.

Future research directions should focus on three key areas: multimodal integration of spectroscopic technologies for comprehensive analysis, development of portable edge computing devices for field applications, and advancement of AI driven analysis systems that can adapt to diverse food matrices and conditions. The establishment of standardized protocols and comprehensive spectral databases will further accelerate technology adoption and improve inter-laboratory reproducibility.

The ultimate goal is establishing a high-precision, sustainable food quality inspection system that spans from production to consumption, ensuring food safety, reducing waste, and meeting the evolving demands of consumers and regulatory bodies. As these technologies continue to mature, they will undoubtedly play an increasingly central role in securing global food supply chains and protecting public health.

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