# Kinetic modelling of *Okra* and *Gracilaria corticata* hydrocolloid mucilage polysaccharides

**Ramesh Subramani**[a], **Charumathi Pushparaj**[b], **Archana Ganesan**[c],*

a- Department of Biotechnology, PSGR Krishnammal College for Women, Coimbatore, India
b- Department of Zoology, PSGR Krishnammal College for Women, Coimbatore, India
c- Department of Food Processing Technology and Management, PSGR Krishnammal College for Women, Coimbatore, India

## Abstract

The biopolymer has become essential component in the recent years to overcome the environmental issues raised from the synthetic polymer. In this aspect we attempt to make such valuable and economical important biopolymer from the natural sources such as Abelmoscus esculentus and *Gracilaria corticata* in an eco-friendly approach with thermally stable biopolymer. Thermal analysis of *Okra* and *Gracilaria corticata* mucilage polysaccharide has been carried out to ascertain their thermal degradation behavior and thermal stability. Thermal analysis of *Okra* and *Gracilaria corticata* mucilage polysaccharide weighed in the range of 5-10 mg was carried out with TGA (thermal gravimetric analyzer) and DSC (differential scanning calorimeter). Activation energy of the biopolymers for degradation studies was predicted and compared with Flynn-Wall-Ozawa (FWO) model. The activation energy obtained showed high $R^2$ value of 0.9999, 0.9951, 0.9997 for *Okra* and 0.9992, 0.9998, 0.9999 for *Gracilaria corticata*, respectively. The obtained results of this study established the thermal characteristics of *Okra* and *Gracilaria corticata* mucilage polysaccharide and suggest their potential application in the food, cosmetic and pharmaceutical sectors.

## Introduction

A large number of plant polysaccharides with excellent water holding capacity are being used as natural hydrogels in functional foods, food additives and herbal products (Akbar *et al.*, 2012). Some of them have been used as biomaterials for tissue engineering, pharmaceutical preparations as thickeners, stabilizer, emulsifier and drug carriers. Natural and biodegradable polymers have limited applications due to their inadequate thermal and mechanical properties. For instance, though polysaccharide is extensively used as gelling agents in the food industry, thermal treatment usually results in poor gelation due to weak structural interactions (Barbosa *et al.*, 2020). The structure development rate (SDR) of the polymers during gelation could be measured under isothermal and non-isothermal conditions by measuring rheological properties. The SDR of protein system has been investigated using the non-isothermal kinetic models (Ben Slima *et al.*, 2022). Temperature is one of the important thermodynamic

parameters involved in most gelation processes at a given biopolymer concentration. Therefore, the gelation mechanism and structure development can be analyzed by interpreting the changes in thermal property of the biopolymers. Depending on the molecular configuration of the polymer network, temperature can have different effects on viscoelastic behavior of the gel (Cruz *et al.*, 2018).

*Okra* polysaccharides contain a repeating unit of α-(1, 2)-linked rhamnosyl and α-(1,4)-linked galacturonosyl residues and dimeric β-(1,4)-linked galactan side chains which are substituted to O-4 of half of the rhamnosyl residues (Distantina & Fahrurrozi, 2011). *Okra* pectin was found to form a gel at a relatively low concentration; however, a stable gel was formed after heating *okra* polysaccharides at 60 °C for 30 mins followed by a coolingat 4 °C for 24 h. Similarly, the main sugars present in *Gracilaria corticata* were galactose (65.4 mol %), 3, 6-anhydrogalactose (25.1 mol %) and 6-O-methylgalactose (9.2 mol %), (Drechsler & Bornhorst, 2018). Gels formed

---

* Corresponding author (archanag@psgrkcw.ac.in)

with such polymers in given thermodynamic conditions, based on aggregation of double helices and the conformational transition occurs at a melting temperature (TF) higher than the re conformational temperature corresponding to the gel formation; Agar has the ability to form gels upon cooling of a hot solution to 30-40 °C and to melt to sols upon heating to 90-95 °C. At temperatures above the melting point of the gel, thermal agitation overcomes the tendency to form helices and the polymer exists in solution as a random coil(Garre *et al.*, 2020). On cooling, a three-dimensional network builds up in which double helices form the junction points of the polymer chains (Halabi *et al.*, 2020). Increasing the heating rate results in a shift of the integral conversion curve towards higher temperatures, and hence, resulting in a shift of the differential curve. The size and shape of the particles influence the heat transfer into the particle and mass transfer from the particle. Therefore, it is very important to ensure the best possible contact between the particle and the heating area. Phenolic resins are known for their wide applications in various areas because of their thermal stability, easy availability, effectiveness and some of their excellent properties as reported by various studies. Recently the methods of thermogravimetry analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetric (DSC) provided reliable information on the physico-chemical parameters, characterizing the processes of transformation of solids or participation of solids in processes of isothermal or non-isothermal heating. Knowledge on degradation kinetics of enzyme inactivation and quality changes including the reaction order, the reaction constant and the energy of activation is essential to predict quality losses during thermal processes. In addition, FTIR investigations are necessary to confirm their chemical properties similar to those of other common ligno cellulosic fibers. The thermal analysis curves revealed that the *okra* fibers were stable until around 220 °C. This is in agreement with the values of many vegetables fibers reported in literature. The goal of this approach is to make a deeper insight into the reaction course of *okra* and *Gracilaria corticata* polysaccharide material; and an early detection of the stability/reactivity (Hansen *et al.*, 2020). The aim of this work is to assess the thermal stability and to determine the thermal degradation pattern of *Okra* and *Gracilaria* polysaccharides by Flynn-Wall-Ozawa model in order.

## Materials and methods

### Sample collection and preparation

Seaweeds species (*Gracilaria corticata*) was collected from mandapam coast in Gulf of Mannar, Tamilnadu, Southeast coast of India at a latitude 9°45' N and longitude 79°0' E on low tide, during December 2012. Collected samples were washed with tap water to remove epiphytes and other marine organisms. The samples were transported to the laboratory in sterile polythene bags. In the laboratory, samples were rinsed with tap water, shade dried and powdered in a mixer grinder. Similarly, *Okra* bio waste (upper crown head) collected from A. C. Tech canteen, Anna University, Chennai, was rinsed

with tap water and was shade dried. The dried *okra* wastes were broken in to powder form in an electrical mixer. It was then sieved into particle sizes of 0.5-4 mm and stored in glass bottles for further use. All reagents used in the experiment were purchased from Sigma Aldrich with 99.9% purity (Hickman *et al.*, 2019).

### Extraction

The mucilage polysaccharide was extracted by the method followed in Distantina and Fahrurrozi (2011). 5 g of clean, dried seaweed and *okra* powder sample were soaked in distilled water for 15 min. After soaking, the water was separated from the seaweed by filtration. Firstly, a known amount of solvent (methanol, acetone; (1/50 g/mL)) was heated in a beaker as an extractor which emerged in a water bath equipped with a stirrer. If the temperature of solvent reached 85 °C, (Mohammed *et al.*, 2020) then the samples were added into solvent, and the time of extraction started was counted. The speed of stirrer was set constant at 275 rpm. The constant ratio of seaweed weight to solvent volume (1/50 g/mL) was maintained by adding hot water. The extraction was stopped after 45 min (Jha *et al.*, 2019). The Filtrate was separated from residue using filter cloth and immediately poured into three volumes of cold (5 °C) acetone (90% w) which caused precipitation of polysaccharides. Precipitation was done for 30 min with stirring gently by hand. The precipitated polysaccharides were collected and oven dried at 50-60 °C to a constant weight. The experiments were carried out with different solvent such as acetone and thermal stability of the extracted polysaccharides was determined (Ji *et al.*, 2019).

### Thermal analysis

The powdered polymers were subjected to a simultaneous TGA and DSC analysis by thermal analyzer SDT, Q-600 (TA instruments, USA), (Kasperowicz *et al.*, 2020). In nitrogen atmosphere (250 mL/min) in a programmed temperature range from 30 to 600 °C at a heating rate of 10 °C/min. Sample weights between 5 and 10 mg were placed in a platinum pan. The baseline correction was applied to DSC scans. The data were analyzed by the isoconversional Flynn-Wall-Ozawa (FWO) model (Li & Lin, 2021).

## Results and discussion
### DSC-TGA analysis

The isolated polysaccharides were white or light brown in colour and showed good swelling in water (Li *et al.*, 2019). Typical DSC-TGA curves of *okra* and *gracilaria* polysaccharide were shown in Fig. (1) and (2). The melting occurred over a wide range of temperatures which might be due to amorphous nature or vaporization of the water which indicates the presence of hydrophilic groups in the crude samples (Liu *et al.*, 2019). An exothermic transition has occurred in *okra* polysaccharide, beginning at ~200 °C and completed at ~400 °C as shown in the Fig. (1), through a peak of 225.48 °C (Madoumier *et al.*, 2019; Merci *et al.*, 2019). The *Okra* polysaccharide showed weight loss of

51.15% at 362 °C and completed decomposed at ~700 °C. In the case of *Gracilaria corticata* polysaccharide, the decomposition took place at three different phases. And corresponding weight loss was shown in the Fig. (2).
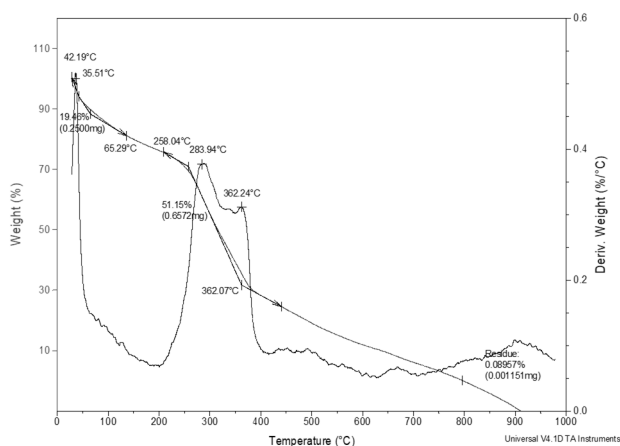


**Fig. 1.** The combination curves of TGA- DSC curves of *Abelmoscus esculentus* polysaccharide powder.
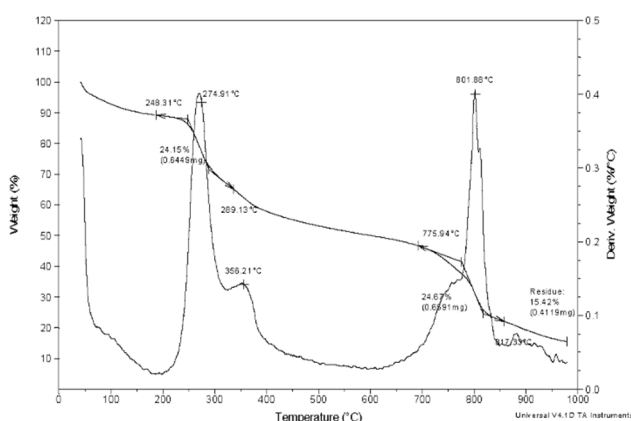


**Fig. 2.** The combination curves of TGA- DSC curves of seaweed (*Gracilaria corticata*) polysaccharide powder.

### Thermal degradation kinetics

The data were analyzed by the isoconversional Flynn-Wall-Ozawa (FWO) method (Eq. 1).

$$Ln\beta = \frac{\ln AEa}{Rg(\alpha)} - 5.331 - 1.052\frac{Ea}{RT} \tag{1}$$

Where $g(\alpha) = \int_0^\alpha \frac{dx}{f(\alpha)}$; $g(\alpha) = \int_0^\alpha \frac{dx}{f(\alpha)}$; $g(\alpha)$ is the integral reaction model; $f(\alpha)$- reaction model; $\beta$-Heating rate; $E_a$- activation energy; A-pre-exponential factor; R-General gas constant and T-temperature (Nawaz *et al.*, 2019).

The FWO method was the first isoconversional linear integral method developed by Flynn and Wall (1966) and Ozawa (1965), (Plazanet *et al.*, 2018). This method is based on the assumption that for a fixed extent of conversion, the reaction rate depends upon temperature only as shown in Fig. (3). Thus, it eliminates the dependence of reaction kinetics on any model, which may be represented by an integral form g($\alpha$). Therefore, this may be termed as a model-free approach and used at different heating rates, thus at fixedRate the plot of a, log vs. 1/T can be a straight line, the slope of which

permits the calculation of $E_a$. The ais defined as $(w_o.w_t)/(w_o.w_f)$, where $w_t$ is the weight of the sample at any temperature T, $w_o$ the initial weight and $w_f$ is the final weight at the temperature at which the mass loss is approximately negligible. Thermal stabilities of the polysaccharides were determined by integral procedural decomposition temperature (IPDT) and comprehensive index of intrinsic thermal stability (ITS), (Schuldt *et al.*, 2018). This method is considered to be most appropriate and reliable to determine these parameters because it takes into account the whole TGA curve by measuring area under it. The ITS and IPDT values were determined from TGA of all four heating rates and mean values are reported for each polysaccharide. The life-times of polysaccharides were also predicted by model-free approach based on Eq. (2). The model-free approach eliminates the limitations of other methods such as ASTM E1641 and E698 methods which assume that the $E_a$ remains constant throughout the degradation step. Therefore, in cases where $E_a$ is not constant in a step the model-free approach is more appropriate.

$$t\alpha = \frac{\int_o^{T\alpha}\exp(-E_./RT)dT}{\beta\exp(-E_./RTo)} \tag{2}$$

Where, t$\alpha$ =time at any given degree of conversion; $\beta$= the heating rate; E= pre-exponential factor; R= gas constant; T= Temperature; $T\alpha$= Temperature at any given degree of conversion and To= Initial temperature.

This relationship exploits the variation of activation energy with a. The integral in the numerator has no analytical solution; however, it can be evaluated by different approximations. In this study we used the Senum-Yang fourth degree approximation. The integral in the numerator of this equation was solved by Senum-Yang fourth degree approximation (Shah *et al.*, 2018).
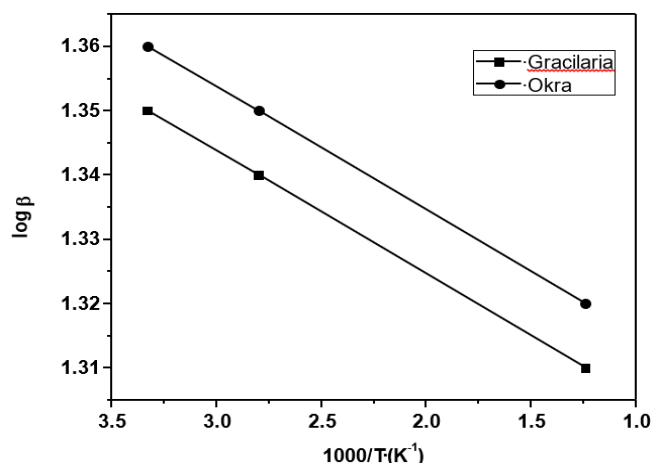


**Fig. 3.** Representative $\alpha$-T curves for *Okra* and *Gracilaria corticate* at a fixed extent of conversion factor ($\alpha$).

### Flynn-Wall-Ozawa analysis

The typical Flynn-Wall-Ozawa plots of *Okra* and *Gracilaria* polysaccharide showed similar trend for activation energy. The average $E_a$-value determined by Flynn–Wall–Ozawa method was found to be in the range of 41-998 kJ.mol$^{-1}$ given

in as shown in Fig. (4) respectively. The $E_a$-$\alpha$ curves showed the dependence of $E_a$ on the degree of conversion $\alpha$ shown in Fig. (5). Both the materials Okra and Gracilaria corticata polysaccharide appeared to be as stable as some of the important commercial materials used as pharmaceutical ingredients (Simpson et al., 2020). Model-fitting analysis revealed that the major degradation step followed first order kinetics. The correlation coefficients are also close to unity. For okra the $E_a$ value was varied between 41.8-621.89 kJ.mol$^{-1}$, R value was 0.999, and for Gracilaria corticatathe values were between 343-1025 kJ.mol$^{-1}$ and 0.999 for $E_a$ and R as shown in Fig. (5).
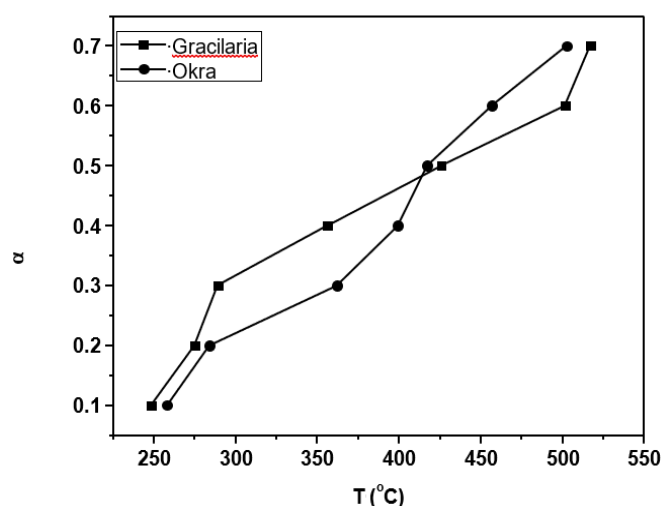


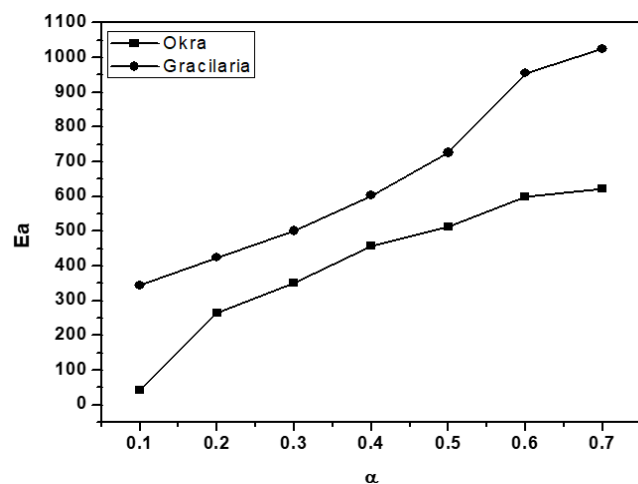**Fig. 4.** FWO plot for Okra and Gracilaria corticata to calculate $E_a$.



**Fig. 5.** Dependence of activation energy ($E_a$) on $\alpha$.

The $E_a$ for Okra and Gracilaria corticata varies with conversion $\alpha$, which suggested a multistep degradation of these materials. The multistep decomposition may be due to the diversity of sugar content of the polysaccharide materials. Based on the correlation coefficient and the closeness of the activation Energy, the FWO model was found to be best for these polysaccharides. All the polysaccharides so far investigated exhibited very high stability as predicted by the model-free analysis (Simpson et al., 2019). The $E_a$ values for both Okra and Gracilaria

corticata polysaccharides increased with increasing heating temperature, which indicated the enhanced thermal stability of polymer materials. The mathematical model used in this study was able to describe the changes of mass loss with temperature; however, there are still some visible differences in the differential curve. The experimental data of sample residue from thermogravimetric analysis were compared with simulated data obtained by the optimization of kinetic parameters of Okra and Gracilaria polysaccharide. Experimental results showed that values of kinetic parameters from both method are in good agreement and can be used to understand the degradation mechanism of solid-state reaction and useful in the individual analysis of polymers in the blends (Vandenberghe et al., 2017). The increased thermal stability of these polysaccharides may help in the development of natural fiber composites, where the thermal stability of natural fiber material is of major concern (Vicent et al., 2019). Thus the establishment of kinetic parameters for these natural polymers over a wide range of temperature may be helpful in the modeling of polymer degradation during various industrial processes the established thermal decomposition kinetic parameters can help aid the development of polymer composites from heat treated Okra and Gracilaria corticata polysaccharides (Ren et al., 2021).

## Conclusion

Temperature is the important thermodynamic parameter involved in most gelation processes at a given biopolymer concentration. Therefore, the gelation mechanism and structure development can be analyzed by interpreting thermal effects on rheological property changes. The weight loss of okra below 200 ℃ was minimal which may be due to increased inorganic materials or impurities in the crude sample. The okra polysaccharide showed good thermal stability. Gracilaria corticata polysaccharide had increased inorganic substances when compared with Okra. This may be due to methylation which releases inorganic materials like oxides and carbonaceous residues. Onset degradation of okra polysaccharide between the temperatures (220-310 ℃) was associated to the thermal depolymerisation of hemicelluloses, pectin and the cleavage of glycoside linkages of cellulose above which the stability of Okra polysaccharide decreased gradually. An exothermic transition has occurred with Gracilaria corticata, running through a peak of 243.30 ℃ with a small enthalpy change of 31.06 J/g. These findings suggested that both Okra and seaweed polysaccharide are highly thermo stable and could be used in the development of biomaterials for various industrial purposes. The numerical algorithms in this work may be useful in modeling of polymer processing. The kinetic model showed nearly similar activation energies for both Okra and Gracilaria corticata that are suitable for the determination of the kinetic parameters of polysaccharide. We demonstrated that the approach was a powerful tool to estimate the activation energy of Okra and Gracilaria corticata polysaccharides for thermal decomposition.

# References

Akbar, J., Iqbal, M. S., Massey, S., & Masih, R. (2012). Kinetics and mechanism of thermal degradation of pentose- and hexose-based carbohydrate polymers. *Carbohydrate Polymers*, *90*(3), 1386-1393. https://doi.org/10.1016/j.carbpol.2012.07.008

Barbosa, J. R., S. Freitas, M. M., Oliveira, L. C., S. Martins, L. H., Almada-Vilhena, A. O., Oliveira, R. M., . . . Carvalho Junior, R. N. (2020). Obtaining extracts rich in antioxidant polysaccharides from the edible mushroom Pleurotus ostreatus using binary system with hot water and supercritical CO2. *Food Chemistry*, *330*, 127173. https://doi.org/10.1016/j.foodchem.2020.127173

Ben Slima, S., Ktari, N., chouikhi, A., Trabelsi, I., Hzami, A., Taktak, M. A., . . . Ben Salah, R. (2022). Antioxidant activities, functional properties, and application of a novel Lepidium sativum polysaccharide in the formulation of cake. *Food Science & Nutrition*, *10*(3), 822-832. https://doi.org/10.1002/fsn3.2713

Cruz, G., Santiago, P. A., Braz, C. E. M., Seleghim, P., & Crnkovic, P. M. (2018). Investigation into the physical–chemical properties of chemically pretreated sugarcane bagasse. *Journal of Thermal Analysis and Calorimetry*, *132*(2), 1039-1053. https://doi.org/10.1007/s10973-018-7041-1

Distantina, S., & Fahrurrozi, M. (2011). Carrageenan properties extracted from Eucheuma cottonii, Indonesia. *International Journal of Chemical and Molecular Engineering*, *5*(6), 501-505. https://doi.org/10.5281/zenodo.1333328

Drechsler, K. C., & Bornhorst, G. M. (2018). Modeling the softening of carbohydrate-based foods during simulated gastric digestion. *Journal of Food Engineering*, *222*, 38-48. https://doi.org/10.1016/j.jfoodeng.2017.11.007

Flynn, J. H., & Wall, L. A. (1966). A quick, direct method for the determination of activation energy from thermogravimetric data. *Journal of Polymer Science Part B: Polymer Letters*, *4*(5), 323-328. https://doi.org/10.1002/pol.1966.110040504

Garre, A., Zwietering, M. H., & den Besten, H. M. W. (2020). Multilevel modelling as a tool to include variability and uncertainty in quantitative microbiology and risk assessment. Thermal inactivation of Listeria monocytogenes as proof of concept. *Food Research International*, *137*, 109374. https://doi.org/10.1016/j.foodres.2020.109374

Halabi, A., Deglaire, A., Hamon, P., Bouhallab, S., Dupont, D., & Croguennec, T. (2020). Kinetics of heat-induced denaturation of proteins in model infant milk formulas as a function of whey protein composition. *Food Chem*, *302*, 125296. https://doi.org/10.1016/j.foodchem.2019.125296

Hansen, M. M., Maidannyk, V. A., & Roos, Y. H. (2020). Thermal gelation and hardening of whey protein beads for subsequent dehydration and encapsulation using vitrifying sugars. *Journal of Food Engineering*, *279*, 109966. https://doi.org/10.1016/j.jfoodeng.2020.109966

Hickman, D. A., Ignatowich, M. J., Caracotsios, M., Sheehan, J. D., & D'Ottaviano, F. (2019). Nonlinear mixed-effects models for kinetic parameter estimation with batch reactor data. *Chemical Engineering Journal*, *377*, 119817. https://doi.org/10.1016/j.cej.2018.08.203

Jha, P. K., Xanthakis, E., Chevallier, S., Jury, V., & Le-Bail, A. (2019). Assessment of freeze damage in fruits and vegetables. *Food Research International*, *121*, 479-496. https://doi.org/10.1016/j.foodres.2018.12.002

Ji, X., Zhang, F., Zhang, R., Liu, F., Peng, Q., & Wang, M. (2019). An acidic polysaccharide from Ziziphus Jujuba cv. Muzao: Purification and structural characterization. *Food Chemistry*, *274*, 494-499. https://doi.org/10.1016/j.foodchem.2018.09.037

Kasperowicz, M. B., Chomka, G. P., & Bil, T. (2020). Determination of Supply Pressure during Cutting Fish Using High-Pressure Water Stream Taking into Account the Cutting Place and Diameter of the Water Nozzle. *International Journal of Food Engineering*, *16*(3). https://doi.org/10.1515/ijfe-2018-0395

Li, Q., Wu, Q. Y., Jiang, W., Qian, J. Y., Zhang, L., Wu, M., . . . Wu, C. S. (2019). Effect of pulsed electric field on structural properties and digestibility of starches with different crystalline type in solid state. *Carbohydr Polym*, *207*, 362-370. https://doi.org/10.1016/j.carbpol.2018.12.001

Li, Z., & Lin, Z. (2021). Recent advances in polysaccharide-based hydrogels for synthesis and applications. *Aggregate*, *2*(2), e21. https://doi.org/10.1002/agt2.21

Liu, Y., Yang, L., Ma, C., & Zhang, Y. (2019). Thermal Behavior of Sweet Potato Starch by Non-Isothermal Thermogravimetric Analysis. *Materials (Basel)*, *12*(5). https://doi.org/10.3390/ma12050699

Madoumier, M., Trystram, G., Sébastian, P., & Collignan, A. (2019). Towards a holistic approach for multi-objective optimization of food processes: A critical review. *Trends in Food Science & Technology*, *86*, 1-15. https://doi.org/10.1016/j.tifs.2019.02.002

Merci, A., Mali, S., & Carvalho, G. M. d. (2019). Waxy maize, corn and cassava starch: Thermal degradation kinetics. *Semina: Ciências Exatas e Tecnológicas*, *40*(1), 13-22. https://doi.org/10.5433/1679-0375.2019v40n1p13

Mohammed, J. K., Mahdi, A. A., Ahmed, M. I., Ma, M., & Wang, H. (2020). Preparation, deproteinization, characterization, and antioxidant activity of polysaccharide from Medemia argun fruit. *International Journal of Biological Macromolecules*, *155*, 919-926. https://doi.org/10.1016/j.ijbiomac.2019.11.050

Nawaz, A., Xiong, Z., Li, Q., Xiong, H., Irshad, S., Chen, L., . . . Regenstein, J. M. (2019). Evaluation of physicochemical, textural and sensory quality characteristics of red fish meat-based fried snacks. *J Sci Food Agric*, *99*(13), 5771-5777. https://doi.org/10.1002/jsfa.9845

Ozawa, T. (1965). A new method of analyzing thermogravimetric data. *Bulletin of the Chemical Society of Japan*, *38*(11), 1881-1886.

Plazanet, I., Zerrouki, R., Montplaisir, D., Gady, C., Boens, B., & Costa, G. (2018). Effect of ionic liquids on dissolution and identification of wood polysaccharides. *Ann Glycomics Lipidomics AGL*, *101*. https://doi.org/10.29011/AGL-101/100001

Ren, Y., Wu, Z., Shen, M., Rong, L., Liu, W., Xiao, W., & Xie, J. (2021). Improve properties of sweet potato starch film using dual effects: Combination Mesona chinensis Benth polysaccharide and sodium carbonate. *LWT*, *140*, 110679. https://doi.org/10.1016/j.lwt.2020.110679

Schuldt, S., Schneider, Y., & Rohm, H. (2018). High-speed cutting of foods: Cutting behavior and initial cutting forces. *Journal of Food Engineering*, *230*, 55-62. https://doi.org/10.1016/j.jfoodeng.2018.02.024

Shah, M. A., Khan, M. N. S., & Kumar, V. (2018). Biomass residue characterization for their potential application as biofuels. *Journal of Thermal Analysis and Calorimetry*, *134*(3), 2137-2145. https://doi.org/10.1007/s10973-018-7560-9

Simpson, R., Jiménez, D., Almonacid, S., Nuñez, H., Pinto, M., Ramírez, C., . . . Angulo, A. (2020). Assessment and outlook of variable retort temperature profiles for the thermal processing of packaged foods: Plant

productivity, product quality, and energy consumption. *Journal of Food Engineering*, *275*, 109839. https://doi.org/10.1016/j.jfoodeng.2019.109839

Simpson, R., Ramirez, C., Jiménez, D., Almonacid, S., Nuñez, H., & Angulo, A. (2019). Simultaneous multi-product sterilization: Revisited, explored, and optimized. *Journal of Food Engineering*, *241*, 149-158. https://doi.org/10.1016/j.jfoodeng.2018.08.007

Vandenberghe, E., Charalambides, M. N., Mohammed, I. K., De Ketelaere, B., De Baerdemaeker, J., & Claes, J. (2017). Determination of a critical stress and distance criterion for crack propagation in cutting models of cheese. *Journal of Food Engineering, 208*, 1-10. https://doi.org/10.1016/j.jfoodeng.2017.04.005

Vicent, V., Ndoye, F.-T., Verboven, P., Nicolaï, B., & Alvarez, G. (2019). Effect of dynamic storage temperatures on the microstructure of frozen carrot imaged using X-ray micro-CT. *Journal of Food Engineering, 246*, 232-241. https://doi.org/10.1016/j.jfoodeng.2018.11.015