CHARACTERIZATION OF BROILER CHICKEN HEAD GELATIN FOR MICROCAPSULES USING CROSSLINKED GELATIN-SAGO STARCH COMPLEX COACERVATES

By

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Malaysia is a surplus poultry producing country, and an immense quantity of poultry by-products are generated, most of which are discarded or underutilized. Chicken heads could be a potential source of gelatin as it is rich in protein. Gelatin extraction methods with combination of alkaline-acid pretreatment (E1), acid pretreatment (E2) and alkaline pretreatment (E3) were studied to extract the gelatin from broiler chicken heads. Methods E1 and E2 produced high bloom Type A gelatin (> 300 g) with < 1% ash content, high gelling (25.8-26.0 °C) and melting temperatures (30.8-32.3 °C), good functionality and physical appearance. Compared to bovine gelatin, gelatins of E1 and E2 had higher viscous (G'') and elastic modulus (G') values on cooling and heating. FTIR spectra indicated different degree of structural denaturation in gelatins. Both methods E1 and E2 yielded higher quality gelatin than E3. Yet, the combination of alkaline-acid pretreatment in E1 was the most effective extraction method to obtain high quality gelatin from chicken heads. Next, the physicochemical properties of gelatin extracted from the chicken head at 60, 75 and 90 °C for 3 and 6 h, respectively were determined. An increase in extraction temperature (ETE) and extraction time (ETI) contributed to higher yield and bloom. At 90 °C, gelatin bloom and viscoelastic properties began to drop. ETE was highly correlated with yield (r = 0.954). Gelatin extracted at 75 °C exhibited superior properties with bloom strength of > 309 g, high in G', G'', gelling (27-28 °C) and melting (33-34 °C) temperatures with great viscoelastic properties. All gelatins were of type A with α-chains as major protein. FTIR bands indicated different degrees of structural change. Glycine was the main amino acid in G75/6 (20.69%) with total imino acid of 23.19%. Regression models were significant ($p < 0.05$) and highly fitted for yield and a* ($R^2 > 0.9779$). Present findings suggest the feasibility to extract high quality gelatin from the chicken head by manipulating ETE and ETI. Complexes formation from chicken head gelatin (CHG) and sago starch (SA) was investigated as a function of pH (8.0-2.0), CHG-SA ratio (1:5-5:1, w/w), biopolymer concentration (0.1-0.9%, w/v) and sago starch concentration (0.1-0.9%, w/v). The optimum conditions for CHG-SA coacervation (1:3, w/w) were identified to be pH 6.02, achieving maximum turbidity and zero ζ potential value. The increased in total biopolymer (0.1%-0.9%) and SA

concentration increase the turbidity value. The pHopt increased as the CHG-SA mixing ratio (1:5-1:1) increased. The CHG-SA complexes had higher amide I peak intensity than CHG in FTIR analysis, indicating the formation of coacervates. Following this, CHG-SA complex coacervates were crosslinked with tannic acid (TA) and employed as the shell material to produce Citronella oil. The secondary structure of gelatin was observed to change in crosslinked CHG-SA coacervates, as evidenced by a shift in the amine spectrum due to hydrogen bonding with TA. Crosslinking improved the thermal stability and particle size of the coacervates due to the hardening effect. Crosslinked coacervates displayed higher peak intensity in X-ray diffraction analysis suggesting enhanced intermolecular bonding (increase in gelatin helix) after crosslinking. Citronella oil microcapsules prepared from crosslinked CHG-SA coacervates had an average particle size of 78 μm with an encapsulation efficiency of 68% and were thermally stable up to 315 °C. Overall, high quality gelatin could be extracted from chicken heads, and this gelatin could form complex with sago starch and to create CHG-SA coacervates. Such coacervates can be used as a wall material to encapsulate citronella oil, preserving its bioactivity for further food applications.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Doktor Falsafah

PENCIRIAN GELATIN KEPALA AYAM BROILER UNTUK PENYEDIAAN MIKROKAPSUL MENGGUNAKAN KOMPLEKS KOASERVASI GELATIN-KANJI SAGU DISAMBUNG SILANG

Oleh

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Industri ternakan ayam berskala besar di Malaysia telah menghasilkan banyak produk sampingan ayam yang kebanyakannya dibuang atau kurang digunakan. Kepala ayam yang kaya dengan protein amat berpotensi untuk dijadikan sumber gelatin. Kaedah pengekstrakan gelatin yang melibatkan penggunaan alkali-asid (E1), asid (E2) dan alkali (E3) telah dikaji untuk mengekstrak gelatin daripada kepala ayam. Kaedah E1 dan E2 menghasilkan gelatin Jenis A dangan kekuatan bloom yang tinggi (> 300 g), kandungan abu < 1%, suhu gel (25.8-26.0 °C) dan suhu lebur (30.8-32.3 °C) yang tinggi, mempunyai fungsi gelatin dan penampilan fizikal yang baik. Gelatin E1 dan E2 mempunyai nilai modulus likat (G'') dan modulus elastik (G') yang lebih tinggi daripada gelatin lembu semasa process penyejukan dan pemanasan. Spektra FTIR menunjukkan struktur gelatin mengalami tahap denaturasi yang berbeza. Kaedah E1 dan E2 menghasilkan gelatin yang lebih berkualiti daripada E3. Walao bagaimanapun, kaedah kombinasi alkali-asid (E1) dikenalpasti sebagai kaedah pengekstrakan terbaik untuk menghasilkan gelatin yang berkualiti tinggi daripada kepala ayam. Seterusnya, pengekstrakan gelatin daripada kepala ayam telah dijalankan pada 60, 75 dan 90 °C selama 3 dan 6 jam dan sifat fizikokimia gelatin tersebut ditentukan. Peningkatan masa (ETI) dan suhu ekstrasi (ETE) meningkatkan hasil ekstraksi dan kekuatan bloom gelatin. Akan tetapi, kekuatan bloom dan sifat viskoelastik mula menurun pada 90 °C. ETE berkorelasi kuat dengan hasil ekstraksi (r = 0.954). Gelatin yang diekstrak pada suhu 75 °C mempamerkan sifat superior dengan kekuatan bloom > 309 g, mempunyai nilai G', G'', suhu gel (27-28 °C) dan suhu lebur (33-34 °C) yang tinggi serta menunjukkan sifat viskoelastik yang baik. Semua gelatin ekstraksi adalah Jenis A dan mempunyai rantai α sebagai protein utama. FTIR menunjukkan struktur gelatin mengalami tahap perubahan yang berbeza. Glycine merupakan asid amino utama dalam gelatin G75/6 (20.69%) dengan kandungan asid imino sebanyak 23.19%. Model regresi adalah signifikan ($p < 0.05$) dan fit untuk hasil ekstraksi dan nilai a* ($R^2 > 0.9779$). Kajian ini mencadangkan kebolehlaksanaan untuk mengekstrak gelatin berkualiti tinggi daripada kepala ayam dengan memanipulasikan ETE dan ETI. Dalam kajian ketiga, pembentukan kompleks daripada gelatin kepala ayam (CHG) dan kanji sago (SA) telah dikaji atas faktor pH (8.0-2.0), nisbah CHG-SA

(1:5-5:1, w/w), kepekatan biopolimer (0.1-0.9%, w/v) dan kepekatan kanji sago (0.1-0.9%, w/v). Keadaan optimum untuk koaservasi CHG-SA (1:3, w/w) dikenal pasti pada pH 6.02, mencapai turbiditi maksimum dan nilai potensi **ζ** sifar. Nilai turbiditi meningkat apabila jumlah kepekatan biopolimer (0.1-0.9%) dan kepekatan SA meningkat. Nilai pHopt meningkat seiring dengan peningkatan nisbah pencampuran CHG-SA (1:5-1:1). Kompleks CHG-SA mempamerkan intensiti puncak amida I yang lebih tinggi berbanding CHG dalam analisis FTIR, ini menunjukkan pembentukan koaservasi. Seterusnya, kompleks koaservasi CHG-SA disambung silang dengan asid tannik (TA), dan digunakan sebagai dinding untuk memikroenkapsulasikan minyak Citronella. Penyilangan mengubah struktur sekunder gelatin dalam koaservasi CHG-SA, seperti yang dibuktikan dalam peralihan amina dalam spektra FTIR akibat ikatan hidrogen dengan TA. Penyilangan meningkatkan kestabilan terma dan ukuran partikel akibat kesan pengerasan proses penyilangan. Analisis difraksi sinar-X menunjukkan koaservasi CHG-SA yang ditaut silang mempunyai intensiti puncak yang lebih tinggi akibat peningkatan helik gelatin dan ikatan antara molekul selepas proses penyilangan. Mikrokapsul minyak Citronella yang disediakan daripada koaservasi CHG-SA disambung silang mempunyai ukuran partikel purata 78 μm dengan kecekapan pengkapsulan 68% dan stabil sehingga 315 °C. Secara keseluruhannya, gelatin berkualiti tinggi boleh diekstrak daripada kepala ayam, dan gelatin ini boleh dikomplekskan dengan kanji sago untuk membentuk koacervasi CHG-SA. Koacervasi ini boleh digunakan sebagai bahan dinding untuk mengkapsulasi minyak Citronella, mengekalkan bioaktivitinya untuk aplikasi makanan selanjutnya.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ATR	Attenuated Total Reflectance
CAGR	Compound Annual Growth Rate
CHG	Chicken head gelatin
CHG-SA	Chicken head gelatin-sago starch
ETE	Extraction temperature
ETI	Extraction time
FTIR	Fourier Transform Infrared Spectroscopy
GMIA	Gelatin Manufacturers Institute of America
HCl	Hydrochloric acid
HPLC	High Performance Liquid Chromatography
Hyp	Hydroxyproline
pI	Isoelectric point
NaCl	Sodium chloride
NaOH	Sodium hydroxide
OECD	The Organization for Economic Cooperation and Development
Pro	Proline
SA	Sago starch
SDS-PAGE	Sodium dodecyl-sulfate polyacrylamide gel electrophoresis
SEM	Scanning Electron Microscope
TA	Tannic acid
TGA	Thermal Gravimetric Analysis
XRD	X-Ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 Background and problem statement

What makes gelatin a popular ingredient in the food industry? It is its versatility, unique thermo-reversible properties and has multiple functions compared to other biopolymers. Gelatin (Latin: gelatos meaning "stiff") is polypeptides obtained by the partial hydrolysis of collagen from animal skin, bones, and white connective tissue. Gelatin is practically tasteless and odourless brittle solid in a faintly yellow color and it has ability to form thermos-reversible gels. It is mainly used in food such as confections, reduced calorie products, baked goods, dairy products, meat and sausages products for its gelling, foaming, emulsifying properties, and other unique functionalities such as texturizer, thickener, water binder, mouthfeel provider, fat reduction, refining agent, colloid stabilizer, and encapsulating properties. In the pharmaceutical, cosmetic and medical industries, gelatin is used to make hard and soft capsules, protein-enriched body-building food products, carbohydrate reducers, dietary supplements, edible films and coatings, hair care products, matrix for implants, plasma expanders, wound dressing, drug delivery microspheres and so on (Karim & Bhat, 2009; Abedinia et al., 2020).

The Global Gelatin Market was valued at USD 2.4 billion in 2022 and is expected to grow to USD 5.9 billion by 2028, at a CAGR of 4.3 % (Figure 1.1). Conventional commercial gelatin sources are mostly manufactured from bovine and porcine bones and hides. Due to the long life cycle of the two conventional sources and increasing global demand in the food and pharmaceutical industries, there has been an aggressive search for alternative gelatin sources with equal or superior properties. Chicken heads could fill in this additional demand of gelatin. This portion of poultry are generally regarded as useless, had been discarded by-poultry processing plants and their uses are more to niche market such as being rendered into poultry by-products meal for feeding farmed fish and shrimp in Malaysia. This underutilized proteinaceous poultry by products have great potential for value-added food applications.

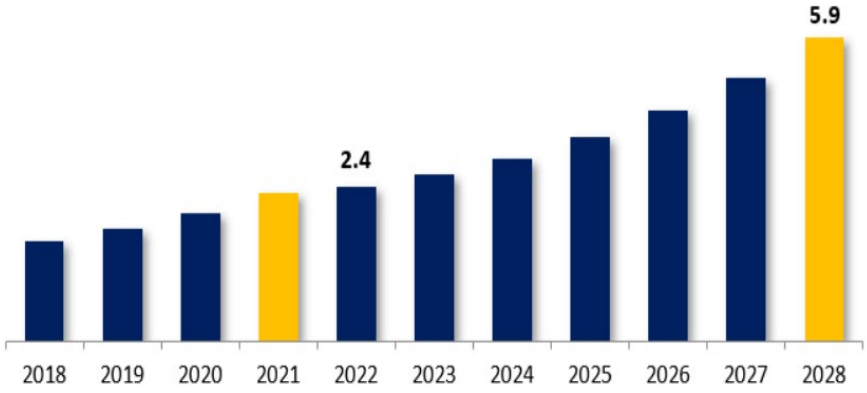

Figure 1.1: The global gelatin market by value (USD Billion), 2018-2028 (Source: BlueWeave Consulting, 2022)

Chicken heads make up around 2% of the body (skin, comb, wattle, cartilages, and bones), although not consumed by human, is an appropriate and promising source for gelatin production due to their high collagen content. Production of gelatin from chicken heads could provide a sustainable gelatin supply as poultry has much shorter production cycle that allows production benefits compared to bovine and porcine. It is economically viable to extract gelatin from chicken head given the projected rapid growth in the industries in years to come with the continuous supply of raw material from poultry processing. Poultry processing industry is possibly one of the world's fastest growing agro-food sectors, with the world poultry meat production is anticipated to reach 141 million metric tonnes by 2028 (OECD/FAO, 2021). At the same time, approximately 22-30% or 40 million metric tonnes of poultry by products (including head, viscera, blood and feathers) were generated. Furthermore, gelatin from poultry has almost no issue with the dietary and religious concern as long as those poultry are raised with proper farming practice and slaughter according to the halal and good slaughtering procedure.

Proteins and polysaccharides are two of the most used essential ingredients that contribute greatly to the functional properties of a food system. Complexation between proteins and polysaccharides through electrostatic interactions lead to formation of complex coacervate or liquid–liquid phase separation, and are influenced by processing conditions such as pH, ionic strength, protein to polysaccharide ratio and crosslinking agent (Devi et al., 2017). Gelatin-polysaccharides complex coacervation system is very attractive due to their availability, biocompatibility, biodegradability and safe characteristics. The preparation of protein-polysaccharide complexes with enhanced functionalities such as improved thermal stability, emulsifying and rheological properties provide opportunities for the development of new ingredients for the food industry. Complexes can be used as food stabilizer, emulsifier, fat replacer, cosmetic and gaining research interest for microencapsulation. Gelatin-polysaccharide complexes was employed as wall material for encapsulating hydrophobic flavor oils into microspheres through coacervation process (Lengyel et al., 2019). During this process, crosslinking reagent such as tannic acid was added to harden and strengthen the structure of

microcapsule walls instead of conventional aldehydes reagents that is toxic and undesirable for food use.

The general objective of this study was to produce gelatin from the chicken head with different extraction methods and conditions. Proper study of the extraction procedures led to the extraction of good quality gelatin from chicken head. The extracted gelatins are stabilized and characterized. Gelatin extraction methods were optimized for quality and yield improvement. Findings on gelatin properties and gelatin recovery prediction may benefit the further industrial sectors. In the second stage, the complexation of extracted gelatin with sago starch was performed under the influence of pH, ratio and concentration of biopolymers. The effect of modification is investigated and the optimum condition for complex coacervation of chicken head gelatin-sago starch (CHG-SA) were identified. Gelatin behaves cationically in coacervation due to its polypeptide structure that favors interactions with wide range of water-soluble anionic polymers to form complex. Sago starch is an underutilized crop with promising industry potential due to its high yield and inexpensive, which makes it worthwhile for exploitation. The fabricated CHG-SA complex was then crosslinked with tannic acid (TA) and employed as wall material to produce citronella oil microcapsules. The resulting CHG-SA complex coacervates and citronella oil microcapsules were characterized in terms of their protein conformation, microstructure and thermal properties.

1.2 Objectives

The objectives of this study were as below,

1. To extract and determine the characteristic of gelatin from chicken heads by acid and alkaline extraction methods.

2. To determine the combined effect of temperature-time using warm water rendering on the properties of extracted chicken head gelatin.

3. To investigate the formation of complex coacervation from gelatin and sago starch as a function of pH, biopolymer ratio and concentration.

4. To investigate the effect of tannic acid crosslinking on gelatin and sago starch complex coacervates

5. To prepare citronella oil microcapsule from tannic acid-crosslinked gelatin and sago starch complex coacervates

REFERENCES

Abedinia, A., Alimohammadi, F., Teymori, F., Razgardani, N., Saeidi Asl, M. R., Ariffin, F., ... & Roslan, J. (2021). Characterization and cell viability of probiotic/prebiotics film based on duck feet gelatin: a novel poultry gelatin as a suitable matrix for probiotics. Foods, 10(8), 1761.

Abedinia, A., Ariffin, F., Huda, N., & Nafchi, A. M. (2017). Extraction and characterization of gelatin from the feet of Pekin duck (*Anas platyrhynchos domestica*) as affected by acid, alkaline, and enzyme pretreatment. International Journal of Biological Macromolecules, 98, 586-594.

Abedinia, A., Nafchi, A. M., Sharifi, M., Ghalambor, P., Oladzadabbasabadi, N., Ariffin, F., & Huda, N. (2020). Poultry gelatin: Characteristics, developments, challenges, and future outlooks as a sustainable alternative for mammalian gelatin. Trends in Food Science & Technology, 104, 14-26.

Abiddin, N. Z., Yusoff, A., & Ahmad, N. (2018). Effect of octenylsuccinylation on physicochemical, thermal, morphological and stability of octenyl succinic anhydride (OSA) modified sago starch. Food Hydrocolloids, 75, 138-146.

Ab Rahim, H., Ahmad, H., & Ab Rahim, M. H. (2021). Extraction of Gelatin from Different Parts of *Gallus Gallus Domesticus*. Current Science and Technology, 1(1), 50-55.

Albano, K. M., & Nicoletti, V. R. (2018). Ultrasound impact on whey protein concentrate-pectin complexes and in the O/W emulsions with low oil soybean content stabilization. Ultrasonics Sonochemistry, 41, 562-571.

Albu, M. G., Ghica, M. V., Giurginca, M., Trandafir, V., Popa, L., & Cotrut, C. (2009). Spectral characteristics and antioxidant properties of tannic acid immobilized on collagen drug-delivery systems. Revista de Chimie, 60, 666–672.

Alexandre, J. D. B., Barroso, T. L. C. T., Oliveira, M. D. A., Mendes, F. R. D. S., Costa, J. M. C. D., Moreira, R. D. A., & Furtado, R. F. (2019). Cross-linked coacervates of cashew gum and gelatin in the encapsulation of pequi oil. Ciência Rural, 49.

Almeida, P. F., & Lannes, S. C. D. S. (2013). Extraction and physicochemical characterization of gelatin from chicken by-product. Journal of Food Process Engineering, 36(6), 824-833.

Almeida, P. F., Silva Lannes, S. C., Calarge, F. A., Brito Farias, T. M., & Santana, J. C. C. (2012). FTIR characterization of gelatin from chicken feet. Journal of Chemistry and Chemical Engineering, 6(11), 1029–1032.

Amalraj, A., Jude, S., Sukumaran, N. P., & Gopi, S. (2019). Nanomaterials in nutraceutical and phytonutrient industries. In Industrial applications of nanomaterials (pp. 441-474). Elsevier.

Anandharamakrishnan, C., Rielly, C. D., & Stapley, A. G. (2010). Spray-freeze-drying of whey proteins at sub-atmospheric pressures. Dairy Science & Technology, 90(2), 321-334.

Anvari, M., & Chung, D. (2016). Dynamic rheological and structural characterization of fish gelatin–Gum arabic coacervate gels cross-linked by tannic acid. Food Hydrocolloids, 60, 516-524.

AOAC (2012). Official Methods of Analysis of AOAC INTERNATIONAL (19th Ed.). AOAC INTERNATIONAL, Gaithersburg.

Araújo, Í. B. D. S., Bezerra, T. K. A., Nascimento, E. S. D., Gadelha, C. A. D. A., Santi-Gadelha, T., & Madruga, M. S. (2018). Optimal conditions for obtaining collagen from chicken feet and its characterization. Food Science and Technology, 38, 167-173.

Aryee, F. N., & Nickerson, M. T. (2012). Formation of electrostatic complexes involving mixtures of lentil protein isolates and gum Arabic polysaccharides. Food Research International, 48(2), 520-527.

Aykın-Dinçer, E., Koç, A., & Erbaş, M. (2017). Extraction and physicochemical characterization of broiler (*Gallus gallus domesticus*) skin gelatin compared to commercial bovine gelatin. Poultry Science, 96(11), 4124-4131.

Azilawati, M. I., Hashim, D. M., Jamilah, B., & Amin, I. (2014). Validation of a reverse-phase high-performance liquid chromatography method for the determination of amino acids in gelatins by application of 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate reagent. Journal of Chromatography A, 1353, 49–56.

Baiocco, D., Preece, J. A., & Zhang, Z. (2021). Microcapsules with a fungal chitosan-gum Arabic-maltodextrin shell to encapsulate health-beneficial peppermint oil. Food Hydrocolloids for Health, 1, 100016.

Bannikova, A., Zyainitdinov, D., Evteev, A., Drevko, Y., & Evdokimov, I. (2020). Microencapsulation of polyphenols and xylooligosaccharides from oat bran in whey protein-maltodextrin complex coacervates: In-vitro evaluation and controlled release. Bioactive Carbohydrates and Dietary Fibre, 23, 100236.

Baranauskaite, J., Kopustinskiene, D. M., & Bernatoniene, J. (2019). Impact of gelatin supplemented with gum arabic, tween 20, and β-cyclodextrin on the microencapsulation of Turkish oregano extract. Molecules, 24(1), 176.

Barbosa, A. E. G., Bastos, L. P. H., & Garcia-Rojas, E. E. (2021). Complex coacervates formed between whey protein isolate and carboxymethylcellulose for encapsulation of β-carotene from sacha inchi oil: stability, in vitro digestion and release kinetics. Food Biophysics, 16(3), 293-305.

Barresi, A. A., Pisano, R., Fissore, D., Rasetto, V., Velardi, S. A., Vallan, A., ... & Galan, M. (2009). Monitoring of the primary drying of a lyophilization process in vials. Chemical Engineering and Processing: Process Intensification, 48(1), 408-423.

Bastos, L. P. H., Vicente, J., dos Santos, C. H. C., de Carvalho, M. G., & Garcia-Rojas, E. E. (2020). Encapsulation of black pepper (*Piper nigrum L.*) essential oil with gelatin and sodium alginate by complex coacervation. Food Hydrocolloids, 102, 105605.

Benjakul, S., Oungbho, K., Visessanguan, W., Thiansilakul, Y., & Roytrakul, S. (2009). Characteristics of gelatin from the skins of bigeye snapper, *Priacanthus tayenus* and *Priacanthus macracanthus*. Food Chemistry, 116, 445–451.

Benjakul, S., Thiansilakul, Y., Visessanguan, W., Roytrakul, S., Kishimura, H., Prodpran, T., & Meesane, J. (2010). Extraction and characterisation of pepsin-solubilised collagens from the skin of bigeye snapper (*Priacanthus tayenus* and *Priacanthus macracanthus*). Journal of the Science of Food and Agriculture, 90, 132–138.

Bichukale, A. D., Koli, J. M., Sonavane, A. E., Vishwasrao, V. V., Pujari, K. H., & Shingare, P. E. (2018). Functional properties of gelatin extracted from poultry skin and bone waste. International Journal of Pure & Applied Bioscience, 6(4), 87-101.

BlueWeave Consulting and Research Pvt Ltd. (2022). Global gelatin market to grow at a CAGR of 4.3% during 2022-2028. Retrieved from https://www.globenewswire.com/en/news-release/2022/06/13/2461445/0/en/Global-Gelatin-Market-to-Grow-at-a-CAGR-of-4-3-during-2022-2028-BlueWeave-Consulting.html

Bordón, M. G., Barrera, G. N., Penci, M. C., Bori, A., Caballero, V., Ribotta, P., & Martínez, M. L. (2020). Microencapsulation of chia seed oil (*Salvia hispanica L.*) in spray and freeze-dried whey protein concentrate/soy protein isolate/gum arabic (WPC/SPI/GA) matrices. Multidisciplinary Digital Publishing Institute Proceedings, 53(1), 22.

Calderón-Oliver, M., Pedroza-Islas, R., Escalona-Buendía, H. B., Pedraza-Chaverri, J., & Ponce-Alquicira, E. (2017). Comparative study of the microencapsulation by complex coacervation of nisin in combination with an avocado antioxidant extract. Food Hydrocolloids, 62, 49-57.

Cattelan, M. G., de Oliveira Nishiyama, Y. P., Gonçalves, T. M. V., & Coelho, A. R. (2018). Combined effects of oregano essential oil and salt on the growth of Escherichia coli in salad dressing. Food microbiology, 73, 305-310.

Chakka, A. K., Muhammed, A., Sakhare, P. Z., & Bhaskar, N. (2017). Poultry processing waste as an alternative source for mammalian gelatin: Extraction and characterization of gelatin from chicken feet using food grade acids. Waste and Biomass Valorization, 8(8), 2583-2593.

Chang, H. W., Tan, T. B., Tan, P. Y., Abas, F., Lai, O. M., Wang, Y., ... & Tan, C. P. (2018). Physical properties and stability evaluation of fish oil-in-water emulsions stabilized using thiol-modified β-lactoglobulin fibrils-chitosan complex. Food Research International, 105, 482-491.

Chen, K. Y., & Yao, C. H. (2011). Repair of bone defects with gelatin-based composites: A review. BioMedicine, 1(1), 29-32.

Chen, C., Yang, H., Yang, X., & Ma, Q. (2022a). Tannic acid: A crosslinker leading to versatile functional polymeric networks: A review. RSC advances, 12(13), 7689-7711.

Chen, K., Zhang, M., Adhikari, B., & Wang, M. (2022b). Microencapsulation of Sichuan pepper essential oil in soybean protein isolate-Sichuan pepper seed soluble dietary fiber complex coacervates. Food Hydrocolloids, 125, 107421.

Chevalier, L. M., Rioux, L. E., Angers, P., & Turgeon, S. L. (2019). Study of the interactions between pectin in a blueberry puree and whey proteins: Functionality and application. Food Hydrocolloids, 87, 61-70.

Chin, S. F., Pang, S. C., & Lim, L. S. (2012). Synthesis and characterization of novel water-soluble starch tartarate nanoparticles. International Scholarly Research Notices, 2012.

Cho, S. H., Jahncke, M. L., Chin, K. B., & Eun, J. B. (2006). The effect of processing conditions on the properties of gelatin from skate (*Raja kenojei*) skins. Food Hydrocolloids, 20(6), 810-816.

Choudhury, N., Meghwal, M., & Das, K. (2021). Microencapsulation: An overview on concepts, methods, properties and applications in foods. Food Frontiers, 2(4), 426-442.

Chua, S. D., Kho, E. P., Lim, S. F., & Hussain, M. H. (2021). Sago palm (Metroxylon sagu) starch yield, influencing factors and estimation from morphological traits. Advances in Materials and Processing Technologies, 1-23.

Costa, A. M., Moretti, L. K., Simões, G., Silva, K. A., Calado, V., Tonon, R. V., & Torres, A. G. (2020). Microencapsulation of pomegranate (*Punica granatum L.*) seed oil by complex coacervation: Development of a potential functional ingredient for food application. LWT, 131, 109519.

da Silva Soares, B., Siqueira, R. P., de Carvalho, M. G., Vicente, J., & Garcia-Rojas, E. E. (2019). Microencapsulation of sacha inchi oil (*Plukenetia volubilis L.*) using complex coacervation: Formation and structural characterization. *Food chemistry*, *298*, 125045.

De Kruif, C. G., Weinbreck, F., & de Vries, R. (2004). Complex coacervation of proteins and anionic polysaccharides. Current opinion in colloid & interface science, 9(5), 340-349.

de Matos, E. F., Scopel, B. S., & Dettmer, A. (2018). Citronella essential oil microencapsulation by complex coacervation with leather waste gelatin and sodium alginate. Journal of Environmental Chemical Engineering, 6(2), 1989-1994.

Devi, N., Sarmah, M., Khatun, B., & Maji, T. K. (2017). Encapsulation of active ingredients in polysaccharide–protein complex coacervates. Advances in colloid and interface science, 239, 136-145.

Djabourov, M., Lechaire, J. P., & Gaill, F. (1993). Structure and rheology of gelatin and collagen gels. Biorheology, 30(3-4), 191-205.

Dong, D., & Cui, B. (2021). Fabrication, characterization and emulsifying properties of potato starch/soy protein complexes in acidic conditions. Food Hydrocolloids, 115, 106600.

Dong, D., Qi, Z., & Cui, B. (2020). Complex formation between soy proteins and potato starch: Effect of pH, biopolymer ratio, and biopolymer concentration. Starch-Stärke, 72(1-2), 1900020.

Dong, Z. J., Xia, S. Q., Hua, S., Hayat, K., Zhang, X. M., & Xu, S. Y. (2008). Optimization of cross-linking parameters during production of transglutaminase-hardened spherical multinuclear microcapsules by complex coacervation. Colloids and Surfaces B: Biointerfaces, 63(1), 41-47.

Du, L., Khiari, Z., Pietrasik, Z., & Betti, M. (2013). Physicochemical and functional properties of gelatins extracted from turkey and chicken heads. Poultry Science, 92, 2463-2474.

Duhoranimana, E., Karangwa, E., Lai, L., Xu, X., Yu, J., Xia, S., ... & Habinshuti, I. (2017). Effect of sodium carboxymethyl cellulose on complex coacervates formation with gelatin: Coacervates characterization, stabilization and formation mechanism. Food Hydrocolloids, 69, 111-120.

Ee, S. C., Bakar, J., Saari, N., Abas, F., & Ismail, A. (2021). Rheological and molecular properties of chicken head gelatin as affected by combined temperature and time using warm water rendering. International Journal of Food Properties, 24(1), 1495-1509.

Ee, S. C., Saari, N., Abas, F., Ismail, A., Abu Bakar, M. K., & Bakar, J. (2019). Properties of chicken head gelatins as affected by extraction method. International Food Research Journal, 26, 499–508.

Emamverdian, P., Kia, E. M., Ghanbarzadeh, B., & Ghasempour, Z. (2020). Characterization and optimization of complex coacervation between soluble fraction of Persian gum and gelatin. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 607, 125436.

Erge, A., & Zorba, Ö. (2018). Optimization of gelatin extraction from chicken mechanically deboned meat residue using alkaline pre-treatment. LWT, 97, 205-212.

Fan, M., & Fu, F. (Eds.). (2016). Advanced high strength natural fibre composites in construction. Woodhead Publishing.

Food Chemicals Codex. (1996). Food Chemicals Codex. Food and Nutrition Board, National Research Council, 4th ed. ed. National Academy Press., Washington, D.C.

Freitas, M. L. F., Albano, K. M., & Telis, V. R. N. (2017). Characterization of biopolymers and soy protein isolate-high-methoxyl pectin complex. Polímeros, 27, 62-67.

Friess, W., & Lee, G. (1996). Basic thermoanalytical studies of insoluble collagen matrices. Biomaterials, 17, 2289–2294.

Gál, R., Mokrejš, P., Mrázek, P., Pavlačková, J., Janáčová, D., & Orsavová, J. (2020). Chicken heads as a promising by-product for preparation of food gelatins. Molecules, 25(3), 494.

Ghica, M. V., Albu, G, M., Popa, L., Leca, M., Brazdaru, L., Trandafir, V., & Cotrut, C. (2009). Drug delivery systems based on collagen-tannic acid matrices. Revue Roumaine de Chimie, 54, 1103–1110.

Ghosh, V., Mukherjee, A., & Chandrasekaran, N. (2014). Eugenol-loaded antimicrobial nanoemulsion preserves fruit juice against, microbial spoilage. Colloids and Surfaces B: Biointerfaces, 114, 392-397.

Giménez, B., Gómez-Guillén, M. C., & Montero, P. (2005a). Storage of dried fish skins on quality characteristics of extracted gelatin. Food Hydrocolloids, 19, 958–963.

Giménez, B., Turnay, J., Lizarbe, M. A., Montero, P., & Gómez-Guillén, M. C. (2005b). Use of lactic acid for extraction of fish skin gelatin. Food Hydrocolloids, 19, 941–950.

Girardi, N. S., García, D., Robledo, S. N., Passone, M. A., Nesci, A., & Etcheverry, M. (2016). Microencapsulation of *Peumus boldus* oil by complex coacervation to provide peanut seeds protection against fungal pathogens. Industrial Crops and Products, 92, 93-101.

Glomm, W. R., Molesworth, P. P., Sandru, E. M., Truong, L. T., Brunsvik, A., & Johnsen, H. (2021). Microencapsulation of peppermint oil by complex coacervation and subsequent spray drying using bovine serum albumin/gum acacia and an oxidized starch crosslinker. Applied Sciences, 11(9), 3956.

GMIA. (2013). Standard testing methods for edible gelatin. Official procedure of the gelatin manufacturers Institute of America, Inc. http://www.gelatin-gmia.com /images/ GMIA_Official_Methods_of_Gelatin_Revised_2013.pdf.

Gomez-Estaca, J., Comunian, T. A., Montero, P., Ferro-Furtado, R., & Fávaro-Trindade, C. S. (2016). Encapsulation of an astaxanthin-containing lipid extract from shrimp waste by complex coacervation using a novel gelatin–cashew gum complex. Food Hydrocolloids, 61, 155-162.

Gómez-Guillén, M. C., Giménez, B., López-Caballero, M. A., & Montero, M. P. (2011). Functional and bioactive properties of collagen and gelatin from alternative sources: A review. Food hydrocolloids, 25(8), 1813-1827.

Gómez-Guillén, M. C., Turnay, J., Fernández-Díaz, M. D., Ulmo, N., Lizarbe, M. a., & Montero, P. (2002). Structural and physical properties of gelatin extracted from different marine species: A comparative study. Food Hydrocolloids, 16, 25–34.

Gudmundsson, M., & Hafsteinsson, H. (1997). Gelatin from cod skins as affected by chemical treatments. Journal of Food Science, 62, 37–39.

Gündem, A., & Tarhan, Ö. (2021). Collagen/gelatin extraction from poultry skin and mechanically deboned meat (mdm) residues. Akademik Gıda, 19(2), 116-125.

Ham, Y. K., Song, D. H., Noh, S. W., Gu, T. W., Lee, J. H., Kim, T. K., ... & Kim, H. W. (2020). Effects of gelatin hydrolysates addition on technological properties and lipid oxidation of cooked sausage. Food Science of Animal Resources, 40(6), 1033.

He, R., Ye, J., Wang, L., & Sun, P. (2020). Preparation and evaluation of microcapsules encapsulating royal jelly sieve residue: Flavor and release profile. Applied Sciences, 10(22), 8126.

Hernández-Nava, R., López-Malo, A., Palou, E., Ramírez-Corona, N., & Jiménez-Munguía, M. T. (2020). Encapsulation of oregano essential oil (*Origanum vulgare*) by complex coacervation between gelatin and chia mucilage and its properties after spray drying. Food Hydrocolloids, 109, 106077.

Hu, S., Wang, T., Fernandez, M. L., & Luo, Y. (2016). Development of tannic acid cross-linked hollow zein nanoparticles as potential oral delivery vehicles for curcumin. Food Hydrocolloids, 61, 821-831.

Huang, G. Q., Xiao, J. X., Qiu, H. W., & Yang, J. (2014). Cross-linking of soybean protein isolate–chitosan coacervate with transglutaminase utilizing capsanthin as the model core. Journal of Microencapsulation, 31(7), 708-715.

Irma, K. K., Qurrota, A., Hanina, M., & Marsasi, M. R. A. (2019, April). Encapsulation of peppermint oil with carboxymethyl kappa carrageenan-gelatine-chitosan. In IOP Conference Series: Materials Science and Engineering (Vol. 515, No. 1, p. 012096). IOP Publishing.

Jain, A., Thakur, D., Ghoshal, G., Katare, O. P., & Shivhare, U. S. (2015). Microencapsulation by complex coacervation using whey protein isolates and gum acacia: an approach to preserve the functionality and controlled release of β-carotene. Food and Bioprocess Technology, 8(8), 1635-1644.

Jamilah, B., & Harvinder, K.G. (2002). Properties of gelatins from skins of fish - Black tilapia (*Oreochromis mossambicus*) and red tilapia (*Oreochromis nilotica*). Food Chemistry 77, 81–84.

Jang, E. G., Lim, J., & Kim, K. -O. (2002). Effect of soaking condition on the physicochemical properties of chicken feet gelatin. Korean Journal of Food Science and Technology, 34, 425–430.

Johnston-Banks, F. A. (1990). Gelatin. In P. Harris (Ed.), Food gels (pp. 233-289). London: Elsevier Applied Science Publishers.

Kadarani, D. K., & Jannah, A. (2022). Optimization chicken bones gelatin extraction using hydrochloric acid immersion and multi-stage thermal treatment. ALCHEMY: Journal of Chemistry, 10(1), 1-7.

Kakaraparthi, P. S., Srinivas, K. V. N. S., Kumar, J. K., Kumar, A. N., Rajput, D. K., & Sarma, V. U. M. (2014). Variation in the essential oil content and composition of Citronella (*Cymbopogon winterianus Jowitt*.) in relation to time of harvest and weather conditions. Industrial Crops and Products, 61, 240-248.

Kang, Y. R., Lee, Y. K., Kim, Y. J., & Chang, Y. H. (2019). Characterization and storage stability of chlorophylls microencapsulated in different combination of gum Arabic and maltodextrin. Food chemistry, 272, 337-346.

Karim, A. A., & Bhat, R. (2009). Fish gelatin: properties, challenges, and prospects as an alternative to mammalian gelatins. Food hydrocolloids, 23(3), 563-576.

Kaushik, P., Dowling, K., McKnight, S., Barrow, C. J., & Adhikari, B. (2016). Microencapsulation of flaxseed oil in flaxseed protein and flaxseed gum complex coacervates. Food research international, *86*, 1-8.

Keirudin, A. A., Zainuddin, N., & Yusof, N. A. (2020). Crosslinked carboxymethyl sago starch/citric acid hydrogel for sorption of Pb^{2+}, Cu^{2+}, Ni^{2+} and Zn^{2+} from aqueous solution. Polymers, 12(11), 2465.

Kemp, W. (1987). Organic Spectroscopy. Mac- millan Education Ltd, Hampshire, UK.

Khong, N. M. H., Yusoff, F. M., Jamilah, B., Basri, M., Maznah, I., Chan, K.W., Armania, N., & Nishikawa, J. (2018). Improved collagen extraction from jellyfish (*Acromitus hardenbergi*) with increased physical-induced solubilization processes. Food Chemistry, 251, 41–50.

Kim, H., Beak, S. E., Yang, S. Y., & Song, K. B. (2018). Application of an antimicrobial packaging material from chicken bone gelatine and cinnamon bark oil to mozzarella cheese. International Journal of Food Science & Technology, 53(3), 619-625.

Kim, H. W., Song, D. H., Choi, Y. S., Kim, H. Y., Hwang, K. E., Park, J. H., ... & Kim, C. J. (2012). Effects of soaking pH and extracting temperature on the physicochemical properties of chicken skin gelatin. Food Science of Animal Resources, 32(3), 316-322.

Kim, T. K., Ham, Y. K., Shin, D. M., Kim, H. W., Jang, H. W., Kim, Y. B., & Choi, Y. S. (2020). Extraction of crude gelatin from duck skin: effects of heating methods on gelatin yield. Poultry science, 99(1), 590-596.

Kittiphattanabawon, P., Benjakul, S., Visessanguan, W., & Shahidi, F. (2010). Comparative study on characteristics of gelatin from the skins of brown banded bamboo shark and blacktip shark as affected by extraction conditions. Food Hydrocolloids, 24, 164–171.

Kuan, Y. H., Nafchi, A. M., Huda, N., Ariffin, F., & Karim, A. A. (2017). Comparison of physicochemical and functional properties of duck feet and bovine gelatins. Journal of the Science of Food and Agriculture, 97(5), 1663-1671.

Laemmli, U.K. (1970). Cleavage of structural proteins during assembly of head of bacteriophage T4. Nature, 277, 680–685.

Lages, L. Z., Radünz, M., Gonçalves, B. T., da Rosa, R. S., Fouchy, M. V., Gularte, M. A., ... & Gandra, E. A. (2021). Microbiological and sensory evaluation of meat sausage using thyme (*Thymus vulgaris, L.)* essential oil and powdered beet juice (*Beta vulgaris L.*, Early Wonder cultivar). LWT, 148, 111794.

Lemos, Y. P., Mariano Marfil, P. H., & Nicoletti, V. R. (2017). Particle size characteristics of buriti oil microcapsules produced by gelatin-sodium alginate complex coacervation: Effect of stirring speed. International journal of food properties, 20(sup2), 1438-1447.

Lengyel, M., Kállai-Szabó, N., Antal, V., Laki, A. J., & Antal, I. (2019). Microparticles, microspheres, and microcapsules for advanced drug delivery. Scientia Pharmaceutica, 87(3), 20.

Li, Y., Zhang, X., Zhao, Y., Ding, J., & Lin, S. (2018). Investigation on complex coacervation between fish skin gelatin from cold-water fish and gum arabic: Phase behavior, thermodynamic, and structural properties. Food Research International, 107, 596-604.

Lin, L., Regenstein, J. M., Lv, S., Lu, J., & Jiang, S. (2017). An overview of gelatin derived from aquatic animals: Properties and modification. Trends in Food Science & Technology, 68, 102–112.

Liu, F., Antoniou, J., Li, Y., Ma, J., & Zhong, F. (2015). Effect of sodium acetate and drying temperature on physicochemical and thermomechanical properties of gelatin films. Food Hydrocolloids, 45, 140-149.

Liu, H., Li, D., & Guo, S. (2008). Rheological properties of channel catfish (*Ictalurus punctaus*) gelatine from fish skins preserved by different methods. LWT – Food Science & Technology, 41, 414-419.

Liu, S., Low, N. H., & Nickerson, M. T. (2009). Effect of pH, salt, and biopolymer ratio on the formation of pea protein isolate-gum arabic complexes. Journal of Agricultural and Food Chemistry, 57(4), 1521.

Mad-ali, S., Benjakul, S., Prodpran, T., & Sajid, M. (2017). Characteristics and gel properties of gelatin from goat skin as affected by extraction conditions. Journal of Food Processing and Preservation, 41(3), 1-10.

Manaf, M. A., Subuki, I., Jai, J., Raslan, R., & Mustapa, A. N. (2018, May). Encapsulation of volatile citronella essential oil by coacervation: Efficiency and release study. In IOP conference series: materials science and engineering (Vol. 358, No. 1, p. 012072). IOP Publishing.

Maphosa, Y., & Jideani, V. A. (2018). Factors affecting the stability of emulsions stabilised by biopolymers. Science and Technology Behind Nanoemulsions, 65-80.

Marfil, P. H. M., Paulo, B. B., Alvim, I. D., & Nicoletti, V. R. (2018). Production and characterization of palm oil microcapsules obtained by complex coacervation in gelatin/gum Arabic. Journal of Food Process Engineering, 41(4), e12673.

Marques, C. F., Diogo, G. S., Pina, S., Oliveira, J. M., Silva, T. H., & Reis, R. L. (2019). Collagen-based bioinks for hard tissue engineering applications: A comprehensive review. Journal of Materials Science: Materials in Medicine, 30(3), 1-12.

Mishra, M. (Ed.). (2015). Handbook of encapsulation and controlled release. CRC press.

Mohamood, T., Fattima'Al-Zahara, N., Zainuddin, N., & Tan, S. W. (2018). Preparation, optimization and swelling study of carboxymethyl sago starch (CMSS)–acid hydrogel. Chemistry Central Journal, 12(1), 1-10.

Mokrejš, P., Mrázek, P., Gál, R., & Pavlačková, J. (2019). Biotechnological preparation of gelatines from chicken feet. Polymers, 11(6), 1060.

Moreira, A. C., Martins, I. M., Fernandes, I., Barreiro, M. F., & Rodrigues, A. E. (2016). Microencapsulation of red and white thyme oil in poly (lactic-co-glycolic) acid: Assessment of encapsulation efficiency and antimicrobial capacity of the produced microcapsules. The Canadian Journal of Chemical Engineering, 94(3), 469-475.

Muhammad, D. R. A., Saputro, A. D., Rottiers, H., Van de Walle, D., & Dewettinck, K. (2018). Physicochemical properties and antioxidant activities of chocolates enriched with engineered cinnamon nanoparticles. European Food Research and Technology, 244(7), 1185-1202.

Muhoza, B., Xia, S., Cai, J., Zhang, X., Duhoranimana, E., & Su, J. (2019). Gelatin and pectin complex coacervates as carriers for cinnamaldehyde: Effect of pectin esterification degree on coacervate formation, and enhanced thermal stability. Food Hydrocolloids, 87, 712-722.

Muhoza, B., Xia, S., & Zhang, X. (2019). Gelatin and high methyl pectin coacervates crosslinked with tannic acid: The characterization, rheological properties, and application for peppermint oil microencapsulation. Food Hydrocolloids, 97, 105174.

Muneratto, V. M., Gallo, T. C. B., & Nicoletti, V. R. (2021). Oregano essential oil encapsulation following the complex coacervation method: Influence of

temperature, ionic strength, and pH on the release kinetics in aqueous medium. Ciência e Agrotecnologia, 45.

Muyonga, J. H., Cole, C. G. B., & Duodu, K. G. (2004). Extraction and physico-chemical characterisation of Nile perch (*Lates niloticus*) skin and bone gelatin. Food Hydrocolloids, 18, 581–592.

Nagarajan, M., Benjakul, S., Prodpran, T., Songtipya, P., & Kishimura, H. (2012). Characteristics and functional properties of gelatin from splendid squid (*Loligo formosana*) skin as affected by extraction temperatures. Food Hydrocolloids, 29, 389–397.

Nannapaneni, R., Chalova, V. I., Crandall, P. G., Ricke, S. C., Johnson, M. G., & O'Bryan, C. A. (2009). Campylobacter and Arcobacter species sensitivity to commercial orange oil fractions. International journal of food microbiology, 129(1), 43-49.

Nazmi, N. N., Isa, M. I. N., & Sarbon, N. M. (2017). Preparation and characterization of chicken skin gelatin/CMC composite film as compared to bovine gelatin film. Food Bioscience, 19, 149-155.

Nie, X., Zhao, L., Wang, N., & Meng, X. (2017). Phenolics-protein interaction involved in silver carp myofibrilliar protein films with hydrolysable and condensed tannins. LWT-Food Science and Technology, 81, 258-264.

Nik Muhammad, N. A., Huda, N., Karim, A. A., & Mohammadi Nafchi, A. (2018). Effects of acid type extraction on characterization and sensory profile of duck feet gelatin: Towards finding bovine gelatin alternative. Journal of Food Measurement and Characterization, 12(1), 480-486.

Nikoo, M., Benjakul, S., Ocen, D., Yang, N., Xu, B., Zhang, L., & Xu, X. (2013). Physical and chemical properties of gelatin from the skin of cultured Amur sturgeon (*Acipenser schrenckii*). Journal of Applied Ichthyology 29, 943–950.

Niu, F., Su, Y., Liu, Y., Wang, G., Zhang, Y., & Yang, Y. (2014). Ovalbumin–gum arabic interactions: Effect of pH, temperature, salt, biopolymers ratio and total concentration. Colloids and Surfaces B: Biointerfaces, 113, 477-482.

Noor, N. Q. I. M., Razali, R. S., Ismail, N. K., Ramli, R. A., Razali, U. H. M., Bahauddin, A. R., ... & Shaarani, S. M. (2021). Application of green technology in gelatin extraction: A review. Processes, 9(12), 2227.

Ockerman, H. W., & Hansen, C. L. (2000). Animal by-product processing and utilization. Technomic Publishing, Lancaster, PA.

OECD/FAO. (2015). OECD-FAO Agricultural Outlook 2015. Organisation for Economic Co-operation and Development. OECD Publishing, Paris. doi:http://dx.doi.org/10.1787/agr_outlook-2015-en

OECD/FAO. (2021) OECD-FAO Agricultural Outlook 2021-2030. Meat (6). https://www.fao.org/3/cb5332en/Meat.pdf. FAO: OECD Publishing.

Okazaki, M. (2018). The structure and characteristics of sago starch. In Sago palm (pp. 247-259). Springer, Singapore.

Pakzad, H., Alemzadeh, I., & Kazemi A. (2013). Encapsulation of peppermint oil with arabic gum-gelatin by complex coacervation method. International Journal of Engineering, 26(8), 807-814.

Park, J. H., Choe, J. H., Kim, H. W., Hwang, K. E., Song, D. H., Yeo, E. J., Kim, H. Y., Choi, Y. S., Lee, S. H., & Kim, C. J. (2013). Effects of various extraction methods on quality characteristics of duck feet gelatin. Korean Journal for Food Science of Animal Resources, 33, 162–169.

Payne, K. J., & Veis, A. (1988). Fourier-transform IR, spectroscopy of collagen and gelatin solutions: Deconvolution of the amide I band for conformational studies. Biopolymers, 27, 1749–1760.

Peng, J., Wang, X., & Lou, T. (2020). Preparation of chitosan/gelatin composite foam with ternary solvents of dioxane/acetic acid/water and its water absorption capacity. Polymer Bulletin, 77(10), 5227-5244.

Picchio, M. L., Linck, Y. G., Monti, G. A., Gugliotta, L. M., Minari, R. J., & Igarzabal, C. I. A. (2018). Casein films crosslinked by tannic acid for food packaging applications. Food Hydrocolloids, 84, 424-434.

Polnaya, F. J., Marseno, D. W., & Cahyanto, M. N. (2013). Effects of phosphorylation and cross-linking on the pasting properties and molecular structure of sago starch. International Food Research Journal, 20(4).

Qiu, L., Zhang, M., Adhikari, B., & Chang, L. (2022). Microencapsulation of rose essential oil in mung bean protein isolate-apricot peel pectin complex coacervates and characterization of microcapsules. Food Hydrocolloids, 124, 107366.

Quek, C. H., Li, J., Sun, T., Chan, M. L. H., Mao, H. Q., Gan, L. M., ... & Yu, H. (2004). Photo-crosslinkable microcapsules formed by polyelectrolyte copolymer and modified collagen for rat hepatocyte encapsulation. Biomaterials, 25(17), 3531-3540.

Raei, M., Rafe, A., & Shahidi, F. (2018). Rheological and structural characteristics of whey protein-pectin complex coacervates. Journal of Food Engineering, 228, 25-31.

Rafieian, F., & Keramat, J. (2015). Physicochemical properties of gelatin extracted from chicken deboner residue. LWT - Food Science and Technology, 64, 1370–1375.

Rafieian, F., & Keramat, J., Kadivar, M. (2013). Optimization of gelatin extraction from chicken deboner residue using RSM method. Journal of food science and technology, 50, 374–80.

Raksa, A., Sawaddee, P., Raksa, P., & Aldred, A. K. (2017). Microencapsulation, chemical characterization, and antibacterial activity of *Citrus hystrix* DC (Kaffir

Lime) peel essential oil. Monatshefte für Chemie-Chemical Monthly, 148(7), 1229-1234.

Rammaya, K., Ying, V. Q., & Babji, A. S. (2012). Physicochemical analysis of Gelatin extracted from mechanically deboned chicken meat (mdcm) residue. International Journal of Food, Nutrition and Public Health, 5, 147-168.

Reichling, J., Schnitzler, P., Suschke, U., & Saller, R. (2009). Essential oils of aromatic plants with antibacterial, antifungal, antiviral, and cytotoxic properties–an overview. Complementary Medicine Research, 16(2), 79-90.

Reis, D. R., Ambrosi, A., & Di Luccio, M. (2022). Encapsulated essential oils: A perspective in food preservation. Future Foods, 100126.

Rivera, J. A., Sebranek, J. G., Rust, R. E., & Tabatabai, L. B. (2000). Composition and protein fractions of different meat by-products used for petfood compared with mechanically separated chicken (MSC). Meat science, 55, 53–59.

Rocha-Selmi, G. A., Favaro-Trindade, C. S., & Grosso, C. R. (2013). Morphology, stability, and application of lycopene microcapsules produced by complex coacervation. Journal of Chemistry, 2013.

Rojas-Moreno, S., Osorio-Revilla, G., Gallardo-Velázquez, T., Cárdenas-Bailón, F., & Meza-Márquez, G. (2018). Effect of the cross-linking agent and drying method on encapsulation efficiency of orange essential oil by complex coacervation using whey protein isolate with different polysaccharides. Journal of microencapsulation, 35(2), 165-180.

Rutz, J. K., Borges, C. D., Zambiazi, R. C., Crizel-Cardozo, M. M., Kuck, L. S., & Noreña, C. P. (2017). Microencapsulation of palm oil by complex coacervation for application in food systems. Food Chemistry, 220, 59-66.

Saenmuang, S., Phothiset, S., & Chumnanka, C. (2020). Extraction and characterization of gelatin from black-bone chicken by-products. Food Science and Biotechnology, 29(4), 469-478.

Salvia-Trujillo, L., Rojas-Graü, M. A., Soliva-Fortuny, R., & Martín-Belloso, O. (2015). Use of antimicrobial nanoemulsions as edible coatings: Impact on safety and quality attributes of fresh-cut Fuji apples. Postharvest Biology and Technology, 105, 8-16.

Samsudin, F. S., Aminal'lah, N., Zain, F. A. M., Kamarudin, A. S., Marlida, Y., & Huda, N. (2018). Physicochemical properties of quail bone gelatin extract with hydrochloric acid and citric acid. Journal of Agrobiotechnology, 9(1S), 92-101.

Santana, J. C., Gardim, R. B., Almeida, P. F., Borini, G. B., Quispe, A. P., Llanos, S. A., ... & Berssaneti, F. T. (2020). Valorization of chicken feet by-product of the poultry industry: high qualities of gelatin and biofilm from extraction of collagen. Polymers, 12(3), 529.

Sarbon, N., Badii, F., & Howell, N. K. (2013). Preparation and characterisation of chicken skin gelatin as an alternative to mammalian gelatin. Food Hydrocolloids, 30, 143–151.

Sarbon, N. M., Badii, F., & Howell, N. K. (2018). Purification and characterization of antioxidative peptides derived from chicken skin gelatin hydrolysate. Food Hydrocolloids, 85, 311-320.

Sarbon, N. M., Howell, N. K., &Wan Ahmad, W. A. N. (2019). Angiotensin-I converting enzyme (ACE) inhibitory peptides from chicken skin gelatin hydrolysate and its antihypertensive effect in spontaneously hypertensive rats. International Food Research Journal, 26(3).

Schmitt, C., & Turgeon, S. L. (2011). Protein/polysaccharide complexes and coacervates in food systems. Advances in colloid and interface science, 167(1-2), 63-70.

Schrieber, R., & Gareis, H. (2007). Gelatine Handbook: Theory and Industrial Practice. Weinheim, Germany: Wiley-VCH GmbH & Co.

Segura-Campos, M., Chel-Guerrero, L., & Betancur-Ancona, D. (2008). Synthesis and partial characterization of octenylsuccinic starch from *Phaseolus lunatus*. Food Hydrocolloids, 22(8), 1467-1474.

Seidavi, A. R., Zaker-Esteghamati, H., & Scanes, C. G. (2019). Chicken processing: impact, co-products and potential. World's Poultry Science Journal, 75(1), 55-68.

Semenova, M. G., Moiseenko, D. V., Grigorovich, N. V., Anokhina, M. S., Antipova, A. S., Belyakova, L. E., Polikarpov, Y. N., & Tsapkina, E. N. (2014). Protein–polysaccharide interactions and digestion of the complex particles. In Food structures, digestion and health (pp. 169-192). Academic Press.

Seow, Y. X., Yeo, C. R., Chung, H. L., & Yuk, H. G. (2014). Plant essential oils as active antimicrobial agents. Critical Reviews in Food Science and Nutrition, 54(5), 625-644.

Shaddel, R., Hesari, J., Azadmard-Damirchi, S., Hamishehkar, H., Fathi-Achachlouei, B., & Huang, Q. (2018). Use of gelatin and gum Arabic for encapsulation of black raspberry anthocyanins by complex coacervation. International Journal of Biological Macromolecules, 107, 1800-1810.

Sharma, R., Rao, R., Kumar, S., Mahant, S., & Khatkar, S. (2019). Therapeutic potential of citronella essential oil: A review. Current drug discovery technologies, 16(4), 330-339.

Silva, F., Torres, L., Silva, L., Figueiredo, R., Garruti, D., Araújo, T., ... & Ricardo, N. (2018). Cashew gum and maltrodextrin particles for green tea (*Camellia sinensis var Assamica*) extract encapsulation. Food Chemistry, 261, 169-175.

Sing, C. E., & Perry, S. L. (2020). Recent progress in the science of complex coacervation. Soft Matter, 16(12), 2885-2914.

Sinthusamran, S., Benjakul, S., & Kishimura, H. (2014). Characteristics and gel properties of gelatin from skin of seabass (*Lates calcarifer*) as influenced by extraction conditions. Food Chemistry 152, 276–284.

Sousa, V. I., Parente, J. F., Marques, J. F., Forte, M. A., & Tavares, C. J. (2022). Microencapsulation of Essential Oils: A Review. Polymers, 14(9), 1730.

Suderman, N., Isa, M. I. N., & Sarbon, N. M. (2018, October). Characterization on the mechanical and physical properties of chicken skin gelatin films in comparison to mammalian gelatin films. In IOP Conference Series: Materials Science and Engineering (Vol. 440, No. 1, p. 012033). IOP Publishing.

Sumardiono, S., & Rakhmawati, R. B. (2017). Physicochemical properties of sago starch under various modification process: An overview. Advanced Science Letters, 23(6), 5789-5791.

Surh, J., Decker, E. A., & McClements, D. J. (2006). Properties and stability of oil-in-water emulsions stabilized by fish gelatin. Food Hydrocolloids, 20(5), 596-606.

Tan, C. C., Karim, A. A., Uthumporn, U., & Ghazali, F. C. (2019). Effect of extraction temperature on the physicochemical properties of gelatine from the skin of black tilapia (*Oreochromis mossambicus*). Journal of Physical Science, 30, 1-21.

Tan, C., Xie, J., Zhang, X., Cai, J., & Xia, S. (2016). Polysaccharide-based nanoparticles by chitosan and gum arabic polyelectrolyte complexation as carriers for curcumin. Food Hydrocolloids, 57, 236-245.

Tavares, L., Barros, H. L. B., Vaghetti, J. C. P., & Noreña, C. P. Z. (2019). Microencapsulation of garlic extract by complex coacervation using whey protein isolate/chitosan and gum arabic/chitosan as wall materials: Influence of anionic biopolymers on the physicochemical and structural properties of microparticles. Food and Bioprocess Technology, 12(12), 2093-2106.

Tavares, L., & Noreña, C. P. Z. (2020). Encapsulation of ginger essential oil using complex coacervation method: Coacervate formation, rheological property, and physicochemical characterization. Food and Bioprocess Technology, 13(8), 1405-1420.

Teng, N. Y., Huda, N., Shariff, A. H. M., Nafchi, A. M., & Zakaria, Z. (2021, March). Physicochemical Properties of Peking Duck Skin Gelatin Extracted Using Acid Pretreatment (ADS) or Mixed Alkaline-Acid Pretreatment (ALDS). In IOP Conference Series: Earth and Environmental Science (Vol. 709, No. 1, p. 012050). IOP Publishing.

Thongkaew, C., Gibis, M., Hinrichs, J., & Weiss, J. (2014). Polyphenol interactions with whey protein isolate and whey protein isolate–pectin coacervates. Food Hydrocolloids, 41, 103-112.

Timilsena, Y. P., Akanbi, T. O., Khalid, N., Adhikari, B., & Barrow, C. J. (2019). Complex coacervation: Principles, mechanisms and applications in

microencapsulation. International Journal of Biological Macromolecules, 121, 1276-1286.

Timilsena, Y. P., Wang, B., Adhikari, R., & Adhikari, B. (2016). Preparation and characterization of chia seed protein isolate–chia seed gum complex coacervates. Food Hydrocolloids, 52, 554-563.

Timung, R., Barik, C. R., Purohit, S., & Goud, V. V. (2016). Composition and anti-bacterial activity analysis of citronella oil obtained by hydro distillation: Process optimization study. Industrial Crops and Products, 94, 178-188.

Transparency market research. (2014). Collagen Peptide and Gelatin Market (Source: Bovine, Porcine, Chicken, Marine and Others; Application: Bone and Joint Health, Nutraceuticals, Cosmeceuticals, Food and Beverage, Pet Food, Photography, Pharmaceuticals and Others) - Global Industry Analysis. New York.

Turek, C., & Stintzing, F. C. (2013). Stability of essential oils: a review. Comprehensive Reviews in Food Science and Food Safety, 12(1), 40-53.

Turgeon, S., Schmitt, C., & Sanchez, C. (2007). Protein-polysaccharide complexes and coacervates. Current Opinion in Colloid & Interface Science, 12(4), 166-178.

Veiga, C. C., Simoni, R. C., de Almeida, M. M. C., Gonçalves, O. H., Shirai, M. A., & Leimann, F. V. (2016). Microencapsulation of roasted coffee oil by complex coacervation with gelatin/gum Arabic enzymatically crosslinked. REBRAPA-Brazilian Journal of Food Research, 7(2), 156-172.

Wahyono, T., Astuti, D. A., Wiryawan, I. K. G., Sugoro, I., & Jayanegara, A. (2019, June). Fourier transform mid-infrared (FTIR) spectroscopy to identify tannin compounds in the panicle of sorghum mutant lines. In IOP Conference Series: Materials Science and Engineering (Vol. 546, No. 4, p. 042045). IOP Publishing.

Wang, B., Adhikari, B., & Barrow, C. J. (2014). Optimisation of the microencapsulation of tuna oil in gelatin–sodium hexametaphosphate using complex coacervation. Food Chemistry, 158, 358-365.

Wang, B., Vongsvivut, J., Adhikari, B., & Barrow, C. J. (2015). Microencapsulation of tuna oil fortified with the multiple lipophilic ingredients vitamins A, D3, E, K2, curcumin and coenzyme Q10. Journal of Functional Foods, 19, 893-901.

Wang, L., Yang, S., Cao, J., Zhao, S., & Wang, W. (2016). Microencapsulation of ginger volatile oil based on gelatin/sodium alginate polyelectrolyte complex. Chemical and Pharmaceutical Bulletin, 64(1), 21– 26.

Widyasari, R., & Rawdkuen, S. (2014). Extraction and characterization of gelatin from chicken feet by acid and ultrasound assisted extraction. Food and Applied Bioscience Journal, 2, 85–97.

Windyasmara, L., Pertiwiningrum, A., Asmoro, N. W., & Afriyanti, A. (2018) Chemical quality of chicken bone waste gelatin extracted using chloride acid. Buletin Peternakan, 42(4), 322-326.

Wu, B. C., & McClements, D. J. (2015). Microgels formed by electrostatic complexation of gelatin and OSA starch: Potential fat or starch mimetics. Food Hydrocolloids, 47, 87-93.

Wu, J., Liao, W., Zhang, J., & Chen, W. (2019). Thermal behavior of collagen crosslinked with tannic acid under microwave heating. Journal of Thermal Analysis and Calorimetry, 135(4), 2329-2335.

Yaacob, B., Mohd, A. M. C. I., Hashim, K., & Abu, B. B. (2011). Optimization of reaction conditions for carboxymethylated sago starch. Iranian Polymer Journal, 20(3), 195-204.

Yeo, Y., Bellas, E., Firestone, W., Langer, R., & Kohane, D. S. (2005). Complex coacervates for thermally sensitive controlled release of flavor compounds. Journal of Agricultural and Food Chemistry, 53(19), 7518-7525.

Yuliani, D., Maunatin, A., Jannah, A., & Fauziyyah, H. H. (2019, June). Effect of phosphoric acid pretreatment on characterization of gelatin from broiler chicken (*Gallus gallus domesticus L.*) bones. In IOP conference series: Earth and Environmental Science (Vol. 293, No. 1, p. 012013). IOP Publishing.

Zhao, Y., Khalid, N., Shu, G., Neves, M. A., Kobayashi, I., & Nakajima, M. (2019). Complex coacervates from gelatin and octenyl succinic anhydride modified kudzu starch: Insights of formulation and characterization. Food Hydrocolloids, 86, 70-77.26.

Zhou, L., Shi, H., Li, Z., & He, C. (2020). Recent advances in complex coacervation design from macromolecular assemblies and emerging applications. Macromolecular Rapid Communications, 41(21), 2000149.

Zhu, F. (2019). Recent advances in modifications and applications of sago starch. Food Hydrocolloids, 96, 412-423.

Zou, W., Mourad, F. K., Zhang, X., Ahn, D. U., Cai, Z., & Jin, Y. (2020). Phase separation behavior and characterization of ovalbumin and propylene glycol alginate complex coacervates. Food Hydrocolloids, 108, 105978.