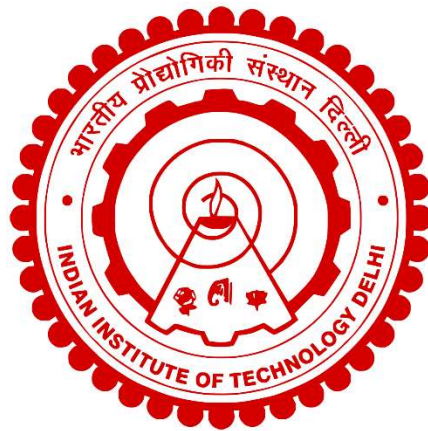


ENGINEERING TRANSITIONAL DYSPHAGIC FOOD

SATHEESHKANTH SSM



**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2025

© Indian Institute of Technology Delhi (IITD), New Delhi, 2025

ENGINEERING TRANSITIONAL DYSPHAGIC FOOD

by

SATHEESHKANTH SSM

Centre for Rural Development and Technology

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

CERTIFICATE

This is to certify that the thesis entitled, “**Engineering Transitional Dysphagic Food**” being submitted by **Mr. Satheeshkanth SSM** to the **Indian Institute of Technology Delhi** for the award of “**Doctor of Philosophy**” is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of the thesis. To the best of our knowledge, the results contained in the thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

Prof. (Dr.) Jatindra K Sahu

Centre for Rural Development & Technology
Indian Institute of Technology Delhi

Prof. (Dr.) Satya Narayan Naik

Centre for Rural Development & Technology
Indian Institute of Technology Delhi

ACKNOWLEDGEMENT

Despite my PhD journey being challenging, it has been extremely satisfying. I would like to express my appreciation and gratitude to all those who supported me throughout these years. Firstly, I am grateful to Prof Jatindra K Sahu and Prof S N Naik, my mentors during my PhD program. Throughout my Ph.D., they consistently showed interest in my research and entrusted me to work under their supervision. Their guidance, advice, and motivation were priceless resources. I thank my SRC members – Prof Vivek Kumar (Chairperson), Prof Hariprasad P., and Prof. James Gomes (Subject Experts) for their supportive feedback during my candidature milestones. My sincere thanks to the Director, Registrar, Deans, Centre Head, and Professors for their valuable support.

I express my deepest and most heartfelt gratitude to Prof. Jatindra K Sahu, not only my PhD supervisor, but also a well-wisher, mentor, teacher, and friend. Throughout this journey, you have been a guiding light, not just in research but in life. In moments of academic confusion, your clarity uplifted me. In phases of self-doubt, it was your unwavering belief that kept me going. Your thoughtful feedback, your patience, and your quiet encouragement have meant far more than words can express. But what has touched me even more deeply is the support you showed for me beyond academics. You stood by me not only as a supervisor but also as someone who genuinely cared during moments when personal struggles felt heavier than professional ones. Your kind words, gestures, and understanding during those times gave me the strength to rise and continue. That kind of support is rare, and I will carry it in my heart always. I still remember those long research discussions that quietly turned into life talks moments that taught me far more than books ever could. You never treated me like 'just a student,' but as someone whose growth both academic and personal mattered to you. That trust empowered me more than you know. Overwhelmed with gratitude, I thank you for shaping not just my research but my resilience, not just my thesis but my thinking, and for being there in ways that truly made this journey human, meaningful, and unforgettable.

I feel truly blessed to work under your supervision, Prof. S. N. Naik. Words are not enough to thank you for your immense support and constant encouragement throughout my research journey. I feel positive and energetic whenever I meet you especially because your ever-smiling face radiates positivity and inspires everyone around you. Your calm demeanor and

kind words have helped me stay focused even during challenging times, and your trust in me has given me the confidence to push my boundaries. Thank you for being a wonderful mentor and a source of motivation, both academically and personally. I express my sincere gratitude and appreciation to IIT Delhi and the Government of India for providing the scholarship for my doctoral studies. I take this opportunity to acknowledge my lab mates, my roommates, the lab staff, IHRF, the institute staff, the CRDT office staff and friends. Your unwavering dedication and willingness to go above and beyond have made a world of difference to me, and I cannot thank you enough. I sincerely thank the Dysphagia Research Society (DRS), International Dysphagia Diet Standardisation Initiative (IDDSI), International Union of Nutritional Sciences (IUNS), Indian Speech and Hearing Association (ISHA), Springer Nature, Australian Institute of Food Science and Technology (AIFST), Association of Food Scientists and Technologists (India) (AFSTI) for supporting and recognising my research work with prestigious awards. I gratefully thank the Industrial Research & Development (IRD) Unit and IIT Delhi for awarding me the Research Excellence Award and providing the travel grant to attend the international conference. Your encouragement inspires me to continue striving for excellence in the field.

I sincerely thank the IIT Delhi Library and CSC for providing excellent resources and a supportive environment that greatly contributed to my research journey. My heartfelt thanks to the doctors and staff of IIT Delhi Hospital for their dedicated support in my research and their compassionate care for my health. I gratefully thank Karakoram Hostel and its dedicated staff members for their unwavering support and care, especially during the challenging times of the COVID-19 pandemic. I thank the housekeeping staff and security team for their hard work and support in keeping the campus clean and safe during my time at IIT Delhi. I thank the chemical vendors, CRF, NRF, CRF-Sonipat campus staff, FITT for patent filling and equipment engineers for their timely support and assistance, which played a vital role in my research work. I sincerely thank IITD-NSS for giving me the opportunity to continue my passion for societal service through meaningful community engagement. I would like to thank the people of Delhi for their warmth and support throughout my PhD journey, which made my experience truly memorable.

I am particularly grateful to my parents, teachers and sister, who have been my unwavering support system and motivation. I am truly grateful to my sister, Kuttypapa, for her unwavering mental support and unconditional love throughout my journey. In moments

when everything felt overwhelming, you were there listening without judgment, comforting without words, and believing in me when I couldn't believe in myself.

I am deeply grateful to my family and relatives, whose constant encouragement and unconditional love gave me the courage to keep going when things felt impossible. To my friends, thank you for your laughter, late-night talks, and unshakeable faith in me. I offer my deepest gratitude to my father, mother and grandparents, who gave me the greatest gift anyone could give: a strong foundation to grow, dream, and achieve. Thank you for raising me with love, patience, and unwavering belief. Your sacrifices, silent strength, and constant encouragement have shaped who I am today. I am truly inspired by my school and college students - your enthusiasm, curiosity, and eagerness to learn motivated me every single day. Teaching you ignited a deeper passion within me to grow, explore, and contribute more, which ultimately led me to pursue my PhD. Thank you for being the driving force behind this journey..(Words alone cannot express my gratitude, so I've shared my memories and heartfelt thank-you note here - <https://myphdplans.blogspot.com/>)

A very special thanks to my wife, Nanahundir Butter Biscuit, who is my rock and continues to help me stay strong and focused throughout my academic journey. Your unwavering support, quiet sacrifices, and constant belief in me carry me through the toughest days. Your presence gives me strength, your words bring me peace, and your love reminds me that I am never alone. You believe in me even when I struggle to believe in myself, and that belief gives me the courage to keep moving forward. Your love is a steady light, comforting me in difficult moments and sharing in my joy during the best ones.

I thank God for the silent strength, unwavering guidance, and for providing positive people in my life throughout this journey. In every challenge and triumph, divine grace has been my constant companion, and for that, I remain humbly grateful.

When I stumbled, you were all there, lifting me, believing in me, and walking beside me. This journey has been long and full of challenges, but I never walked it alone. From the bottom of my heart, thank you. *Aski thengo moro monnu bor ಎಲ್ಲರೂ dhannu kalallares.*

I wish to dedicate my thesis to my family and teachers.

(Satheeshkanth SSM)

Abstract

Dysphagia is a pathophysiological condition that disrupts the deglutitive process, affecting oral, pharyngeal, or oesophageal phases due to neurological, muscular, or structural abnormalities. It leads to complications such as choking, pneumonia, and malnutrition that increase the fatality rate and necessitate comprehensive diagnostic and therapeutic interventions. Food texture modification is one of the key medical interventions that greatly aids in dysphagia management practices. Recent advancements in additive manufacturing have revolutionised dysphagia management by enabling precise control over the textural and structural properties of transitional foods with customized nutrition that benefit the elderly dysphagia population. Transitional foods are unique in that they change from a solid to a swallow-safe, soft semi-solid when exposed to moisture or heat. Research in this area is limited, mainly due to challenges in combining nutritious ingredients with suitable processing methods. While 3D printing has been used to create dysphagia-friendly foods in previous studies, meeting the IDDSI's strict size requirements for soft, bite-sized pieces remains difficult, and the conversion process of transitional foods is often overlooked. However, transitional foods are ideal as ready-to-eat options, offering extended shelf life and reducing the workload for caregivers, making them especially useful in residential healthcare settings. This study systematically evaluates the development of plant-based soft and bite-sized 3D-printed transitional food using treated horse gram flour (THGF) and defatted chia seed flour (DCF), optimised for compliance with the International Dysphagia Diet Standardisation Initiative (IDDSI) guidelines.

Initial studies focused on investigating strategies that improve the printability of horse gram with the addition of functional texture modifier chia flour. Each modification (pretreatment, CSF level) was tested separately, measuring water-holding, viscosity, digestibility, and textural properties. Results were compared to untreated and unmodified controls. Pretreatment protocols involving germination (24–36 h, 30±1 °C) and roasting (150±5 °C, 7 min) enhanced the functional properties of HGF, increasing water-holding capacity by 3.43 times compared to raw flour, while 10–15% CSF substitution improved rheological performance by reducing apparent viscosity from 28.9±0.2 Pa.s to 14.45±0.17 Pa.s. Pretreatment also increased the protein digestibility of HGF from 72.4±1.6 to 78.1±1.1%. Increasing CSF beyond 15% led to structural deformation due to lower yield stress and weak gelation. Textural analysis demonstrated IDDSI Level 6 compliance, with

hardness reduction from 6.77 ± 0.24 N to 3.86 ± 0.10 N through CSF substitution, validated by IDDSI platform tests.

To address the dimensional accuracy and stability challenges, the effect of defatted chia flour and printing parameters in improving printing performance was investigated in further objectives. The defatting process improved the structural and nutritional properties of the constructs. The extracted omega-3-rich chia oil (Omega-3 concentration: $59.1 \pm 0.4\%$) was also fortified in the formulation. Each parameter (printing, post-processing) was optimized and its effects measured on dimensional accuracy, textural properties, and rehydration. Printed and moulded constructs were directly compared for these outcomes. Through 3D printing experiments, printer parameters such as nozzle diameter, speed, and layer height % were varied and optimised for better-printed food construct. At fixed total solids of 28%, the formulation was prepared and printed with a 0.8 mm diameter nozzle at 90%-layer height and at a speed range of 8 to 12 $\text{mm} \cdot \text{s}^{-1}$; it showed more than 90%-dimensional accuracy with a lesser deformation percentage ($<7\%$).

Post-processing techniques are crucial in transforming the construct into a ready-to-eat transitional food construct. RTE transitional foods simplify manufacturing, reducing the need for skilled labor and allowing for centralized, industrial production. The combination of microwave (MW) treatment and freeze-drying (FD) was adopted in the transitional product development process to improve the structural stability and rehydration characteristics of the constructs. Through shape recovery percentage during rehydration, the microwave treatment parameters (900W; 120s) were optimized. Mathematical modeling of the rehydration curve was done and the Pilosof model identified as the best curve fit for moulded (absorption rate constant, $k = 0.051$) and printed construct (absorption rate constant, $k = 0.11$). Printed constructs had more void space so printed constructs rehydrated faster than moulded constructs. By decreasing the infill percent (25%), the hardness of the fresh and rehydrated 3D printed constructs hardness was reduced than the hardness of moulded constructs significantly. Texture attributes of different chewing orientations reveal the unique characteristics of printed constructs that have two different textural profiles, whereas moulded constructs possess only one feature.

Additionally, with the aim of scaling up the product into the market, this study explored consumer perception, shelf life, digestibility, and nutritional profiling of the developed

transitional dysphagic food. Instrumental analysis was performed and validated with real-time studies to overcome the irregularities with the IDDSI platform test. Bolus rheology studies demonstrated enhanced cohesiveness in printed constructs, exhibiting 34% lower hysteresis energy ($4197 \pm 87 \text{ Pa}\cdot\text{s}^{-1}\cdot\text{cm}^3$) compared to moulded variants ($4995 \pm 127 \text{ Pa}\cdot\text{s}^{-1}\cdot\text{cm}^3$), reducing bolus fragmentation risks during swallowing. Oral processing studies using electromyography revealed 32.5% reduction in chewing time and 34.7% fewer chew counts compared to moulded constructs, correlating with 56% lower hardness during top-press compression. Sensory analysis results revealed that, increased porosity (25% infill density) enhanced soup absorption capacity and improved the perceived taste intensity and mouthfeel. Tribological analysis confirmed smoother bolus transit in printed constructs, exhibiting 0.619–0.689 friction coefficients. Accelerated shelf-life testing predicted 45 days of shelf life for developed constructs under vacuum packaging at room temperature. Normal packaging showed rancidity development after 30 days and was unsuitable for consumption.

Development of printing cartridges with extended shelf-life increases the feasibility of printing operations at a mass level. Even though low-temperature storage facilitates shelf-life extension, due to syneresis, water separation from the formulation alters its flow property and affects printability. To control the syneresis, functional hydrocolloid chia mucilage at different concentration was added and investigated the printability of bioformulation with respect to widely used xanthan gum hydrocolloid. Due to the increased syneresis during freezing cycle, increased the flow point and it decreased the extrusion rate from 2.22 ± 0.14 to $0.97 \pm 0.27 \text{ g}\cdot\text{min}^{-1}$. Meanwhile, the optimized concentrations of 2% chia mucilage and 0.5% xanthan gum provided good-quality prints. Through printing performance with reference to the formulations FC0, 2% chia mucilage incorporation was chosen for long-term storage studies. In long-term storage studies, Normal and vacuum-packed samples were stored under $4 \pm 1^\circ\text{C}$ refrigerated condition, and observed their physicochemical properties changes for up to 60 days. Through storage kinetic modelling shelflife was predicted. Control formulations were safe and maintained quality for up to 8 days, whereas normally packed up to 12 days and vacuum-packed formulations sustained up to 27 days with good printability. Addition of ascorbic acid and vacuum packaging increased the activation energy from 331 ± 11 to $427 \pm 21 \text{ KJ}\cdot\text{mol}^{-1}$. Thus, vacuum packed formulations were more stable than the normally packed control ones. During storage, microbial growth increased the titratable acidity from 0.64 ± 0.11 to $1.2 \pm 1.07\%$ and reduced pH from 6.6 to 5.9, which leads to syneresis. Chia mucilage maintained the flow point and

extrusion rate in the range of 758 ± 25 Pa and 2.32 ± 0.17 g.min⁻¹ with 90% printing accuracy up to 45 days under vacuum packaging. Ascorbic acid addition and vacuum packaging extended the shelf-life of the printing cartridge, whereas the addition of chia mucilage maintained the printing quality throughout the storage. For a better understanding of the overall methodology, the study systematically varied key ingredients and processing treatments individually and in combination and assessed their effects using standardized tests for texture, rheology, rehydration, shelf-life, and sensory qualities. Each modification was compared to appropriate controls, and both instrumental and sensory analyses, along with real-time and accelerated shelf-life studies, ensured robust and practical results. This approach allowed the specific impact of each variable to be clearly identified.

These findings establish 3D printing as a transformative approach for dysphagia food design, combining IDDSI compliance with enhanced nutritional retention and oral processing efficiency. This study is technically significant because it systematically develops plant-based, 3D-printed transitional foods for dysphagia that meet IDDSI standards, optimize nutrition and texture, and ensure shelf stability. It advances prior work by thoroughly addressing the food's safe transition during swallowing, validating printability and storage for industrial use, and using comprehensive instrumental and sensory analyses to confirm safety and consumer acceptability. This comprehensive investigation establishes 3D printing as a transformative technology for dysphagia food production, successfully addressing the tripartite challenges of nutritional adequacy, textural safety, and industrial scalability. These findings provide a robust scientific foundation for advancing dysphagia management through additive manufacturing technologies, promising improved patient outcomes and reduced healthcare burdens associated with swallowing disorders.

Keywords: *Dysphagia; IDDSI; Food printing; Vegan transitional food*

सारांश

डिस्फेगिया एक पैथोफिजियोलॉजिकल स्थिति है जो न्यूरोलॉजिकल, मांसपेशियों या संरचनात्मक असामान्यताओं के कारण मौखिक, ग्रसनी या अन्नप्रणाली के चरणों को प्रभावित करते हुए, निगलने की प्रक्रिया को बाधित करती है। यह घुटन, निमोनिया और कुपोषण जैसी जटिलताओं को जन्म देता है जो मृत्यु दर को बढ़ाता है और व्यापक नैदानिक और चिकित्सीय हस्तक्षेप की आवश्यकता होती है। खाद्य बनावट संशोधन प्रमुख चिकित्सा हस्तक्षेपों में से एक है जो डिस्फेगिया प्रबंधन प्रथाओं में बहुत सहायता करता है। एडिटिव मैन्युफैक्चरिंग में हाल की प्रगति ने बुजुर्ग डिस्फेगिया आबादी को लाभ पहुंचाने वाले अनुकूलित पोषण के साथ संक्रमणकालीन खाद्य पदार्थों की बनावट और संरचनात्मक गुणों पर सटीक नियंत्रण को सक्षम करके डिस्फेगिया प्रबंधन में क्रांति ला दी है। यह अध्ययन अंकुरित-भुने हुए घोड़े के आटे (THGF) और वसा रहित चिया बीज के आटे (DCF) का उपयोग करके पौधे-आधारित नरम और काटने के आकार के 3D-मुद्रित भोजन के विकास का व्यवस्थित रूप से मूल्यांकन करता है, जो अंतर्राष्ट्रीय डिस्फेगिया आहार मानकीकरण पहल (IDDSI) दिशानिर्देशों के अनुपालन के लिए अनुकूलित है। प्रारंभिक अध्ययनों में उन रणनीतियों की जांच पर ध्यान केंद्रित किया गया जो कार्यात्मक बनावट संशोधक चिया आटे के साथ कुल्थी चने की प्रिंटेबिलिटी में सुधार करते हैं। अंकुरण (24-36 घंटे, 30 ± 1 °C) और भूने (150 \pm 5 °C, 7 मिनट) से जुड़े प्रीट्रीटमेंट प्रोटोकॉल ने HGF के कार्यात्मक गुणों को बढ़ाया, कच्चे आटे की तुलना में पानी धारण करने की क्षमता में 3.43 गुना वृद्धि की, जबकि 10-15% CSF प्रतिस्थापन ने स्पष्ट चिपचिपाहट को 28.9 \pm 0.2 Pa.s से 14.45 \pm 0.17 Pa.s तक कम करके रियोलॉजिकल प्रदर्शन में सुधार किया। प्रीट्रीटमेंट ने HGF की प्रोटीन पाचन क्षमता को 72.4 \pm 1.6 से 78.1 \pm 1.1% तक बढ़ा दिया। 15% से अधिक CSF बढ़ाने से कम उपज तनाव और कमजोर जेलेशन के कारण संरचनात्मक विरूपण हुआ। बनावट विश्लेषण ने IDDSI स्तर 6 अनुपालन का प्रदर्शन किया, जिसमें CSF प्रतिस्थापन के माध्यम से कठोरता में 6.77 \pm 0.24 N से 3.86 \pm 0.10 N तक की कमी आई, जिसे IDDSI प्लेटफॉर्म परीक्षणों द्वारा मान्य किया गया।

आयामी सटीकता और स्थिरता चुनौतियों का समाधान करने के लिए, मुद्रण प्रदर्शन को बेहतर बनाने में वसा रहित चिया आटे और मुद्रण मापदंडों के प्रभाव की आगे के उद्देश्यों में जांच की गई। वसा रहित प्रक्रिया ने निर्माणों के संरचनात्मक और पोषण संबंधी गुणों में सुधार किया। निकाले गए ओमेगा-3 से भरपूर चिया तेल (ओमेगा-3 सांद्रता: 59.1 \pm 0.4%) को भी फॉर्मूलेशन में फोर्टिफाइड किया गया था। 3D प्रिंटिंग प्रयोगों के माध्यम से, नोजल व्यास, गति और परत की ऊंचाई % जैसे प्रिंटर मापदंडों को अलग-अलग किया गया और बेहतर मुद्रित खाद्य निर्माण के लिए अनुकूलित किया गया। 28% के निश्चित कुल ठोस पदार्थों पर, फॉर्मूलेशन तैयार

किया गया और 90%-परत की ऊंचाई पर 0.8 मिमी व्यास वाले नोजल के साथ और 8 से 12 मिमी.एस-1 की गति सीमा पर मुद्रित किया गया; इसने कम विरूपण प्रतिशत (<7%) के साथ 90% से अधिक आयामी सटीकता दिखाई। निर्माण को खाने के लिए तैयार संक्रमणकालीन खाद्य निर्माण में बदलने के लिए पोस्ट-प्रोसेसिंग तकनीक महत्वपूर्ण हैं। आरटीई संक्रमणकालीन खाद्य पदार्थ विनिर्माण को सरल बनाते हैं, कुशल श्रम की आवश्यकता को कम करते हैं और केंद्रीकृत, औद्योगिक उत्पादन की अनुमति देते हैं। निर्माण की संरचनात्मक स्थिरता और पुनर्जलीकरण विशेषताओं में सुधार करने के लिए संक्रमणकालीन उत्पाद विकास प्रक्रिया में माइक्रोवेव (MW) उपचार और फ्रीज-ड्राइंग (FD) के संयोजन को अपनाया गया था। पुनर्जलीकरण के दौरान आकार पुनर्प्राप्ति प्रतिशत के माध्यम से, माइक्रोवेव उपचार मापदंडों (900W, 120s) को अनुकूलित किया गया। पुनर्जलीकरण वक्र का गणितीय मॉडलिंग किया गया और पिलोसोफ मॉडल को मोल्डेड (अवशोषण दर स्थिरांक, $k = 0.051$) और मुद्रित निर्माण (अवशोषण दर स्थिरांक, $k = 0.11$) इनफिल प्रतिशत (25%) को कम करके, ताजा और पुनर्जलीकृत 3D मुद्रित संरचनाओं की कठोरता मोल्डेड संरचनाओं की कठोरता की तुलना में काफी कम हो गई थी। विभिन्न चबाने वाले अभिविन्यासों की बनावट विशेषताएँ मुद्रित संरचनाओं की अनूठी विशेषताओं को प्रकट करती हैं जिनमें दो अलग-अलग बनावट प्रोफाइल होती हैं, जबकि मोल्डेड संरचनाओं में केवल एक विशेषता होती है। इसके अतिरिक्त, उत्पाद को बाजार में लाने के उद्देश्य से, इस अध्ययन ने उपभोक्ता धारणा, शेल्फ लाइफ, पाचनशक्ति और विकसित संक्रमणकालीन डिस्फेगिक भोजन की पोषण संबंधी रूपरेखा का पता लगाया। IDDSI प्लेटफॉर्म परीक्षण के साथ अनियमितताओं को दूर करने के लिए वास्तविक समय के अध्ययनों के साथ वाद्य विश्लेषण किया गया और मान्य किया गया। बोलस रियोलॉजी अध्ययनों ने मुद्रित संरचनाओं में बढ़ी हुई सामंजस्यता का प्रदर्शन किया, मोल्डेड वेरिएंट ($4995 \pm 127 \text{ Pa/s}\cdot\text{cm}^3$) की तुलना में 34% कम हिस्टैरिसिस ऊर्जा ($4197 \pm 87 \text{ Pa/s}\cdot\text{cm}^3$) प्रदर्शित की, जिससे निगलने के दौरान बोलस विखंडन जोखिम कम हो गया। इलेक्ट्रोमायोग्राफी का उपयोग करके मौखिक प्रसंस्करण अध्ययनों से पता चला कि मोल्डेड कंस्ट्रक्ट्स की तुलना में चबाने के समय में 32.5% की कमी और 34.7% कम चबाने की गिनती, टॉप-प्रेस संपीड़न के दौरान 56% कम कठोरता के साथ सहसंबंधित है। संवेदी विश्लेषण के परिणामों से पता चला कि, बढ़ी हुई छिद्रता (25% इनफिल घनत्व) ने सूप अवशोषण क्षमता को बढ़ाया और कथित स्वाद की तीव्रता और मुंह के स्वाद में सुधार किया। ट्रिबोलॉजिकल विश्लेषण ने मुद्रित निर्माणों में चिकनी बोलस पारगमन की पुष्टि की, जिसमें 0.619-0.689 घर्षण गुणांक प्रदर्शित हुए। त्वरित शेल्फ-लाइफ परीक्षण ने कमरे के तापमान पर वैक्यूम पैकेजिंग के तहत विकसित निर्माणों के लिए 45 दिनों के शेल्फ जीवन की भविष्यवाणी की। सामान्य पैकेजिंग ने 30 दिनों के बाद बासीपन का विकास दिखाया और उपभोग के लिए अनुपयुक्त था।

विस्तारित शेल्फ-लाइफ के साथ प्रिंटिंग कार्ट्रिज के विकास से बड़े पैमाने पर प्रिंटिंग संचालन की व्यवहार्यता बढ़ जाती है। भले ही कम तापमान पर भंडारण शेल्फ-लाइफ एक्सटेंशन की सुविधा देता है, लेकिन सिनेरेसिस के कारण, फॉर्मूलेशन से पानी का पृथक्करण इसके प्रवाह गुण को बदल देता है और प्रिंटेबिलिटी को प्रभावित करता है। सिनेरेसिस को नियंत्रित करने के लिए, विभिन्न सांद्रता में कार्यात्मक हाइड्रोकोलोइड चिया म्यूसिलेज को जोड़ा गया और व्यापक रूप से उपयोग किए जाने वाले ज़ैथन गम हाइड्रोकोलोइड के संबंध में बायोफॉर्मूलेशन की प्रिंटेबिलिटी की जांच की गई। फ्रीजिंग चक्र के दौरान बढ़ी हुई सिनेरेसिस के कारण, प्रवाह बिंदु में वृद्धि हुई और इसने एक्सट्रूजन दर को 2.22 ± 0.14 से घटाकर $0.97 \pm 0.27 \text{ g.min}^{-1}$ कर दिया। इस बीच, 2% चिया म्यूसिलेज और 0.5% ज़ैथन गम की अनुकूलित सांद्रता ने अच्छी गुणवत्ता वाले प्रिंट प्रदान किए। FCO फॉर्मूलेशन के संदर्भ में प्रिंटिंग प्रदर्शन के माध्यम से, 2% चिया म्यूसिलेज समावेश को दीर्घकालिक भंडारण अध्ययनों के लिए चुना गया था। दीर्घकालिक भंडारण अध्ययनों में, सामान्य और वैक्यूम-पैक नमूनों को $4 \pm 1^\circ\text{C}$ रेफ्रिजरेटेड स्थिति में संग्रहीत किया गया था, और 60 दिनों तक उनके भौतिक-रासायनिक गुणों में परिवर्तन देखा गया था। भंडारण गतिज मॉडलिंग के माध्यम से शेल्फलाइफ की भविष्यवाणी की गई थी। नियंत्रण फॉर्मूलेशन सुरक्षित थे और 8 दिनों तक गुणवत्ता बनाए रखते थे, जबकि सामान्य रूप से पैक किए गए 12 दिनों तक और वैक्यूम-पैक फॉर्मूलेशन अच्छी प्रिंटेबिलिटी के साथ 27 दिनों तक टिके रहे। भंडारण के दौरान, सूक्ष्मजीवों की वृद्धि ने अनुमापनीय अम्लता को 0.64 ± 0.11 से $1.2 \pm 1.07\%$ तक बढ़ा दिया और pH को 6.6 से 5.9 तक घटा दिया, जिससे तालमेल पैदा हुआ। चिया म्यूसिलेज ने वैक्यूम पैकेजिंग के तहत 45 दिनों तक 90% मुद्रण सटीकता के साथ $758 \pm 25 \text{ Pa}$ और $2.32 \pm 0.17 \text{ g.min}^{-1}$ की सीमा में प्रवाह बिंदु और एक्सट्रूजन दर को बनाए रखा। एस्कॉर्बिक एसिड के अतिरिक्त और वैक्यूम पैकेजिंग ने प्रिंटिंग कार्ट्रिज के शेल्फ-लाइफ को बढ़ाया, जबकि चिया म्यूसिलेज के अतिरिक्त ने पूरे भंडारण के दौरान मुद्रण की गुणवत्ता को बनाए रखा। ये निष्कर्ष 3D प्रिंटिंग को डिस्फेगिया खाद्य डिजाइन के लिए एक परिवर्तनकारी दृष्टिकोण के रूप में स्थापित करते हैं, जो IDDSI अनुपालन को बेहतर पोषण प्रतिधारण और मौखिक प्रसंस्करण दक्षता के साथ जोड़ता है। यह व्यापक जांच डिस्फेगिया खाद्य उत्पादन के लिए एक परिवर्तनकारी तकनीक के रूप में 3D प्रिंटिंग को स्थापित करती है, जो पोषण पर्याप्तता, बनावट सुरक्षा और औद्योगिक मापनीयता की त्रिपक्षीय चुनौतियों को सफलतापूर्वक संबोधित करती है। ये निष्कर्ष एडिटिव मैनुफैक्चरिंग प्रौद्योगिकियों के माध्यम से डिस्फेगिया प्रबंधन को आगे बढ़ाने के लिए एक मजबूत वैज्ञानिक आधार प्रदान करते हैं, जिससे रोगियों के बेहतर परिणाम और निगलने संबंधी विकारों से जुड़े स्वास्थ्य सेवा बोझ में कमी का वादा किया जाता है।

कीवर्ड: डिस्फेगिया; IDDSI; खाद्य मुद्रण; शाकाहारी संक्रमणकालीन भोजन

CONTENT

	CERTIFICATE	<i>i</i>
	ACKNOWLEDGEMENT	<i>ii-iv</i>
	ABSTRACT	<i>v -xi</i>
	TABLE OF CONTENT	<i>xii-xviii</i>
	LIST OF FIGURES	<i>xix-xxiv</i>
	LIST OF TABLES	<i>xxv-xxvi</i>
	LIST OF ABBREVIATIONS	<i>xxvii-xxix</i>
Chapter I	Background, Aim and Objectives	1-7
	1.1 Background	1-5
	1.2 Research Questions	5
	1.3 Research Aim and Objectives	6
	1.4 Thesis Structure	6
Chapter II	Literature Review	8-23
	2.1 Background	8
	2.2 Dysphagia	8
	2.3 International Dysphagia Diet Standardization Initiative	11-12
	2.3.1 Transitional foods	12
	2.4 State-of-art of 3D Food Printing in Development of Dysphagia Diets	12-14
	2.4.1 Hydrocolloids in 3DFP for dysphagia foods	18
	2.5 Plant-based Ingredients for Dysphagia Diet Formulation	20-22
	2.6 Conclusion and Future Directions	22-23
Chapter III	Investigation on the 3D Printability of Horse Gram (<i>Macrotyloma uniflorum</i>) and Chia Seed(<i>Salvia hispanica L.</i>) Flour to Engineer Soft and Bite-Sized Dysphagia Food	24-46
	3.1 Background of the chapter	24
	3.2 Materials and Methods	25
	3.2.1 Materials	25

3.2.2	Preparation of protein-rich composite formulations	25
3.2.3	Water holding capacity	26
3.2.4	Functional group Analysis	27
3.2.5	Rheological characterization of formulations	27
3.2.6	Modelling and 3D printing process	27
3.2.7	Printing performance	27
3.2.8	IDDSI Tests	28
3.2.9	Microstructural analysis	28
3.2.10	Texture Profile Analysis	28
3.2.11	Statistical analysis	28
3.3	Results and Discussion	29
3.3.1	Water holding capacity of the formulations	29
3.3.2	FTIR analysis of HGF	30
3.3.3	Rheological characterization of the formulations	31
3.3.3.1	Shear thinning behavior	31
3.3.3.2	Viscoelastic properties	31-32
3.3.3.3	Shear recoverability	33
3.3.4	3D Printing Performance	35
3.3.4.1	Correlation of rheological characteristics and printing performance of formulation	38
3.3.5	IDDSI Test	40
3.3.6	Microstructural analysis of printed constructs	42
3.3.7	Texture Profile of the printed constructs	43
3.4	Key Findings of this Objective	45-46
Chapter IV	Investigation on the effect of printing and post-processing parameters on the textural properties of transitional food	47-92
4.1	Background of the chapter	47
4.2	Materials and Methods	48
4.2.1	Materials	48
4.2.2	Preparation of printing formulation	49

4.2.3	Rheological characterization of formulation	49
4.2.4	3D printing and molding of developed formulation	49-51
4.2.5	Process optimization of the bioformulation	52
4.2.6	Post-processing of constructs	53
4.2.7	The IDDSI Test	54
4.2.8	Textural properties evaluation of developed constructs	54
4.2.9	Internal and external surface image analysis	54
4.2.9.1	Internal surface morphology	55
4.2.9.2	External surface morphology	55
4.2.10	Sensory analysis of rehydrated constructs	55
4.2.11	Statistical analysis	55
4.3	Results and Discussion	56
4.3.1	Characteristics of raw material	56
4.3.2	Rheological characteristics of composite flour and printing formulation	58-62
4.3.3	Printing performance of the developed formulation	62
4.3.3.1	Effect of total solids and printing parameters on the extrusion yield and printing score of the bioformulation	63
4.3.3.2	Optimization of process variables with model validation	70
4.3.4	Drying and rehydration characteristics of molded and 3D printed constructs	71
4.3.4.1	Rehydration kinetics of moulded and printed constructs	75-79
4.3.5	IDDSI test of developed construct	80-81
4.3.6	Textural attributes of developed molded and	83-87

	printed constructs	
	4.3.7 Surface morphology of treated and untreated constructs	88
	4.3.8 Sensory analysis of rehydrated constructs	90
	4.4 Key Findings of this Objective	92
Chapter V	Analyzing the <i>in-vitro</i> Digestion, IDDSI Platform Tests, Consumer Perception, and Shelf life of the Developed Transitional Dysphagic Vegan Meat	93-127
5.1	Background of the chapter	93
5.2	Materials and Methods	94
5.2.1	Materials	94
5.2.2	Preparation of texturized transitional vegan meat	94
5.2.2.1	Bioformulation preparation	94
5.2.2.2	Processing methodology of transitional vegan meat	95
5.2.3	Implementation of IDDSI Platform test on moulded and printed constructs	97
5.2.4	Instrumental analysis of developed construct	98
5.2.4.1	Texture profile analysis of developed constructs	98
5.2.4.2	Bolus rheology of constructs	99
5.2.4.3	Mastication assay	99
5.2.4.4	Tribological studies of constructs	99
5.2.5	Real time experimental analysis on developed constructs	100
5.2.5.1	Sensory analysis of rehydrated constructs	100
5.2.5.2	Biosensor based chew profile study	101
5.2.6	Storage kinetics modelling study of developed construct	102
5.2.6.1	Omega-3 fatty acid analysis	103

	5.2.6.2	Spectrophotometric method of lycopene determination	103
	5.2.6.3	Colour value determination	103
	5.2.7	Proximate analysis of constructs	104
	5.2.8	Invitro digestibility	105
5.3		Results and Discussion	105
	5.3.1	IDDSI platform test observations on moulded and printed constructs	105
	5.3.2	Instrumental analysis of rehydrated moulded and printed constructs	107
	5.3.2.1	Effect of printing on textural properties of constructs	107
	5.3.2.2	Effect of printing and rehydration time on bolus rheology	112
	5.3.2.3	Mastication assay of developed constructs	114
	5.3.2.4	Effect of rehydration and printing on tribological characteristics of constructs	115
	5.3.3	Real time experimental analysis on developed constructs	117
	5.3.3.1	Sensory analysis of rehydrated constructs	117
	5.3.3.2	Chewing profile of rehydrated moulded and printed constructs	119
	5.3.4	Storage kinetics modelling and shelf-life prediction of developed constructs	122
	5.3.5	In vitro digestibility of raw material and developed construct	125
5.4		Key Findings of this Objective	127

Chapter VI	Evaluation of the Stability of the formulations during storage in the development of printer cartridges	128-153
6.1	Background of the objective	129
6.2	Materials and Methods	130
6.2.1	Extraction and characterization of chia mucilage and chia oil	130
6.2.1.1	Extraction of chia mucilage	130
6.2.1.2	Storage stability study on extracted chia oil	130
6.2.1.3	Fatty acid analysis of chia oil	131
6.2.2	Preparation of formulation	131
6.2.3	Syneresis and per cent weight loss	134
6.2.4	Rheological characterization of bio-formulation	134
6.2.5	Extrusion rate, and printing performance	134
6.2.6	Experimental design of long-term Storage studies	134-136
6.2.6.1	pH and Titratable acidity	136
6.2.6.2	Kinetic modelling of Omega-3 degradation	136
6.3	Results and Discussion	137
6.3.1	Characterization of extracted chia oil and chia mucilage	137
6.3.2	Effect of freeze-thaw cycle on physicochemical properties of bio-formulation during short-term studies	140
6.3.2.1	Effect of freeze-thaw cycle on syneresis and water loss percentage	140
6.3.2.2	Effect of freezing cycle on rheological characteristics of bio-formulation during short-term storage	142

	6.3.2.3	Effect of freezing cycle on printing characteristics of bio-formulation during short-term storage	144
	6.3.3	Long-term bio-formulation storage stability studies	149-155
	6.3.3.1	Effect of chia mucilage and packaging condition on printing characteristics of bioformulation during long-term storage under refrigerated condition	149
	6.3.3.2	Effect of packaging condition and storage time on physico-chemical properties of bio-formulation under refrigerated temperature during long-term storage	155
	6.3.3.2.1	Omega-3 degradation kinetics modelling	155
	6.4	Key Findings of this Objective	157
Chapter VII		Summary and Conclusion	158-161
		References	162-179
		Appendix	179-194
		Biodata	195-197

LIST OF TABLES

Table	Description	Page No.
2.1	Dysphagia severity rating scale (DSRS)	10
2.2	Current research on protein-rich printed dysphagia foods	16-17
3.1	Proportion of chia seed flour with treated horse gram flour in the composite flour	26
3.2	Rheological properties of formulations	32
3.3	Printing performance of the formulations	36
3.4	Textural characteristics of printed constructs of formulations with varied chia seed flour proportion	44
4.1	Composition of printing bio-formulations	49
4.2	Design, printer head, and printer parameter setting values	51
4.3	Different levels of the independent variables and coded values	53
4.4	Physiochemical characteristics of raw materials	57
4.5	Fatty acids profile of chia oil	58
4.6	Effect of total solid content on flow characteristics of bioformulation	61
4.7	Effect of total solids and printing parameters on the printing accuracy	66
4.8	Quadratic equations (actual) of different response variables	71
4.9	Optimum process conditions of bioformulation and validation of the model construct for the prediction of response variables	71
4.10	Drying and rehydration characteristics of moulded and printed constructs	72
4.11	Mathematical modelling of rehydration kinetics of developed constructs	77
4.12	Texture profile of constructs under various stage of processing	87
5.1	Composition of formulation	95
5.2	Texture profile of moulded and printed constructs	111
5.3	Predicted shelf-life of normally packed and vacuum-packed constructs	125
5.4	Nutritional composition of constructs	126

6.1	Composition of bioformulation for short-term accelerated storage study	132
6.2	Composition of bioformulation for long-term storage study	136
6.3	Fatty acids composition of chia oil	138
6.4	Preliminary observations on the effect of packaging conditions under refrigerated storage	150
6.5	Effect of storage conditions on rheological and printing characteristics of bio-formulations	151
6.6	Predicted shelf-life of bio-formulations	157

LIST OF FIGURES

Figure	Description	Page no.
2.1	A pictorial representation of (a) stages of swallowing, and (b) (i) normal swallowing process and (ii) obstruct swallowing - dysphagia	9
2.2	IDDSI Standards	11
2.3	3D printing process of bioformulation: (a) CAD modeling, (b) Slicing and G Coding process, and (c) printing process of bioformulation	13
2.4	Images of (a) horse gram (<i>Macrotyloma uniflorum</i>), (b) chia seeds (<i>Salvia hispanica L.</i>), and (c) extracted chia seed oil	22
3.1	Effect of chia seed flour (CSF) substitution on water holding capacity of the formulations (C: raw horse gram flour, germinated and roasted horse gram flour (THGF), chia seed flour (CSF), F1: 100% THGF, F2: 5% CSF & 95% THGF, F3: 10% CSF & 90% THGF, F4:15% CSF & 85 % THGF, F5:20% CSF & 80% THGF)	29
3.2	FTIR spectra of raw and germinated roasted horse gram flour	30
3.3	Rheological characteristics of formulations with substitution of chia seed flour (CSF) in the proportion of 5, 10, 15 & 20% (w/w): (a) variation of apparent viscosity with shear rate, (b) variation in storage (G') and loss (G'') moduli with strain, and (c) variation of storage (G') and loss (G'') moduli with angular frequency, and (d) shear recoverability under alteration of high and low shear rates (C: raw horse gram flour, germinated and roasted horse gram flour (THGF), chia seed flour (CSF), F1: 100% THGF, F2: 5% CSF & 95% THGF, F3: 10% CSF & 90% THGF, F4:15% CSF & 85 % THGF, F5:20% CSF & 80% THGF)	34
3.4	Effect of chia seed flour addition on extrusion rate and its impact on shape accuracy of the printed constructs. (germinated and roasted horse gram flour (THGF), chia seed flour (CSF),	36

	F1: 100% THGF, F2: 5% CSF & 95% THGF, F3: 10% CSF & 90% THGF, F4:15% CSF & 85 % THGF, F5:20% CSF & 80% THGF)	
3.5	Printability (a) 1D, (b) 2D and (c) 3D printability of the formulations (germinated and roasted horse gram flour (THGF), chia seed flour (CSF), F1: 100% THGF, F2: 5% CSF & 95% THGF, F3: 10% CSF & 90% THGF, F4:15% CSF & 85 % THGF, F5:20% CSF & 80% THGF)	37
3.6	3D design model and printed constructs: (a) images of (i) cube design, and (ii) sliced model, (b) printed constructs of formulations with varying CSF proportion (F1: 100% treated horse gram flour (THGF), F2: 5% CSF & 95% THGF, F3:10% CSF & 90% THGF, F4: 15% CSF & 85% THGF, F5: 20% CSF & 80% THGF), (c) IDDSI Level 6 soft bize-sized standard design), and (d) 3D printed constructs e.g., squirrel and boat with F3 formulation	38
3.7	IDDSI standard tests: (a) Fork and spoon pressure tests on Level 6 ‘soft and bite-sized food’, and Cut or Break apart test on Level 7 ‘easy to chew’ 3D printed constructs, (b) Fork pressure, Fork drip, spoon tilt, and lump tests on Level 5 ‘Minced and moist’ 3D printed constructs	41
3.8	Morphology of 3D printed constructs derived from formulations (a) F2, (b) F3 and (c) F4 (germinated and roasted horse gram flour (THGF), chia seed flour (CSF), F2: 5% CSF & 95% THGF, F3: 10% CSF & 90% THGF, F4:15% CSF & 85 % THGF)	43
4.1	Image of sliced cube design with optimized design parameters	51
4.2	Images of (a) whole chia seed flour, (b) defatted chia seed flour, and (c) chia oil	56
4.3	Effect of deffating on sieving efficiency of chia flour	58
4.4	Effect of total solids on printing performance: Image represents printing performance of bio-formulation with <26% TS	61

4.5	Effect of total solids on rheological characteristics (a) apparent viscosity of formulations under controlled shear rate, (b) storage (G') and loss (G'') moduli of the formulations under controlled shear strain, (c) extrusion behaviour of formulations and (d) variation of storage (G') and loss (G'') moduli with angular frequency of bioformulations	62
4.6	Images of F3 formulation construct printed with (a) 0.8 mm and (b) 1.2 mm diameter nozzle at 25% infill design (ND: nozzle diameter, LH: layer height)	63
4.7	Effect of total solids and printing parameters on printing performance	67
4.8	Response surface plot of printing score as a function of total solids and printing parameters	68
4.9	Response surface plot of extrusion yield as a function of total solids and printing	69
4.10	Predicted vs. actual plots of (a) printing score, and (b) extrusion yield	70
4.11	Effect of microwave treatment and infill percentage on the drying characteristics of developed constructs	71
4.12	Images of microwave treated (a) moulded and (b) printed constructs	73
4.13	Images of (i) microwave treated and untreated freeze-dried (a) moulded and (b) printed constructs (ii) microwave treated moulded and printed constructs	74
4.14	Effect of microwave treatment on structural integrity of printed construct during rehydration	74
4.15	Effect of printing on the rehydration characteristics of developed constructs	75
4.16	Rehydration pattern of (a) moulded and (b) printed constructs	79
4.17	Effect of infill percentage and rehydration time on density of developed constructs	80
4.18	Implementation of IDDSI spoon pressure test on rehydrated moulded and printed constructs	82

4.19	Effect of printing and rehydration time on the hardness profile of developed constructs	85
4.20	Texture profile of dried and rehydrated moulded and printed constructs	86
4.21	Cross sectional view of moulded and printed constructs	86
4.22	SEM image of internal surface morphology of (a) Untreated freeze-dried (M0) and Microwave-treated and freeze-dried (M3) constructs	88
4.23	External surface roughness profile of (a) freshly prepared constructs, (b) untreated freeze-dried constructs, and (c) microwave treated and freeze-dried constructs	90
4.24	Image of rehydrated moulded and printed constructs in soup medium	92
4.25	Effect of printing and moulding process on sensory analysis of developed constructs	92
5.1	(a) Bio-formulation fortified with omega-3 rich chia oil, and (b) bio-formulation fortified with omega-3 rich chia oil and lycopene	95
5.2	3D printing process of vegan meat bio-formulation	96
5.3	A Flow process of transitional mould and printed construct preparation	96
5.4	Lateral and cross-section images of (i) molded and (ii) printed constructs	97
5.5	Application of image processing approach on dimensional accuracy measurement	98
5.6	Customized design of biosensor chew activity experimental setup	102
5.7	Vacuum packed (a) moulded and (b) printed construct	103
5.8	IDDSI platform test observations on developed construct	107
5.9	Hardness profile of moulded and printed construct on different chewing orientations	110
5.10a	Effect of printing on bolus rheology of fully rehydrated constructs (moulded vs printed constructs)	113

5.10b	Effect of rehydration time on bolus rheology of moulded and printed constructs	113
5.11	Mastication assay of rehydrated moulded and printed construct	115
5.12	Tribological characteristics of moulded and printed constructs at different rehydration times	116
5.13	Sensory analysis of rehydrated moulded and printed constructs	119
5.14	Chewing profile of rehydrated moulded and printed construct	120
5.15	Correlation of instrumental analysis and real time analysis of developed constructs	121
5.16	Effect of packaging conditions and storage time on colour and lycopene degradation	123
5.17	Effect of packaging and storage time on colour degradation of printed constructs under room temperature storage	124
5.18	Effect of packaging and storage conditions on omega-3 concentration of printed constructs during accelerated shelf-life study	124
5.19	Protein digestibility of the raw materials and constructs. a, b, and c denote significant difference among protein digestibility % and p, q, r, and s denote significant difference among protein content % of the raw horse gram flour (HGF), germinated and roasted HGF (THGF), raw chia seed flour (CSF), defatted CSF (DCF), moulded and printed product samples	126
6.1	Chia seed mucilage extraction process	132
6.2	Process flow of bioformulation packaging	135
6.3	FT-IR spectra of extracted chia mucilage	139
6.4	Effect of freeze-thaw cycles on control bioformulation (CTRL FC1), causing syneresis and water separation during printing	141
6.5	Effect of freezing cycle and chia mucilage on syneresis of bio-formulation	140
6.6	Effect of freezing cycle and xanthan gum on syneresis of bio-formulation	142
6.7	Effect of chia mucilage and xanthan gum on the viscosity of bio-formulation under freezing cycle	142

6.8	Effect of chia mucilage and xanthan gum on the flow point of bio-formulation under freezing cycle.	142
6.9	Effect of hydrocolloids ((a)xanthan gum and (b)chia mucilage) and freezing cycle on extrusion rate of bioformulations	146
6.10	Effect of xanthan gum and freezing cycle on printing quality of bioformulations	147
6.11	Effect of chia mucilage and freezing cycle on printing quality of bioformulations	148
6.12	Preliminary observations on the effect of packaging conditions on rheological and printing characteristics under refrigerated storage	151
6.13	Preliminary observations on the effect of chia mucilage on moisture retention and printing characteristics under refrigerated storage	151
6.14	Effect of syneresis and storage days on rheological characteristics of bio-formulations	154
6.15	Images of (a) normally packed, and (b) vacuum packed bio-formulation under refrigerated storage on 30th day	154
6.16	Degradation kinetics of omega-3 fatty acids of vacuum-packed bio-formulations	156

LIST OF SYMBOLS AND ABBREVIATIONS

%	Percent
<	Less than
>	Greater than
≥	Greater than or equal to
±	Plus or minus
ω	Omega
AOAC	Association of Official Analytical Chemists
ANOVA	Analysis of variance
a _w	Water activity
CFU	Colony Forming Unit
CFU.g ⁻¹	Colony Forming Unit per gram
°C	Degree Celsius
°C min ⁻¹	Degree Celsius per minute
cm	Centimeter
d.b.	Dry basis
E _a	Activation energy
eg.	Example
Eq.	Equation
Ev	Electronvolt
FAO	Food and Agriculture Organization
Fig.	Figure
FTIR	Fourier Transform Infrared Spectroscopy
FSSAI	Food Safety and Standards Authority of India
g	gram
g/L	gram per litre
G'	Storage modulus
G''	Loss modulus
GA	Genetic Algorithm
GC	Gas chromatography
GRAS	Generally recognized as safe
h	Hour

IDDSI	International Dysphagia Diet Standard Initiative
J	Joule
K	Kelvin
kg	Kilogram
kg.cm ⁻²	Kilogram per centimeter square
kg.m ⁻³	Kilogram per meter cube
kg s ⁻¹	Kilogram per second
kJ	Kilo Joule
kJ mol ⁻¹	Kilo Joule per Mole
kJ mol ⁻¹ K ⁻¹	Kilo Joule per Mole per Kelvin
kPa	Kilo Pascal
kW	Kilo watt
kWh	Kilo watt hour
log	logarithmic
μm	micrometer
μL	microlitre
mg	milligram
mL	milliliter
mL min ⁻¹	milliliter per minute
mV	millivolt
Meq	milli equivalent
MPa	mega Pascal
min	minute
mol	Mole
MS	Mass Spectroscopy
no.	number
nm	nanometer
O ₂	Oxygen

$^{\circ}\text{C min}^{-1}$	Degree Celsius per minute
Pa	Pascal
Pa.s	Pascal second
R^2	Coefficient of determination
rad s^{-1}	Radian per second
RMSE	Root mean square error
RPM	rotation per minute
s	Second
SD	Standard deviation
SEM	Scanning Electron Microscopy
v/v	volume/volume
V	Volt
viz.	videre licet
WHO	World Health Organization
w	weight
w.b.	wet basis
w/w	weight/weight
w/v	weight/volume
τ	shear stress
γ	shear rate
η	viscosity