ENGINEERING TRANSITIONAL DYSPHAGIC FOOD

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by

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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.

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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 oesophagal 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±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 mm.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±87 $\text{Pa.s}^{-1}\text{.cm}^{3}$) compared to moulded variants (4995±127 $\text{Pa.s}^{-1}\text{.cm}^{3}$), 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±0.27 g.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±1°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±21 KJ.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±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 भूनने (150±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±0.2 Pa.s से 14.45±0.17 Pa.s तक कम करके रियोलॉजिकल प्रदर्शन में सुधार किया। प्रीट्रीटमेंट ने HGF की प्रोटीन पाचन क्षमता को 72.4±1.6 से 78.1±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±0.24 N से 3.86±0.10 N तक की कमी आई, जिसे IDDSI प्लेटफ़ॉर्म 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±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 प्रोफ़ाइल 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 प्लेटफ़ॉर्म 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±127 Pa/s·cm^3) की तुलना में 34% कम हिस्टैरिसीस ऊर्जा (4197±87 Pa/s·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 हाइड्रोकोलॉइड चिया म्यूसिलेज को जोड़ा गया और व्यापक रूप से उपयोग किए जाने वाले ज़ैंथन गम हाइड्रोकोलॉइड के संबंध में बायोफ़ॉर्मूलेशन की प्रिंटेबिलिटी की जाँच की गई। फ्रीजिंग चक्र के दौरान बढ़ी हुई सिनेरेसिस के कारण, प्रवाह बिंदु में वृद्धि हुई और इसने एक्सट्रूज़न दर को 2.22 ± 0.14 से घटाकर 0.97 ± 0.27 g.min-1 कर दिया। इस बीच, 2% चिया म्यूसिलेज और 0.5% ज़ैंथन गम की अनुकूलित सांद्रता ने अच्छी गुणवत्ता वाले प्रिंट प्रदान किए। FC0 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±1°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 शेल्फ़लाइफ़ 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±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±25 Pa और 2.32±0.17 g.min-1 की सीमा में प्रवाह बिंदु और एक्सट्रूज़न 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 मैन्युफैक्चरिंग 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

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

%	Percent
<	Less than
>	Greater than
$\geq$	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 chromotography
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

°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