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WYDZIAŁ NAUK O ŻYWNOŚCI I BIOTECHNOLOGII

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ZASTOSOWANIE BIAŁEK I SYROPÓW DO OTRZYMYWANIA BATONÓW DLA OSÓB AKTYWNYCH FIZYCZNIE

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Spis treści

1. Streszczenie

Poprawa standardów życia ludzi, w obecnych czasach, przejawia się zwiększonym spożyciem cukru oraz produktów wysokotłuszczowych, które przyczyniają się do znacznego wzrostu wskaźników otyłości (Mota et al., 2019). Z tego powodu batony wysokobiałkowe (HPB – *ang. high protein bars*) stały się popularne jako prozdrowotna żywność o wysokiej zawartości białka i stosunkowo niskiej zawartości węglowodanów. Batony wysokobiałkowe mogą być definiowane jako rodzaj produktu żywnościowego o zawartości białka na poziomie 20–50%, niskiej kaloryczności, wysokiej wartości odżywczej i łatwym, lekkim w transporcie opakowaniu (Kelly, 2019). Wychodząc naprzeciw wymaganiom konsumentów dbających o dietę, uprawiających sport czy rekonwalescentów, batony wysokobiałkowe stały się ciekawą alternatywą dla tradycyjnych przekąsek, dostarczającą organizmowi wysokiej jakości białko. Bogate w składniki odżywcze produkty wysokobiałkowe, jakimi są m.in. batony wysokobiałkowe, mają szerokie perspektywy rozwoju i wykazują silną konkurencyjność rynkową wśród wielu produktów spożywczych (Adámek et al., 2018).

Tekstura żywności jest wynikiem interakcji między produktami żywnościowymi a zmysłami człowieka. Określa się, że bez analizy sensorycznej nie da się zrozumieć konsystencji konkretnego produktu spożywczego. Spośród wszystkich cech żywności, które stymulują zmysły, konsystencja może wywoływać najbardziej złożone doznania zmysłowe (Banach et al., 2016). Na przykład twardość próbki żywności nie może być wyczuwana wyłącznie poprzez umieszczenie jej w ustach. Zęby muszą wywierać siłę, aby odkształcić lub rozbić żywność, w celu określenia jej twardości (Mojet & Köster, 2005). W związku z tym twardnienie batonów wysokobiałkowych podczas przechowywania wpływa bezpośrednio na ocenę sensoryczną konsumenta, zmniejszając jego preferencje do tego typu produktów, co może znacznie utrudniać rozwój rynku batonów wysokobiałkowych. Obecnie troska o zminimalizowanie twardnienia tego typu produktów w czasie okresu przechowywania, stanowi poważne wyzwanie dla producentów żywności w branży FMCG (*ang. fast-moving consumer goods*). Większość dostępnych na półkach sklepowych batonów wysokobiałkowych należy do kategorii produktów spożywczych

o wilgotności wahającej się w granicach 10–30%, aktywności wody na poziomie 0,6–0,8, oraz okresie przydatności do spożycia od 6 do 12 miesięcy w temperaturze pokojowej. Jednak smak, barwa i cechy teksturalne wszystkich batonów wysokobiałkowych ulegają zmianie podczas okresu przechowywania, przy czym największe zmiany dotyczą twardości oraz innych parametrów tekstury powiązanych z twardością (Sherwin & Labuza, 2003).

Batony wysokobiałkowe, dostępne komercyjnie, składają się przede wszystkim z dwóch głównych składników: białek pochodzących z koncentratów lub izolatów białek serwatkowych i sojowych oraz syropów na bazie cukru lub syropów glukozowo-fruktozowych czy glukozowych (Li et al., 2008; Zainal Abidin et al., 2020). Udział poszczególnych składników to zazwyczaj 20-40% białka, 10-50% węglowodanów i 10-15% tłuszczu bądź oleju. Z tego powodu udział tych składników w produkcie wywiera największy wpływ na cechy, które posiada wytworzony wyrób gotowy (Zhu & Labuza, 2010).

Na przestrzeni ostatnich lat białka roślinne są coraz częściej wykorzystywane jako ekonomiczna i wszechstronna alternatywa zastępująca źródło białka pochodzenia zwierzęcego w żywieniu człowieka, a także jako składniki funkcjonalne stosowane coraz chętniej przez producentów do formułowania nowych wyrobów spożywczych. Wykorzystanie białek zwierzęcych wiąże się ze zwiększającymi się kosztami oraz coraz bardziej ograniczoną podażą i jest silnie związane ze zmianą klimatu, wyczerpywaniem się wody słodkiej, utratą bioróżnorodności oraz zagrożeniami dla zdrowia ludzi związanymi m.in. z chorobami układu krążenia (Alemayehu et al., 2015; Gomes et al., 2020; Sun-Waterhouse et al., 2014). Istnieje wiele potencjalnych źródeł białek roślinnych. Niektóre rodzaje zostały jednak szczególnie dokładnie przebadane i mogą być ciekawą alternatywą dla białek zwierzęcych. Są to przede wszystkim białka roślin strączkowych (soja, groch) (Coda et al., 2017; Tuśnio et al., 2017), zboża (ryż, pszenica) (Zhao et al., 2020), nasiona (dynia i słonecznik) (Mattila et al., 2018), czy migdały i orzechy (De Oliveira Sousa et al., 2011).

Ze względu na aktualne trendy związane z ograniczaniem ilości spożycia cukru oraz redukcją wartości kalorycznej żywności, producenci poszukują alternatyw dla powszechnie stosowanych syropów cukrowych, glukozowo-fruktozowych i glukozowych oraz środków intensywnie słodzących, które są powszechnie stosowane w produktach spożywczych. Węglowodany nie podlegające trawieniu w układzie pokarmowym człowieka, w tym polisacharydy nieskrobiowe, skrobie oporne,

oligosacharydy (takie jak oligofruktoza czy inne błonniki płynne pochodzenia roślinnego) lub alkohole wielowodorotlenowe (takie jak maltitol czy sorbitol) mogą być ciekawą alternatywą dla powszechnie stosowanych syropów (Erickson & Carr, 2020; Stanner & Spiro, 2020).

W związku z informacjami przedstawionymi powyżej, tematem moich badań było zastosowanie białek pochodzenia roślinnego (słonecznika, pszenicy, soi, konopi, dyni, grochu, ryżu, alg morskich) i zwierzęcego (białek serwatkowych) oraz wybranych płynnych substancji syropowych (oligoruktozy, syropu maltitolowego, płynnych błonników roślinnych: grochowo-kukurydzianego, tapiokowego oraz syropu glukozowego) do otrzymywania innowacyjnych batonów wysokobiałkowych o właściwościach funkcjonalnych i potencjalnie prozdrowotnych oraz z zachowaniem zdolności do wdrożenia receptur w warunkach przemysłowych.

Summary

Improving human living standards nowadays is manifested by increased sugar consumption and high-fat products, which are the reasons for a significant increase in obesity rates (Mota et al., 2019). That is why high protein bars (HPB) have become popular as nutritious healthy food with a high protein content and relatively low carbohydrate content. High-protein bars can be defined as a type of food product with a protein content of 20-50%, low in calories, high in nutritional value and easy to transport in a unit packaging (Kelly, 2019). Meeting the requirements of consumers who care about their diet, engage in sports or convalescents, high-protein bars have become a healthy alternative to traditional snacks, providing the body with high-quality protein. High-protein products rich in nutrients, such as high-protein bars have broad development prospects and show strong market competitiveness among many food products (Adámek et al., 2018).

The texture of food is the result of the interaction between food products and the human senses. It is determined that without a sensory analysis it is impossible to understand the consistency of a particular food product. Of all the sensory stimulating characteristics of food, texture can evoke the most complex sensory experiences (Banach et al., 2016). For example, the hardness of a food sample cannot be felt just by placing it in the mouth. The teeth must exert force to deform or break the food in order to determine its hardness (Mojet & Köster, 2005). Therefore, the hardening of high-protein bars during storage directly affects the consumer's sensory assessment, reducing his preferences for this type of product, which may significantly hinder the development of the high-protein bar market. Currently, the concern to minimize the hardening of this type of product during the storage period is a serious challenge for food producers in the FMCG (fast-moving consumer goods) industry. Most of the high-protein bars available on store shelves belong to the category of food products with a moisture content of 10–30%, a water activity of 0.6–0.8, and a shelf life of 6 to 12 months at room temperature. However, the taste, color and texture characteristics of all high protein bars change during the storage period, with the greatest changes being changes in hardness and other texture parameters related to hardness (Sherwin & Labuza, 2003).

Commercially available high-protein bars consist primarily of two main ingredients: proteins derived from whey and soy protein concentrates or isolates, and syrups based on sugar or glucose-fructose or glucose syrups (Li et al., 2008; Zainal

Abidin et al., 2020). The proportion of the individual ingredients is usually 20-40% protein, 10-50% carbohydrates and 10-15% fat or oil. For this reason, the share of these ingredients in the product has the greatest impact on the characteristics of the finished product (Zhu & Labuza, 2010).

In recent years, plant proteins have been increasingly used as an economic and versatile alternative to replace the source of animal protein in human nutrition, as well as functional ingredients used more and more willingly by producers to formulate new food products. The use of animal proteins is associated with rising costs and more and more limited supply, and is strongly associated with climate change, freshwater depletion, loss of biodiversity and threats to human health related to e.g. with cardiovascular diseases (Alemayehu et al., 2015; Gomes et al., 2020; Sun-Waterhouse et al., 2014). There are many potential sources of plant proteins. Some types, however, have been thoroughly tested and can be an interesting alternative to animal proteins, they are primarily legume proteins (soybeans, peas) (Coda et al., 2017; Tuśnio et al., 2017), grains (rice, wheat) (Zhao et al., 2020), seeds (pumpkin and sunflower) (Mattila et al., 2018), almonds and nuts (De Oliveira Sousa et al., 2011).

Due to the current trends in reducing the amount of sugar consumption and reducing the caloric value of food, producers are looking for alternatives to the commonly used sugar, glucose-fructose and glucose syrups. Intense sweeteners are typically used in dairy products, sweets, and chewing gums. Non-digestible carbohydrates in the human digestive system, including non-starch polysaccharides, resistant starches, oligosaccharides (such as oligofructose or other plant-derived liquid fibers) or polyhydric alcohols (such as maltitol or sorbitol) may be an interesting alternative to currently used syrups (Erickson & Carr, 2020; Stanner & Spiro, 2020).

In connection with the information presented above, the subject of my research was the use of proteins of plant and animal origin (sunflower, wheat, soybean, hemp, pumpkin, pea, rice, sea algae and whey proteins) and selected liquid syrups (oligofructose, maltitol syrup, liquid vegetable fibers: pea-corn, tapioca and glucose syrup) to obtain innovative high-protein bars with functional and potentially health-promoting properties and with the ability to implement recipes in industrial conditions.

2. Lista publikacji wchodzących w skład rozprawy doktorskiej

PUBLIKACJA I

Małecki J., Muszyński S., Sołowiej B.G., 2021, Proteins in Food Systems—Bionanomaterials, Conventional and Unconventional Sources, Functional Properties, and Development Opportunities. *Polymers*, 13(15), 2506.

Punkty MEiN: 100 pkt IF $_{(2021)}$: 4,329 Liczba cytowań wg Web of Science (6)/Scopus (5)

PUBLIKACJA II

Małecki J.; Tomasevic I.; Djekic I.; Sołowiej B.G., 2020, The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People. *Foods*, 9(10), 1467.

Punkty MEiN: 100 pkt IF$_{(2021)}$: 4,350 Liczba cytowań wg Web of Science (8)/Scopus (8)

PUBLIKACJA III

Małecki J.; Tomasevic I.; Sołowiej B.G., 2022, The Influence of the Syrup Type on Rheology, Color Differences, Water Activity, Nutritional and Sensory Aspects of High-Protein Bars for Sportsmen. *Journal of Food Quality*, 1(1), 2317676.

Punkty MEiN: 40 pkt IF$_{(2021)}$: 2,450 Liczba cytowań wg Web of Science (0)/Scopus (0)

PUBLIKACJA IV

Małecki J., Terpiłowski K., Nastaj M., Sołowiej B.G., 2022, Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used. *International Journal of Environmental Research and Public Health*, 19, 3923.

Punkty MEiN: 140 pkt IF$_{(2021)}$: 3,390 Liczba cytowań wg Web of Science (0)/Scopus (0)

Sumaryczna liczba pkt. według komunikatu MEiN z dn. 21 grudnia 2021 r. obowiązującego w roku wydania pracy: **380 pkt**
Sumaryczny IF (zgodnie z rokiem opublikowania): **14,519**
Sumaryczna liczba cytowań wg Web of Science (**14**) oraz Scopus (**13**)

3. Wprowadzenie teoretyczne na podstawie publikacji: Małecki J., Tomasevic I., Djekic I., Sołowiej B.G. "The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People" (*publikacja II*) oraz Małecki J., Tomasevic I., Sołowiej B.G. "The Influence of the Syrup Type on Rheology, Color Differences, Water Activity, Nutritional and Sensory Aspects of High-Protein Bars for Sportsmen" (*publikacja III)*

Produkty wysokobiałkowe, w tym batony proteinowe, cieszą się nieustannie zwiększającą się popularnością (Goodbody, 2013). Tego typu wyroby mogą być stosowane w segmencie szybkich przekąsek (przeznaczonych do chwilowego zaspokojenia głodu), w żywieniu sportowców (zwiększenie tkanki mięśniowej) czy produktach przeznaczonych do żywienia osób starszych (uzupełnienie diety w substancje białkowe), oraz osób zagrożonych rozwojem chorób związanych z zanikiem mięśni czy sarkopenią (zanikiem mięśni) (Clary et al., 2010). W wyniku tak dużego zainteresowania rynku produktami wysokobiałkowymi, producenci wychodzą naprzeciw wymaganiom konsumentów i starają się opracowywać innowacyjne produkty, które wpisują się w aktualne trendy prawidłowego żywienia (Li-Chan & Lacroix, 2018). W tym celu poszukiwane są odpowiednie alternatywy dla powszechnie stosowanych składników, takich jak syropy o wysokiej zawartości fruktozy i glukozy, tłuszcze czy białka konwencjonalne, na ich alternatywne składniki, np. alkohole polihydroksylowe, fruktooligosacharydy, płynne błonniki roślinne czy różne źródła białka (roślinne i zwierzęce), przy jednoczesnej maksymalizacji zachowania parametrów technologicznych procesu produkcyjnego. Produkty powstałe w wyniku takich działań mogą być szczególnie interesujące dla osób stosujących różne rodzaje diet (Potes et al., 2014; Walia et al., 2019).

Najczęściej spotykane na półkach sklepowych batony wysokobiałkowe zawierają w swym składzie białka zarówno pochodzenia roślinnego (przede wszystkim koncentraty i izolaty białek sojowych), jak i zwierzęcego (zwłaszcza izolaty i koncentraty białek serwatkowych). Stwierdzono, że dodatek hydrolizatów białek serwatkowych stosowanych w aplikacjach batonów wysokobiałkowych wywiera pozytywny wpływ na utrzymanie miękkiej struktury tych produktów, ale może powodować lekko gorzkie posmaki (Hogan et al., 2012). Koncentraty lub izolaty białek serwatkowych są bogatymi źródłami alfa-laktoalbuminy i beta-laktoglobuliny.

W produktach spożywczych produkowanych na skalę przemysłową, białka tego typu znajdują szerokie zastosowanie ze względu na ich wysoką wartość odżywczą, pożądane właściwości sensoryczne (mleczne posmaki) oraz doskonałe właściwości technologiczne (Weeks, 2007). Od pewnego czasu zauważalny jest jednak gwałtowny wzrost zainteresowania alternatywnymi źródłami białek (zwłaszcza roślinnymi), które mogłyby konkurować z powszechnie stosowanymi białkami serwatkowymi pod względem właściwości fizykochemicznych, teksturalnych czy odżywczych (Wang & Xiong, 2019). Z tego powodu białka roślinne są coraz częściej wykorzystywane jako ekonomiczna i wszechstronna alternatywa dla źródeł białka pochodzenia zwierzęcego w żywieniu człowieka, a także źródło składników funkcjonalnych do formułowania nowych produktów. Pozyskiwanie białek zwierzęcych wiąże się ze znacznie większymi kosztami i ograniczoną podażą, co jest silnie związane ze zmianami klimatu, wyczerpywaniem się wody słodkiej, utratą bioróżnorodności i zagrożeniami dla zdrowia ludzkiego związanymi np. z chorobami układu krążenia (Sá et al., 2020). Ponadto wykorzystanie białek roślinnych w opracowywanych, nowych produktach spożywczych (m.in. batonach wysokobiałkowych) mogą również zwiększyć zainteresowanie tymi wyrobami wśród wegan, wegetarian, oraz osób prowadzących aktywny tryb życia czy będących na diecie (Ermiş & Karasu, 2020).

Batony białkowe, dostępne komercyjnie, składają się w głównej mierze z dwóch głównych składników: białek pochodzących z koncentratów lub izolatów białek serwatkowych i sojowych oraz syropów na bazie cukru (tzw. syropy cukrowe) lub syropów glukozowo-fruktozowych czy glukozowych (Li et al., 2008). Udział poszczególnych składników to zazwyczaj 20-40% białka, 10-50% węglowodanów i 10-15% tłuszczów (Zhu & Labuza, 2010). Batony wysokobiałkowe zawierają często również inne składniki, w tym aromaty, stabilizatory, a niekiedy także orzechy (migdały, orzechy laskowe, orzeszki arachidowe), czy suszone lub kandyzowane owoce (McMahon et al., 2009). Izolaty oraz koncentraty białek serwatkowych (WPI/WPC) są jednymi z najczęściej używanych preparatów służących do wzbogacania produktów spożywczych w białko. Płynną mieszanką syropową, służącą do połączenia wszystkich składników przewidzianych recepturą, są zwykle mieszaniny syropów o wysokiej zawartości cukrów redukujących oraz alkoholi wielowodorotlenowych (glicerolu, sorbitolu lub maltitolu), które pełnią funkcję dostarczania wody potrzebnej do wytworzenia masy oraz zabezpieczają wyrób gotowy przed nadmiernym wysychaniem.

Tłuszczami, które najczęściej stosuje się w tego typu produktach są tłuszcze i oleje roślinne (Molina-Rubio et al., 2010).

Większość komercyjnych batonów wysokobiałkowych (HPB) należy do kategorii średnio-wilgotnej żywności (*ang. IMF - intermediate-moisture food*) o aktywności wody (a_w) w zakresie 0,50–0,85 (Li et al., 2008). Ważne jest, aby parametr ten był jak najniższy, tak by zapewnić długi okres przydatności do spożycia i uniknąć zachodzenia niepożądanych reakcji chemicznych, fizycznych i biologicznych, które mogą negatywnie wpłynąć na jakość produktu. Dotyczy to przede wszystkim zmian smaku, barwy i konsystencji, czyniąc produkty mniej atrakcyjnymi dla konsumentów (Jovanov et al., 2021). Na rynku dostępnych jest wiele różnych rodzajów batonów, w tym zastępujące posiłki lub dostosowane do wymagań żywieniowych diabetyków, dzieci, sportowców i kobiet (Rawat & Darappa, 2015). Rynek tych wyrobów podzielony jest na cztery główne kategorie: batony musli, batony odżywcze, batony śniadaniowe i przekąski ryżowe. Kategoria batoników odżywczych, jest również podzielona na cztery grupy, w tym batony wysokobiałkowe, batony energetyczne, zdrowe przekąski oraz produkty dietetyczne. Segment batonów wysokobiałkowych jest największy i obejmuje 34% całego rynku batonów odżywczych (Szydłowska et al., 2020). Według niektórych źródeł istnieje również różnica między odżywczymi batonami wysokobiałkowymi (*ang. HPNB – high-protein nutrition bars*) a batonami białkowymi. Uważa się, że baton wysokobiałkowy powinien zawierać więcej białka (15-20 g białka na porcję), w porównaniu z batonem proteinowym (5-15 g białka na porcję). Najważniejszym dokumentem regulującym nazewnictwo i możliwość umieszczenia określonych oświadczeń żywieniowych na opakowaniach produktów jest Rozporządzenie (WE) nr 1924.2006 Parlamentu Europejskiego i Rady z dnia 20 grudnia 2006 r. w sprawie oświadczeń żywieniowych i zdrowotnych dotyczących żywności, mówiące iż o produkcie wysokobiałkowym mówimy wówczas, gdy co najmniej 20% jego wartości energetycznej pochodzi z białka (Reuterswärd, 2007). Grupą docelową batonów wysokobiałkowych są głównie kulturyści, którzy używają tego rodzaju batonu jako suplementu. W ostatnim czasie, producenci batonów odżywczych odnotowali duży wzrost sprzedaży na rynku, przede wszystkim dzięki dobremu wizerunkowi, a entuzjastami tego segmentu produktów nie są już wyłącznie sportowcy (Piernas & Popkin, 2010).

3.1. Otrzymywanie batonów wysokobiałkowych

Ze względu na różnorodność linii technologicznych, dostępnych urządzeń, użytych do procesu surowców itp. dostępnych w zakładach produkcyjnych, w których batony wysokobiałkowe mogą być wytwarzane, nie można określić jednego schematu procesu produkcyjnego, mogącego jednoznacznie określić sposób produkcji tego typu produktów. Jednak w przypadku każdej zastosowanej technologii i metody, można zauważyć kilka zgodnych ze sobą etapów produkcji (Rysunek 1), jakimi są:

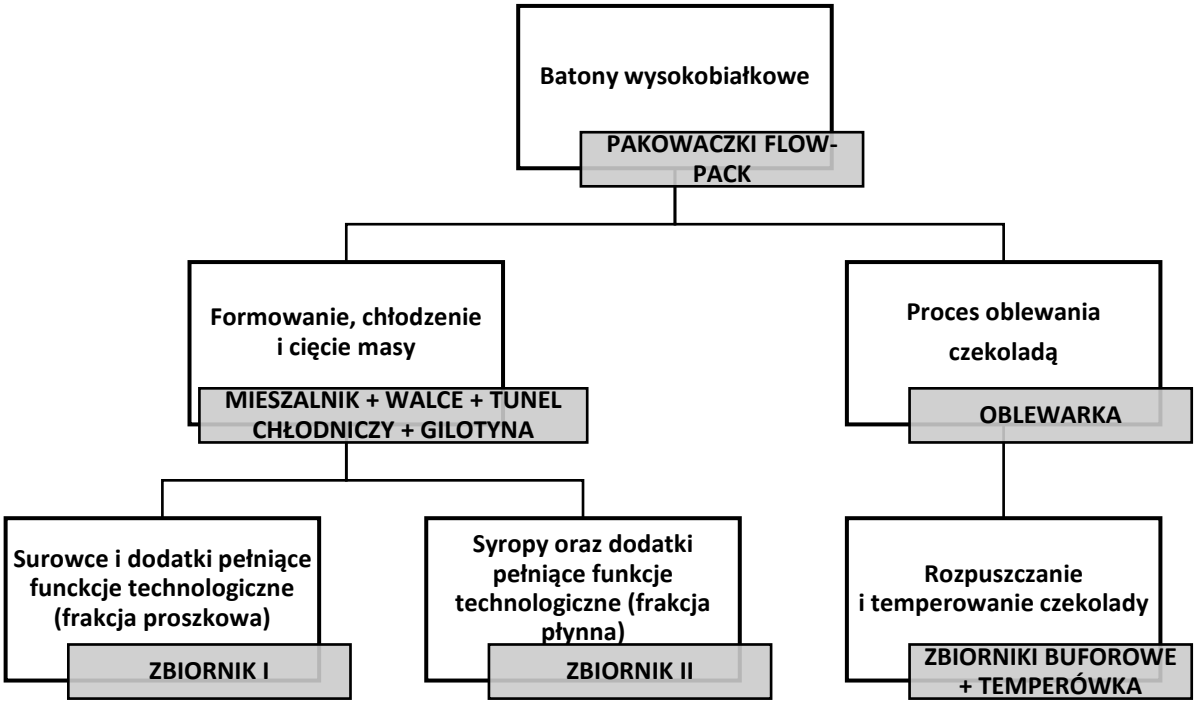
a) Przygotowanie mieszanki suchej, składającej się z surowców sypkich przewidzianych recepturą. Do najczęściej stosowanych zalicza się: preparaty białkowe, ekstrudaty zbożowe (chrupki, płatki), błonniki w postaci sypkiej itd.

b) Przygotowanie mieszanki syropowej. Cukry, syropy cukrowe i inne substancje syropowe pełniące tę funkcję. Oprócz zapewnienia słodkiego smaku wiążą wodę, zwiększają temperaturę wrzenia i zmniejszają temperaturę zamarzania roztworów, zwiększają lepkość i zmieniają teksturę produktów spożywczych, zapewniają wiązanie masy, służą jako prekursory do rozwoju smaku i koloru. W skład mieszanki syropowej wchodzą zazwyczaj syropy glukozowo-fruktozowe, glukozowe lub cukrowe połączone często z niewielkimi ilościami (1-5%) substancji utrzymujących wilgoć (glicerol, sorbitol itp.). Zalecany jest także dodatek tłuszczu będącego przede wszystkim nośnikiem smaku i witamin rozpuszczalnych w tłuszczach tj. A, D, E, K. W zależności od zastosowanego rodzaju oleju lub tłuszczu, wytwarzany produkt będzie cechował się zróżnicowanymi cechami tekstury oraz różnorodną tendencją do procesów związanych z jełczeniem i reakcjami ciemnienia nieenzymatycznego. Ze względu na dużą stabilność, w aplikacjach cukierniczych najczęściej stosowanymi frakcjami olejowymi są tłuszcze roślinne (palmowe, palmowo-rzepakowe, kokosowe), w większości częściowo lub całkowicie utwardzone (Clemens et al., 2016; Rolls, 2012).

c) Połączenie składników sypkich z syropem, w wyniku czego dochodzi do utworzenia spójnej masy, która następnie jest przygniatana za pomocą walców formujących (określona wysokość utworzonej masy będzie gwarantowała uzyskanie powtarzalnej wagi wyrobu), schładzana i cięta za

pomocą szeregu noży (wzdłużnych i poprzecznych) w celu uzyskania finalnego kształtu.

d) W zależności od rodzaju produkowanego asortymentu możliwe jest także pokrycie produktu czekoladami lub polewami na urządzeniach oblewających (oblewarkach przemysłowych). W przypadku zastosowania czekolad, konieczne jest również uwzględnienie procesu temperowania czekolady, ze względu na obecność tłuszczu kakaowego.
e) Ostatnim procesem jest zapakowanie produktu w opakowania jednostkowe i zbiorcze oraz magazynowanie i dystrybucja wyrobu gotowego (Abd El-Salam & El-Shibiny, 2020; Cho, 2010; Imtiaz et al., 2012).



Rysunek 1. Uproszczony schemat procesu produkcyjnego batonów wysokobiałkowych w warunkach przemysłowych. Opracowanie własne.

Osoby opracowujące nowe produkty stają przed wieloma wyzwaniami podczas procesu tworzenia oraz produkcji batonów funkcjonalnych. Składniki muszą spełniać określone wymagania żywieniowe, a produkt końcowy powinien odpowiadać potrzebom konsumentów w zakresie doznań smakowych i korzyści zdrowotnych. Konieczne jest zatem dobranie odpowiedniej kompozycji składników, aby stworzyć produkty o pożądanych cechach sensorycznych i wartościach odżywczych powiązanych

z kryteriami zdrowotnymi dla konkretnego rodzaju batonu (Kumar et al., 2018). Istnieje wiele opracowanych receptur, lecz w przypadku niektórych batonów dostępnych na rynku, nie osiągnięto jeszcze akceptowalnego smaku. Tego rodzaju produkty zazwyczaj nie cieszą się powodzeniem, ponieważ jednym z najlepszych sposobów na zwiększenie liczby powtarzalnych i udanych receptur jest przede wszystkim dobry smak i tekstura, w przeciwnym razie, produkt „zginie" na półce sklepowej niezależnie od tego, jak bardzo byłby prozdrowotny (Rao et al., 2016). Istotne jest zatem, aby tworząc wysokobiałkowe batony odżywcze, optymalizować zarówno właściwości sensoryczne (wygląd, barwa, smak, konsystencja), jak i właściwości funkcjonalne różnych składników (w celu zapewnienia maksymalnej równowagi pomiędzy poszczególnymi komponentami), tak aby uzyskać produkt o jak największej akceptowalności konsumentów i powtarzalnej jakości (Jovanov et al., 2021). Dlatego ciągłe doskonalenie opracowywanych produktów jest kluczowym czynnikiem dla przetrwania wielu firm oraz jest ściśle uzależnione od wymagań i preferencji konsumentów (Srebernich et al., 2016).

3.2. Określanie terminu przydatności do spożycia batonów wysokobiałkowych

Określanie terminu przydatności do spożycia przetworzonej żywności to jeden z głównych problemów z jakimi borykają się firmy spożywcze, wprowadzając produkty na rynek lub modyfikując niektóre jego składniki. Problem ten jest szczególnie istotny w przypadku produktów stosunkowo odpornych na psucie, gdzie potrzeba wielu miesięcy, aby produkt uległ zepsuciu. Dlatego bardzo ważne jest stosowanie metod, które prawidłowo szacują trwałość wyrobów spożywczych (Mirza et al., 2017). Ogólną definicją terminu przydatności do spożycia nazywany jest okres czasu, w którym żywność zachowuje cechy i jakość odpowiednią do spożycia przez ludzi. W przemyśle spożywczym natomiast terminem przydatności do spożycia żywności nazywany jest czas pomiędzy wyprodukowaniem lub zapakowaniem produktu a momentem, w którym staje się on niedopuszczalny do spożycia, natomiast konsumpcja wspomnianej żywności może stanowić zagrożenie dla zdrowia konsumenta, w określonych warunkach środowiskowych (Leistner, 2000). Dyrektywa 2000/13/WE Parlamentu Europejskiego i Rady z dnia 20 marca 2000 r. w sprawie zbliżenia ustawodawstw Państw Członkowskich w zakresie etykietowania, prezentacji i reklamy środków

spożywczych określa termin przydatności do spożycia jako czas od wyprodukowania do przekroczenia przez wyrób poziomu skażenia mikrobiologicznego, w wyniku którego zmienia on swoje właściwości fizykochemiczne i organoleptyczne (Abdulmumeen et al., 2012).

Istnieje kilka czynników wpływających na pogorszenie lub utratę oryginalnej jakości produktów żywnościowych. Czynniki te można podzielić na dwa typy: wewnętrzne (związane z charakterem samej żywności) lub zewnętrzne (warunki w jakich znajduje się żywność). Są one determinowane różnymi parametrami jakości: organoleptycznymi, żywieniowymi, higienicznymi, fizycznymi, chemicznymi lub mikrobiologicznymi (Aneja et al., 2014). Czynniki wewnętrzne, które wpływają na termin przydatności do spożycia, można zatem nazwać wzajemnymi interakcjami i właściwości poszczególnych składników zawartych w danym produkcie. Czynniki wewnętrzne determinowane są przede wszystkim przez rodzaj surowców, z których wykonany jest dany produkt (jego parametry mikrobiologiczne i fizykochemiczne), substancje dodatkowe, aktywność wody, kwasowość i wartość pH, potencjał oksydoredukcyjny, oraz dostęp tlenu. Biorąc pod uwagę powyższe informacje, producenci mogą dostosowywać systemy, które maksymalizują termin przydatności do spożycia produktu zgodnie z potrzebami i wymaganiami. Czynnikami zewnętrznymi, które wpływają na trwałość żywności, są głównie te obecne w procesie pakowania i przechowywaniu produktu, tj. ekspozycja na promienie słoneczne, temperatura, wilgotność, jakość materiału opakowaniowego i jego interakcje z żywnością (Smith, 2011).

Do najpowszechniej stosowanych metod określania terminu przydatności do spożycia produktów spożywczych należą:

a) Metoda bezpośrednia – polegająca na badaniach przeprowadzanych w czasie rzeczywistym, które polegają na przechowywaniu produktu w warunkach zbliżonych do tych, w których produkt finalnie będzie umieszczany, aby monitorować jego zmiany w regularnych odstępach czasu. Główną zaletą tej metody jest bardzo dokładne oszacowanie czasu maksymalnego terminu przydatności do spożycia produktu. Wadą jest jednak stosunkowo długi czas potrzebny do wykonania analizy. Tego rodzaju badania nie uwzględniają także faktu, że warunki przechowywania produktu nie zawsze są stabilne w czasie (Manzocco et al., 2010).

b) Metoda predykcji mikrobiologicznej – metodologia polega w tym przypadku na badaniu określonych rodzajów drobnoustrojów żywności w różnych warunkach środowiskowych, w oparciu o modele matematyczne i statystyczne, w celu określenia przewidywanego zachowania mikroorganizmów w produkcie. Ten rodzaj badania jest szeroko stosowany przy opracowywaniu nowych produktów. Uwzględnia zmieniające się warunki jakim produkt może zostać poddany. Głównym ograniczeniem metody jest to, iż oznacza ona większą złożoność dla producenta, a wyniki odpowiadają symulacji, która może nie być dokładnym odzwierciedleniem stanu faktycznego (Calligaris et al., 2008).
c) Metoda przyspieszonych testów trwałości - w tego rodzaju testach, warunki takie jak temperatura, ciśnienie powietrza, stężenie tlenu lub zawartość wilgoci są modyfikowane w celu przyspieszenia reakcji psucia się żywności. Te przewidywania pozwalają przybliżyć zachowanie żywności w określonych warunkach i oszacować, jak będzie zachowywać się w określonych warunkach przechowywania. Przyspieszone testy pozwalają na uwzględnienie zmieniających się warunków środowiskowych i zmian stężeń składników, z których się składają. Badania te są bardzo wszechstronne, tanie dla producenta i pozwalają na porównanie różnych scenariuszy. Oczywiście, ze względu na fakt, że nie jest to dokładne odwzorowanie rzeczywistości, w uzyskanych wynikach, istnieje pewien margines błędu (Corradini & Peleg, 2007).
d) Metoda „przetrwania” - jest to rodzaj badania, które opiera się na opinii konsumentów o właściwościach fizycznych i sensorycznych produktu. Polega na poznaniu opinii konsumentów odnośnie tego samego produktu o różnych datach produkcji, aby ustalić, czy chcieliby go spożywać, czy też nie. Ta metoda ma na celu ustalenie związku między terminem przydatności do spożycia a postrzeganą jakością produktu. Chociaż nie jest to metoda dokładnego oszacowania terminu przydatności do spożycia, ważne jest, żeby wykonywana była rzetelnie i systematycznie, tak aby ustalić datę przydatności do spożycia produktu (Giménez et al., 2012).

Produkty spożywcze, w tym batony wysokobiałkowe, będą sprzyjać wzrostowi mikrobiologicznemu, ponieważ pod względem chemicznym składają się z wody,

tłuszczu, węglowodanów, białek i niewielkich ilości związków organicznych i mineralnych. Wszystkie te elementy są źródłem energii dla wzrostu drobnoustrojów. Z tego względu stosuje się wiele metod zapobiegawczych aby temu zapobiegać (Sharp & Harris, 2020). Substancje konserwujące to naturalne lub syntetyczne substancje chemiczne, które mogą być dodawane do różnego rodzaju produktów, w tym żywności. Utrzymanie jakości żywności jest niezbędne do zapewnienia stosowania żywności o wysokich wartościach odżywczych, co jest ważne dla zdrowia człowieka. Zatem metody konserwacji są najlepszym sposobem na zachowanie jakości żywności i zapobieganie jej przedwczesnemu psuciu. Obecnie dostępne są różne rodzaje metod konserwacji, które można wykorzystać do utrzymania jakości produktów spożywczych przez długi czas, zarówno przy użyciu konwencjonalnych, jak i nowoczesnych metod konserwacji. Niektóre z tych technik wykorzystują substancje dodatkowe, które można podzielić na sztuczne i naturalne kategorie konserwantów (Gokoglu, 2019). Idealny konserwant powinien być skuteczny w niskich stężeniach, być nietoksyczny i kompatybilny z innymi składnikami preparatu oraz być stabilny w całym zakresie terminu przydatności do spożycia danej żywności. Sztuczne konserwanty są wytwarzane przez człowieka w wyniku syntezy chemicznej i działają przeciwko różnym drobnoustrojom w małych stężeniach. Komisja Unii Europejskiej nadaje dodatkowi numer „E" po dopuszczeniu przez Komitet Naukowy ds. Żywności (SCF), który jest odpowiedzialny za ocenę bezpieczeństwa dodatków do żywności. Numery „E" to kody środków chemicznych dopuszczonych do użytku na terenie Unii Europejskiej i Szwajcarii oraz przyjęte przez przemysł spożywczy na całym świecie. Zakres numerów „E" przypisanych do klasy „Konserwanty" wynosi od 200 do 299 (Anand & Sati, 2013). Jednak w ostatnich latach konsumenci domagają się zastępowania chemicznie syntetyzowanych konserwantów ich naturalnie występującymi odpowiednikami w celu wydłużenia okresu przydatności do spożycia żywności oraz jego bezpieczeństwa. Obecnie, szczególną uwagę zwraca się na substancje zawarte najczęściej w przyprawach, owocach czy warzywach (witamina C, witamina E, tokoferole, kwas mlekowy, flawonoidy itd.) (Hassoun et al., 2020).

3.3. Analiza sensoryczna batonów wysokobiałkowych

Badania właściwości sensorycznych żywności mogą być postrzegane jako proces gromadzenia informacji służący do pomiaru, analizy i interpretacji reakcji

behawioralnych na produkty żywnościowe w oparciu o pięć zmysłów: wzroku, słuchu, smaku, zapachu i dotyku, w których wykorzystuje się osoby oceniające, jako „przyrządy" do pomiaru jakości produktu spożywczego. Analiza składa się z zestawu technik, które są wykorzystywane do pomiaru ludzkich reakcji, jednocześnie minimalizując stronniczość, spowodowaną potencjalnymi, mylącymi źródłami, które obejmują branding i inne informacje, które mogą wpływać na pozytywne, jak i negatywne postrzegania konsumentów (Singh-Ackbarali & Maharaj, 2014). Wyniki uzyskane z badań sensorycznych żywności dostarczają ważnych informacji na temat jej jakości i właściwości, które mogą być następnie wykorzystywane w kilku aspektach, takich jak opracowywanie nowych produktów, zrozumienie konsumentów, profilowanie zapachu i smaku oraz kontrola jakości. W takich badaniach główne cele oceny można często luźno zaklasyfikować do:

a) analizy smaku, która w dużej mierze wiąże się z określeniem związków chemicznych związanych ze smakami i zapachami produktu spożywczego, których doświadczają konsumenci;

b) profilowania sensorycznego, czyli określania cech sensorycznych takich jak: słodycz, przeżuwalność, oraz szereg innych atrybutów związanych z teksturą;

c) testy hedoniczne, w których określa się akceptację lub preferencje konsumentów do określonego produktu (Vivek et al., 2019).

Analiza smaku opiera się w dużej mierze na pomiarze zawartości lotnych i nielotnych związków w produktach spożywczych, które mogą wpływać na profile smakowe i zapachowe produktu. Ta forma danych jest zwykle wykonywana za pomocą aparatury analitycznej (metody chromatograficzne). Dane sensoryczne odnoszą się do oceny sensorycznej przypisanej do cech sensorycznych produktu spożywczego przez panel oceniających. Atrybuty te odnoszą się nie tylko do profilu smakowego i zapachowego produktu, ale mogą rozciągać się na inne właściwości, w tym tekstury, właściwości fizykochemicznych oraz właściwości zewnętrzne, takie jak cena, marka i informacje żywieniowe (Iannario et al., 2012).

W testach hedonicznych głównym elementem związanym z akceptacją jest sympatia konsumentów. Dostarcza to informacji o tym, jak dobrze produkt odbierany jest na rynku, co stanowi cenną wskazówkę zarówno dla konsumentów jak i producentów żywności. Analizy sensoryczne produktów spożywczych oraz przeprowadzanie eksperymentów w zakresie analizy sensorycznej żywności wymagają prawidłowego zaprojektowania, zaplanowania technik analitycznych, a następnie

interpretacji uzyskanych w badaniach wyników i obserwacji. To z kolei wymaga od eksperymentatora wykorzystania najczęściej metod statystycznych, w celu stworzenia analizy porównawczej i wyciągnięcia wniosków w tego typu analizach (Muñoz, 2002).

3.4. Przeznaczenie batonów wysokobiałkowych oraz problematyka związana z opisywaną grupą asortymentową

Batony wysokobiałkowe to grupa asortymentowa zawierająca w swym składzie najczęściej około 20-50% białka. Ideą tworzenia tego typu produktów jest możliwość skutecznego i szybkiego dostarczania energii potrzebnej organizmowi człowieka do wykonywania różnorodnej aktywności fizycznej. Znajdują zastosowanie jako pełnowartościowe przekąski dla sportowców czy żołnierzy. Tego typu produkty są doskonałym sposobem na uzupełnienie niezbędnych składników odżywczych po wysiłku fizycznym czy zaspokojenie uczucia głodu (Hassan, 2020).

Występuje jednak szereg problemów, z którymi borykają się producenci batonów wysokobiałkowych (twardnienie czy posmaki związane z pochodzeniem białek). Głównym z nich jest jednak twardnienie podczas procesu przechowywania, co zauważalne jest już kilka dni od daty produkcji. Proces ten jest najprawdopodobniej związany z interakcjami składników wewnątrz masy batonowej oraz działaniem warunków środowiska zewnętrznego. Prowadzi to do niepożądanych zmian właściwości batonów białkowych, związanych przede wszystkim z teksturą czy smakiem (Hogan et al. 2016). Zjawisko to negatywnie wpływa na wartość rynkową batonów wysokobiałkowych. Głównymi czynnikami wpływającymi na twardnienie podczas przechowywania batonów białkowych są przede wszystkim: krystalizacja cukrów, migracja wody, samoagregacja białek, rozdzielanie faz i reakcje nieenzymatycznego brunatnienia. Proces twardnienia batonów wysokobiałkowych to skomplikowany proces, obejmujący zmiany fizyczne na wczesnym etapie magazynowania i reakcje chemiczne zachodzące w czasie okresu długotrwałego przechowywania (Kumar et al. 2018). Z tego względu producenci decydują się na różnorodne modyfikacje, do których można zaliczyć:

a) dobór odpowiednich surowców, mających na celu ograniczenie wysychania i migracji wilgoci podczas procesu przechowywania (zastosowanie humektantów);

b) substytucję białek standardowych ich hydrolizowanymi odpowiednikami;

c) modyfikacje rodzaju białek, które w zależności od pochodzenia mogą posiadać różnorodne właściwości fizykochemiczne i teksturalne;

d) zmiany warunków przechowywania i sposobu pakowania (Molina-Rubio et al., 2010).

W związku z powyższym producenci w dalszym ciągu poszukują najlepszych metod, które będą w stanie wpływać na spowolnienie lub minimalizowanie problematyki związanej z twardnieniem. Dlatego, poszukiwanie najlepszego rozwiązania i poruszanie tematyki związanej z tym zagadnieniem jest wyjątkowo zasadne i istotne, zarówno pod względem technologicznym, jak i marketingowym.

4. Hipoteza oraz cel pracy badawczej

Na podstawie problemu badawczego zgłoszonego przez firmę EUROHANSA Sp. z o. o. oraz dokonanego przeglądu literaturowego sformułowano następującą hipotezę badawczą:
Batony wysokobiałkowe dla osób aktywnych fizycznie na bazie różnych źródeł białka (grochowe, ryżowe, pszenne, słonecznikowe, konopne, sojowe, alg morskich, dyniowe) oraz płynnych substancji syropowych (błonnik z korzenia cykorii, syrop maltitolowy, błonnik grochowo-kukurydziany, błonnik z tapioki), które są zamiennikami białek serwatkowych oraz syropu glukozowego i nie są powszechnie stosowane w tego typu produktach, stanowią innowacyjną formułę o potencjalnych właściwościach aplikacyjnych.

Głównym celem pracy było określenie wpływu poszczególnych rodzajów składników ujętych w formule opracowanego produktu, przede wszystkim na jego cechy tekstury (twardość, kruchość, przylegalność, adhezyjność, spójność), lepkość, właściwości lepkosprężyste - moduły sprężystości i lepkości (G′ i G″) oraz inne cechy t.j. kąt fazowy, aktywność wody, mikrostrukturę, barwę [CVS – Komputerowy System Wizyjny (Computer Vision System)], wartość odżywczą i energetyczną, cechy sensoryczne, zwilżalność, stabilność (TSI – Turbiscan Stability Index).

W celu weryfikacji sformułowanych koncepcji badawczych dokonano wyznaczenia następujących celów szczegółowych:

- Określenie możliwości zastąpienia koncentratu białek serwatkowych innym rodzajem białka w proporcji 1:1 w produkcji batonów wysokobiałkowych;
- Ocena wpływu zastosowanych ekwiwalentów koncentratu białek serwatkowych na cechy fizykochemiczne i sensoryczne batonów wysokobiałkowych;
- Wykorzystanie płynnych substancji syropowych jako potencjalnych zastępników powszechnie stosowanego syropu glukozowego;
- Określenie wpływu zastosowanych płynnych substancji syropowych na właściwości fizykochemiczne i sensoryczne wyrobów gotowych (batonów wysokobiałkowych);

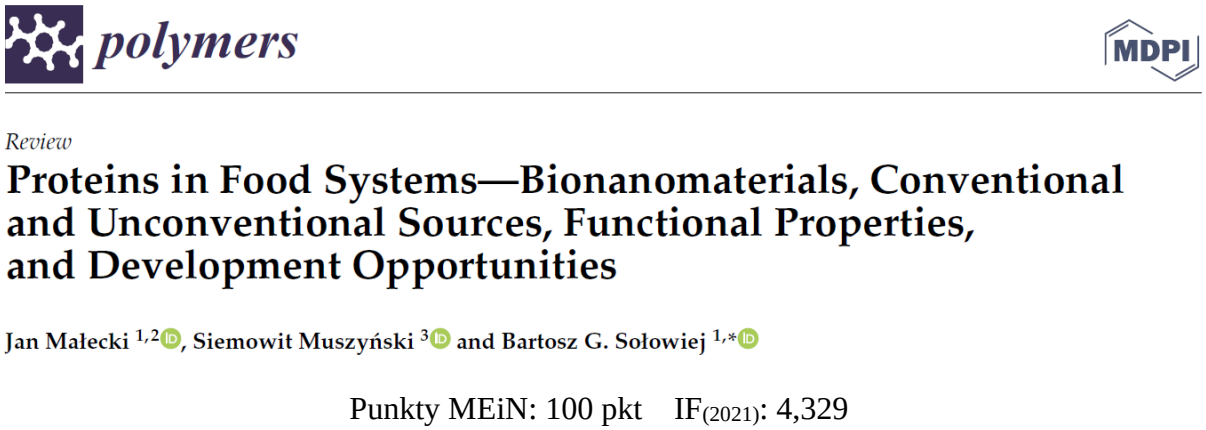
- Dokonanie interpretacji polegającej na określeniu najlepszego połączenia określonego rodzaju białka i syropu w celu osiągnięcia najbardziej pożądanych cech fizykochemicznych i sensorycznych do opracowanych funkcjonalnych batonów wysokobiałkowych.

5. Struktura przeprowadzanych doświadczeń

5.1. Etapy weryfikacji koncepcji badawczych

Weryfikacji założeń badawczych dokonywano poprzez wykonywanie odpowiednich doświadczeń i analiz, zgodnie z założeniami przedstawionymi w **Tabeli 1.** Efekty dokonanej weryfikacji załączono w formie publikacji, które stanowią przedmiot rozprawy doktorskiej.

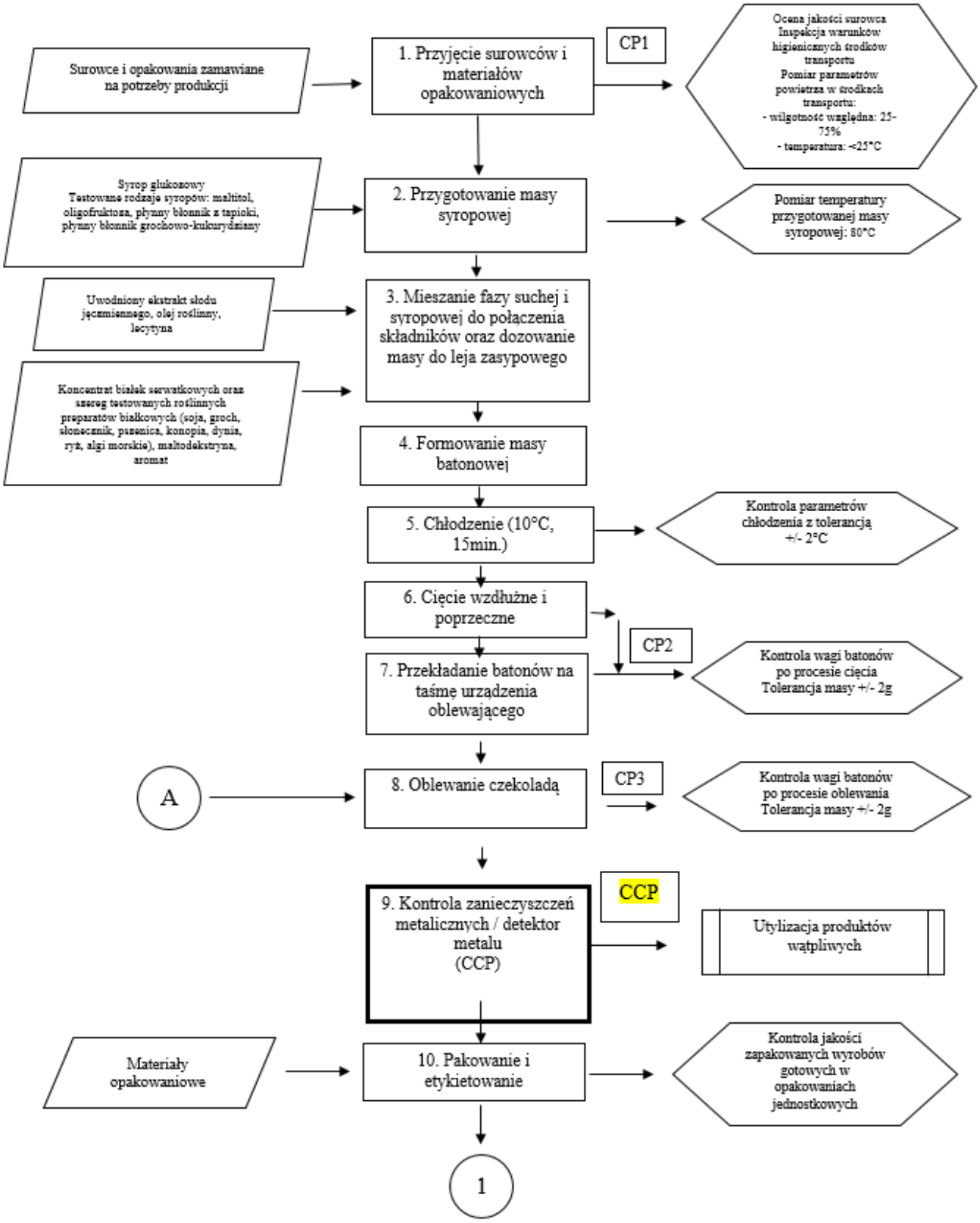
Tabela 1. Etapy weryfikacji koncepcji badawczych

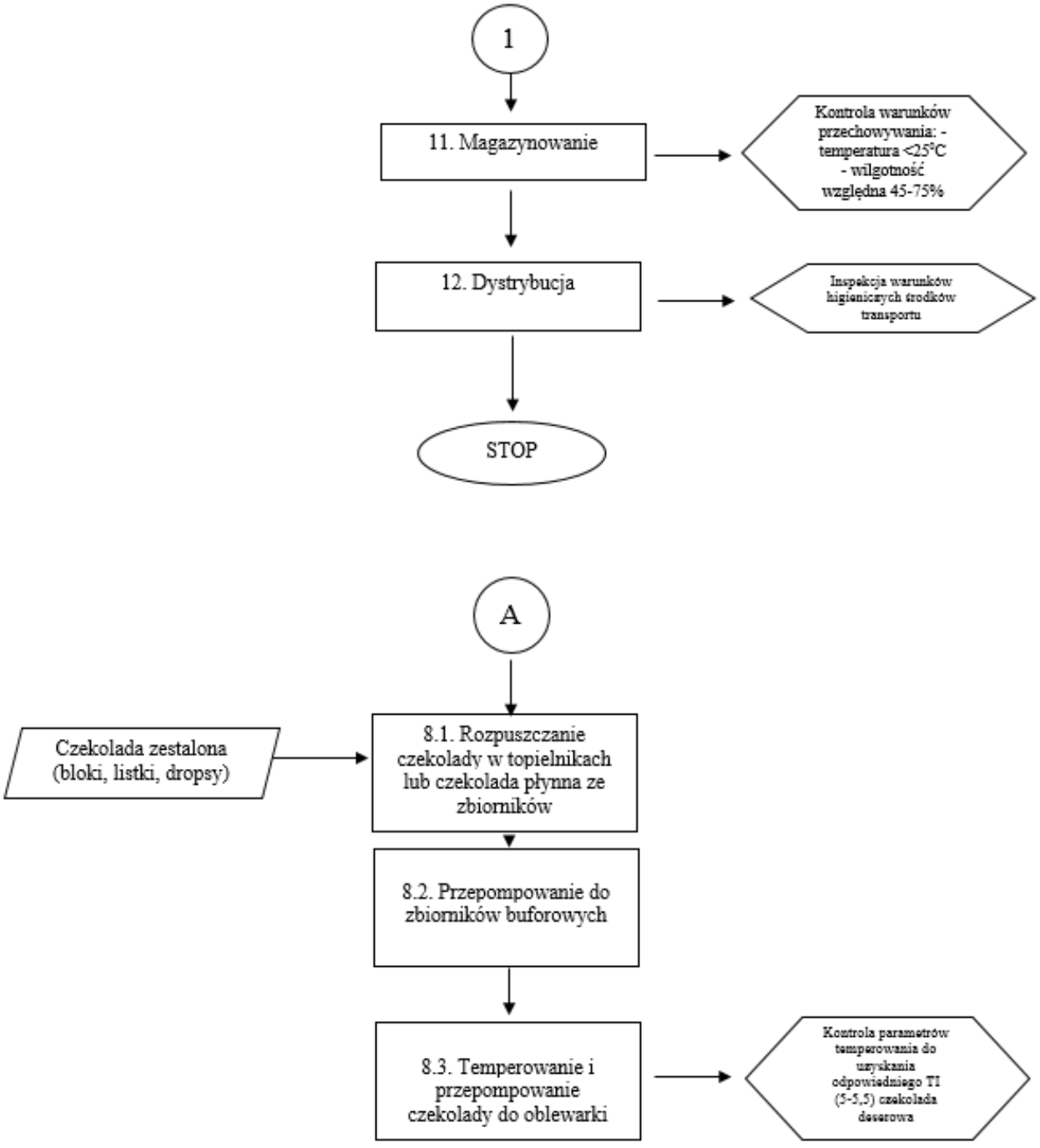
ETAP	ZAŁOŻENIA	PUBLIKACJA
	Publikacja I	
I	Analiza rynku oraz dostępnych materiałów źródłowych. Opracowanie tematycznego przeglądu literatury oraz publikacji naukowej opisującej rolę białek w przemyśle spożywczym oraz możliwości zastosowania preparatów białkowych konwencjonalnych i alternatywnych.	

II	**Publikacja II** Opracowanie receptury bazowej. Badanie wpływu zastosowanych zamienników koncentratu białek serwatkowych (białko grochowe, ryżowe, pszenne, słonecznikowe, konopne, sojowe, alg morskich, dyniowe) na właściwości fizykochemiczne i sensoryczne batonów wysokobiałkowych.	foods MDPI *Article* **The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People** Jan Małecki [1,2], Igor Tomasevic [3], Ilija Djekic [4] and Bartosz G. Sołowiej [1,*] Punkty MEiN: 100 pkt IF$_{(2021)}$: 4,350
III	**Publikacja III** Analiza wpływu użytych ekwiwalentów syropu glukozowego – substancje syropowe płynne (błonnik z korzenia cykorii, syrop maltitolowy, błonnik grochowo-kukurydziany, błonnik z tapioki) na właściwości fizykochemiczne i sensoryczne batonów wysokobiałkowych.	Hindawi Journal of Food Quality Volume 2022, Article ID 2317676, 12 pages https://doi.org/10.1155/2022/2317676 WILEY | Hindawi *Research Article* **The Influence of the Syrup Type on Rheology, Color Differences, Water Activity, and Nutritional and Sensory Aspects of High-Protein Bars for Sportsmen** Jan Małecki [1,2] Igor Tomasevic [3] and Bartosz G. Sołowiej [1] Punkty MEiN: 40 pkt IF$_{(2021)}$: 2,450

	Publikacja IV	
IV	Zastosowanie kombinacji białek i syropów, które na podstawie wcześniejszych analiz zostały zaklasyfikowane jako najlepiej rokujące. Ocena wpływu użytych kombinacji pod względem właściwości fizykochemicznych i sensorycznych.	 International Journal of *Environmental Research and Public Health* MDPI *Article* **Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used** Jan Małecki [1,2,3], Konrad Terpiłowski [4], Maciej Nastaj [1] and Bartosz G. Sołowiej [1,*] Punkty MEiN: 140 pkt $IF_{(2021)}$: 3,390

5.2. Schemat technologii produkcji opracowanego produktu (baton wysokobiałkowy) z wykorzystaniem linii technologicznej Sollich Conbar 600




1
11. Magazynowanie
Kontrola warunków przechowywania: - temperatura <25°C - wilgotność względna 45-75%
12. Dystrybucja
Inspekcja warunków higienicznych środków transportu
STOP
A
Czekolada zestalona (bloki, listki, dropsy)
8.1. Rozpuszczanie czekolady w topielnikach lub czekolada płynna ze zbiorników
8.2. Przepompowanie do zbiorników buforowych
8.3. Temperowanie i przepompowanie czekolady do oblewarki
Kontrola parametrów temperowania do uzyskania odpowiedniego TI (5-5,5) czekolada deserowa

5.3. Opracowana na potrzeby badań receptura bazowa

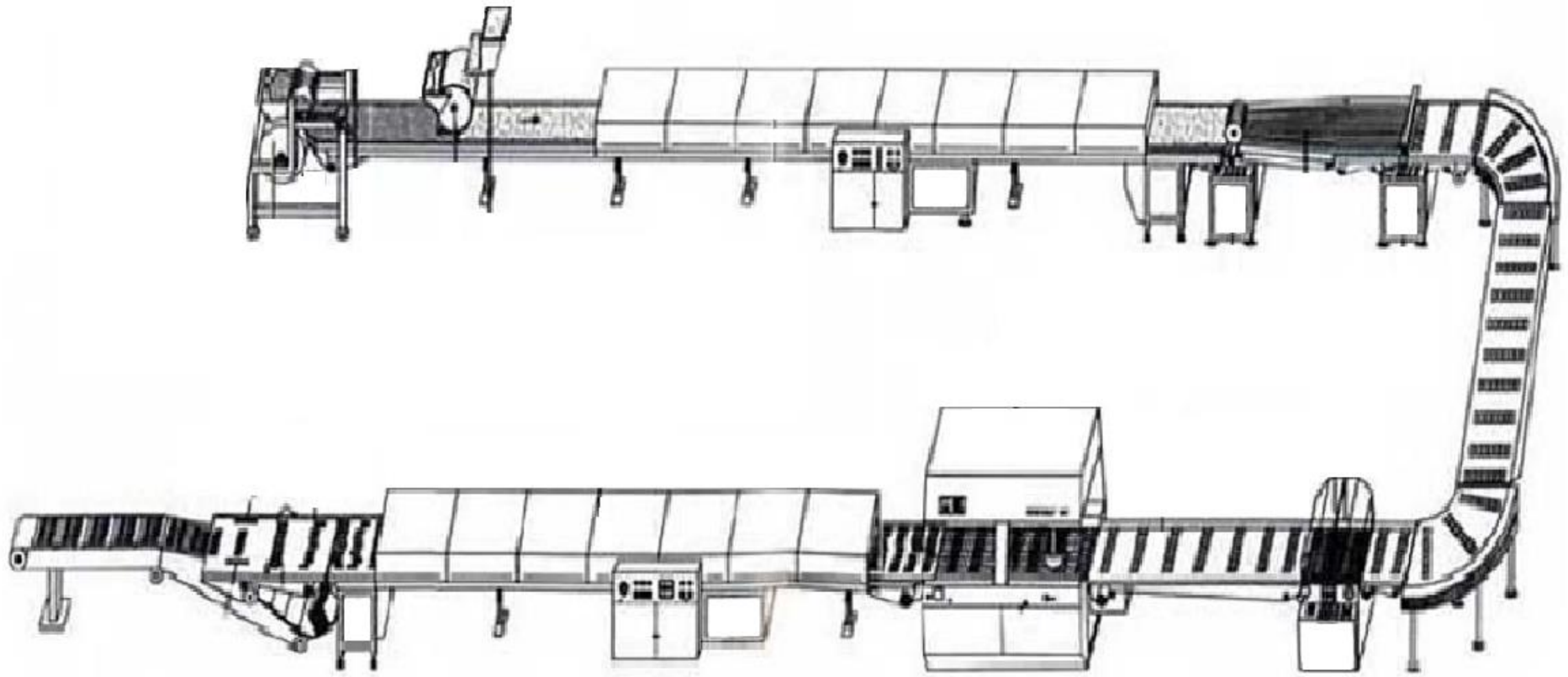
Tabela 1. Kompozycja zaprojektowanych batonów wysokobiałkowych

Kompozycja projektowanych batonów wysokobiałkowych bez czekolady	
Składnik	**Udział w wyrobie gotowym (%)**
*Komponent białkowy (WPC, SPI, PAP, RPC, WHP, ALP, SUP, HEP lub PMP)	38,18
**Substancja syropowa (GS, OF, ML, PM, TF)	31,82
Olej rzepakowy	13,64
Maltodekstryna	5,45
Woda	5,45
Ekstrakt słodu jęczmiennego w proszku	3,64
Lecytyna sojowa	0,91
Aromat waniliowy	0,91
Kompozycja projektowanych batonów wysokobiałkowych w czekoladzie	
Składnik	**Udział w wyrobie gotowym (%)**
*Komponent białkowy (WPC, SPI, PAP, RPC, WHP, ALP, SUP, HEP lub PMP)	30,2
**Syrop glukozowy (GS, OF, ML, PM, TF)	25,0
Olej rzepakowy	10,8
Maltodekstryna	4,3
Woda	4,3
Ekstrakt słodu jęczmiennego w proszku	2,9
Lecytyna sojowa	0,7
Aromat waniliowy	0,7
Czekolada	21,1

*Komponenty białkowe: białka serwatkowe - WPC, grochowe - PAP, ryżowe - RPC, pszenne - WHP, słonecznikowe - SUP, konopne - HEP, sojowe - SPI, alg morskich - ALP, dyniowe – PMP

**Substancje syropowe: syrop glukozowy - GS, błonnik z korzenia cykorii - OF, syrop maltitolowy - ML, błonnik grochowo-kukurydziany - PM, błonnik z tapioki – TF

5.4. Schematyczne przedstawienie procesu produkcyjnego batonów wysokobiałkowych będących przedmiotem wdrożenia na linii technologicznej Sollich Conbar 600. Opracowanie własne na podstawie dostępnej dokumentacji zakładowej.



6. Dyskusja i omówienie wyników

6.1. Prezentacja aktualnego stanu wiedzy na temat zastosowania i roli białek w przemyśle (publikacja I)

Obecny stan wiedzy na temat roli białek w przemyśle spożywczym, bionanomateriałach, możliwości pozyskiwania konwencjonalnych i niekonwencjonalnych źródeł białka i ich szanse na rozwój w różnych gałęziach przemysłu przedstawiono w **publikacji I (Małecki J., Muszyński S., Sołowiej B.G., 2021, *Proteins in Food Systems—Bionanomaterials, Conventional and Unconventional Sources, Functional Properties, and Development Opportunities*. Polymers, 13(15), 2506**. W przygotowanym artykule przeglądowym, dokonano próby przedstawienia możliwości wykorzystania białek w różnych gałęziach przemysłu spożywczego oraz materiałowego. Opisano najważniejsze właściwości strukturalno-funkcjonalne białek, które są najpowszechniej wykorzystywane w przemyśle spożywczym oraz dokonano klasyfikacji ich poszczególnych cech funkcjonalnych. Przedstawiono możliwości rozwoju rynku produktów wykorzystujących białka niekonwencjonalne oraz potencjalne źródła pozyskiwania tego rodzaju protein, przede wszystkim ze źródeł pochodzenia roślinnego. Stworzono porównanie polegające na określeniu wad i zalet pod względem technologicznym, funkcjonalnym i zdrowotnym, zarówno białek pochodzenia zwierzęcego, jak i roślinnego.

6.2. Badania dotyczące wpływu określonego źródła białka na właściwości fizykochemiczne, strukturalne oraz wartość odżywczą batonów wysokobiałkowych (publikacja II)

Białkami, które są najpowszechniej wykorzystywane wśród aplikacji związanych z produktami wysokobiałkowymi są białka serwatkowe pod postacią koncentratów (WPC) lub izolatów (WPI) tychże białek. Koncentraty oraz izolaty są bogatym źródłem pełnowartościowego białka, w szczególności alfa-laktoalbuminy i beta-laktoglobuliny. W przemyśle spożywczym białka serwatkowe znajdują bardzo szerokie zastosowanie ze względu na ich wysoką wartość odżywczą, pożądane właściwości sensoryczne (posmaki mleczne) oraz doskonałe właściwości użytkowe. Od pewnego czasu obserwuje się jednak gwałtowny wzrost zainteresowania alternatywnymi źródłami białek, w szczególności pochodzenia roślinnego, które mogłyby konkurować z powszechnie stosowanym koncentratem białek serwatkowych (WPC) pod względem właściwości fizykochemicznych, teksturalnych czy odżywczych w otrzymywaniu produktów wysokobiałkowych (Wang & Xiong, 2019). Białka roślinne są także coraz częściej stosowane jako ekonomiczna i wszechstronna alternatywa dla białek zwierzęcych w żywieniu człowieka. Pozyskiwanie białek zwierzęcych wiąże się ze zwiększającymi się kosztami i ograniczoną podażą, co jest silnie związane ze zmianami klimatu, wyczerpywaniem się wody słodkiej, utratą bioróżnorodności oraz zagrożeniami dla zdrowia ludzkiego powiązanymi z licznymi alergiami (Gomes et al., 2020). Ponadto, zastosowanie białek roślinnych w formułowaniu nowych produktów spożywczych (w tym batonów wysokobiałkowych) może być również sposobem na wzrost zainteresowanie tymi produktami wśród wegan, wegetarian i osób prowadzących aktywny tryb życia (Ermiş & Karasu, 2020).W odniesieniu do powyższych informacji, wykonano szereg badań, które miały na celu określenie możliwości zastosowania alternatywy dla białek serwatkowych w produkcji batonów wysokobiałkowych.

Analizie poddano właściwości tekstury tj. twardość, kruchość, przylegalność (adhezyjność - kleistość), spójność czy siłę potrzebną do przecięcia produktów. Przeprowadzono badania parametrów fizykochemicznych i sensorycznych (aktywność wody, lepkość dynamiczna, zawartość metali ciężkich, zawartość aminokwasów, ocena sensoryczna, wartość odżywcza i energetyczna, analiza barwy ($L^*a^*b^*$, natężenie barwy – Komputerowy System Wizyjny - CVS) oraz mikrostruktura (skaningowa mikroskopia elektronowa) opracowanych batonów wysokobiałkowych. Wyniki przeprowadzonych badań i analiz przedstawiono w **publikacji II (Małecki J.; Tomasevic I.; Djekic I.; Sołowiej B.G., 2020,**

***The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People*. Foods, 9(10), 1467)**.

Tabela 2a. Wpływ rodzaju białka na cechy tekstury batonów wysokobiałkowych pokrytych czekoladą.

Rodzaj białka zastosowany w batonach wysokobiałkowych pokrytych czekoladą	Badana cecha tekstury			
	Twardość [N]	Kruchość [N]	Adhezyjność / Przylegalność [J]	Spójność
WPC – białka serwatkowe	54,66 ^{e} ± 0,303	0,06 ^{a} ± 0,005	382,87 ^{g} ± 4,977	0,14 ^{f} ± 0,001
RPC – białka ryżowe	20,95 ^{a} ± 0,164	0,06 ^{a} ± 0,004	57,54 ^{c} ± 2,588	0,07 ^{c} ± 0,001
SPI – białka sojowe	25,25 ^{c} ± 0,358	20,85 ^{b} ± 0,152	66,85 ^{c} ± 1,773	0,04 ^{a} ± 0,004
SUP – białka słonecznika	136,61 ^{g} ± 0,406	115,56 ^{f} ± 0,255	225,61 ^{f} ± 4,861	0,10 ^{de} ± 0,001
WHP – białka pszenne	88,33 ^{f} ± 0,092	55,38^{e} ± 0,288	123,42 ^{d} ± 3,724	0,11 ^{e} ± 0,004
HEP – białka konopne	27,74 ^{d} ± 0,152	0,03 ^{a} ± 0,005	27,15 ^{b} ± 2,528	0,13 ^{f} ± 0,003
PAP – białka grochu	27,44 ^{d} ± 0,302	25,86 ^{d} ± 0,461	145,78 ^{e} ± 4,853	0,06 ^{b} ± 0,002
PMP – białka dyni	23,52 ^{b} ± 0,338	23,27 ^{c} ± 0,215	7,34 ^{a} ± 0,392	0,09 ^{d} ± 0,004
ALP – białka alg morskich	276,43 ^{h} ± 0,286	0,13 ^{a} ± 0,012	129,67 ^{d} ± 0,577	0,19 ^{g} ± 0,008

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–h}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

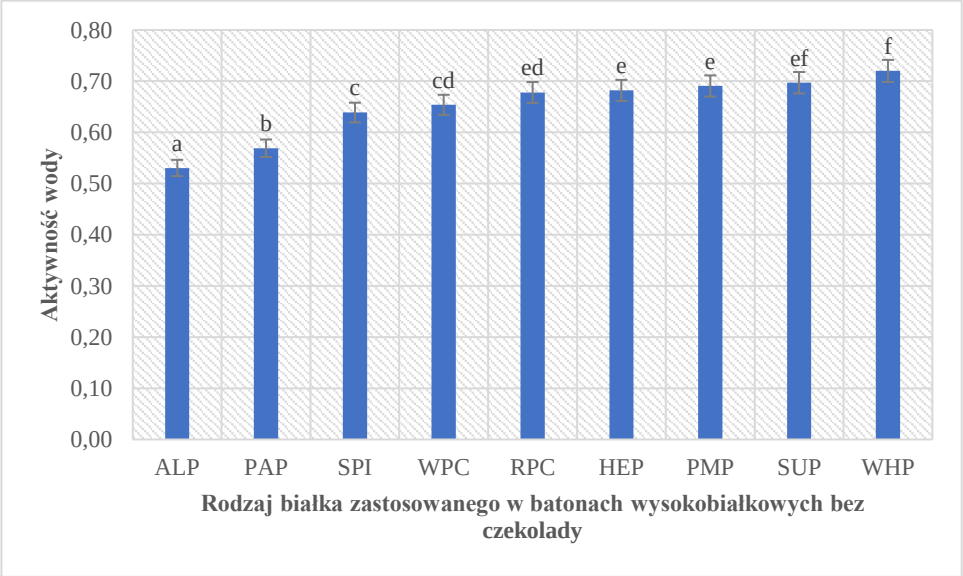
Tabela 2b. Wpływ rodzaju białka na cechy tekstury batonów wysokobiałkowych bez czekolady.

Rodzaj białka zastosowany w batonach wysokobiałkowych bez czekolady	Badana cecha tekstury			
	Twardość [N]	Kruchość [N]	Adhezyjność / Przylegalność [J]	Spójność
WPC – białka serwatkowe	34,53 ^{f} ± 0,277	0,30 ^{a} ± 0,024	56,23 ^{d} ± 4,336	0,12 ^{d} ± 0,001
RPC – białka ryżowe	18,64 ^{c} ± 0,327	0,11 ^{a} ± 0,018	34,16 ^{c} ± 2,166	0,05 ^{b} ± 0,001
SPI – białka sojowe	16,38 ^{b} ± 0,201	16,39 ^{b} ± 0,306	5,88 ^{a} ± 0,681	0,03 ^{a} ± 0,002
SUP – białka słonecznika	149,19 ^{h} ± 0,198	122,52 ^{e} ± 0,439	16,23 ^{b} ± 2,171	0,15 ^{e} ± 0,001
WHP – białka pszenne	81,31 ^{g} ± 0,172	0,08 ^{a} ± 0,004	130,15 ^{e} ± 2,157	0,22 ^{g} ± 0,010
HEP – białka konopne	21,50 ^{e} ± 0,170	35,59 ^{c} ± 0,450	3,37 ^{a} ± 0,479	0,09 ^{c} ± 0,006
PAP – białka grochu	13,62 ^{a} ± 0,246	36,81 ^{d} ± 0,217	1,69 ^{a} ± 0,246	0,06 ^{b} ± 0,004
PMP – białka dyni	19,67 ^{d} ± 0,167	0,03 ^{a} ± 0,004	322,85 ^{f} ± 2,695	0,21 ^{g} ± 0,006
ALP – białka alg morskich	288,50 ^{i} ± 0,326	0,07 ^{a} ± 0,004	27,79 ^{c} ± 2,947	0,17 ^{f} ± 0,002

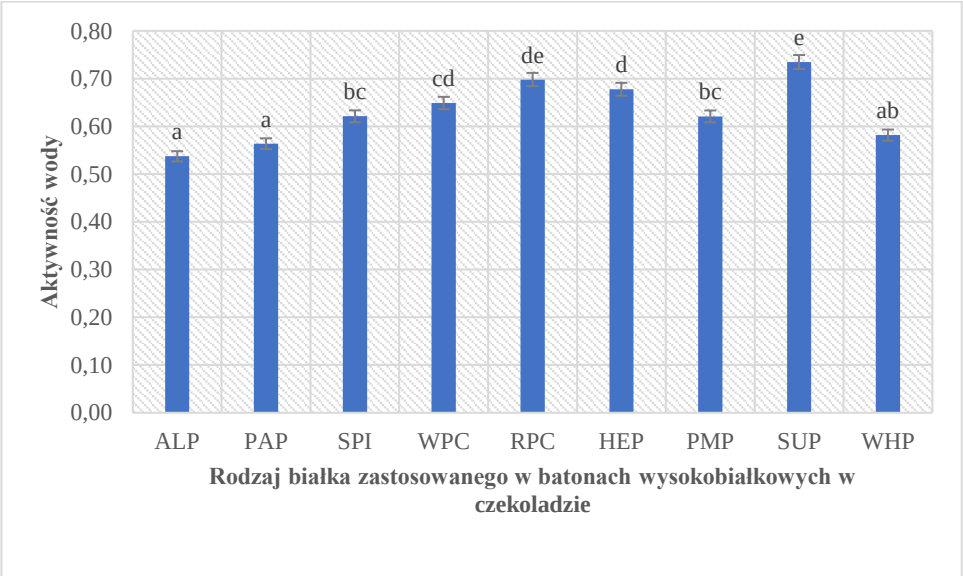
Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–h}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Pierwszymi badaniami wykonywanymi na opracowanych produktach, w których modyfikowano rodzaj zastosowanego białka, były: analiza profilowa tekstury (TPA) t.j. twardość, kruchość, adhezyjność, spójność oraz test cięcia (Tabela 2a,b; Tabela 3), skaningowa mikroskopia elektronowa (SEM) oraz aktywność wody. Opracowane batony wysokobiałkowe wykazywały się dużym zróżnicowaniem ww. parametrów. Zaobserwowano istotne różnice ($p< 0,05$). W obu przypadkach najwyższą twardością wykazywał się baton wykonany z białek alg morskich (ALP) (276,43 N z czekoladą i 288,50 N bez pokrycia czekoladą), natomiast najniższą twardością charakteryzowały się batony z białek grochu (PAP) w wariancie bez czekolady (13,62 N) oraz białek ryżu (RPC) w próbce pokrytej czekoladą (20,95 N). Biorąc pod uwagę uzyskane wyniki oraz badania Banacha i in. (Banach et al., 2017), można zauważyć pewną prawidłowość w przypadku batonów wykonanych z białek serwatkowych. Relatywnie niska wartość parametru twardości przekłada się na wysokie wartości adhezyjności i spójności (spoistości), a jednocześnie niskie poziomy kruchości. Zupełnie inną sytuację można zaobserwować w przypadku produktu z białkami z alg morskich. Pomimo wysokiej twardości batonu wykonanego z tego rodzaju białka, w batonie oblanym czekoladą zaobserwowano wysokie wartości parametrów adhezyjności i spoistości oraz bardzo niskie wartości kruchości. Na uwagę zasługują również wyniki uzyskane z badań batonika z białek słonecznika (SUP) ze względu na stosunkowo wysoki poziom wszystkich parametrów TPA, w szczególności w próbce oblanej czekoladą. Przyciąganie międzycząsteczkowe, dzięki któremu elementy ciała lub masy materiału są utrzymywane razem, decyduje o jego spoistości (Trinh & Glasgow, 2012). Banach i in. (Banach et al., 2016) znaleźli związek między twardością batoników a wielkością cząsteczek białka użytego do wykonania produktu. Na podstawie analizy wyników (Tabela 2a,b**)** oraz zdjęć mikrostruktury batonów można przypuszczać, że użyte do produkcji batonów wysokobiałkowych białka o dużych rozmiarach cząstek, mogą powodować znaczny wzrost twardości produktu końcowego. Zgodnie z tym założeniem, białka drobnoziarniste mają znacznie mniejszą skłonność do tworzenia twardych struktur podczas procesu przechowywania i pozwalają na stworzenie delikatnej i miękkiej struktury produktu (Cho, 2010). Zaobserwowano, że batoniki pokryte czekoladą wykazywały w większości przypadków wyższe wartości twardości niż w przypadku próbek nieoblewanych. Główną tego przyczyną może być stopień wytemperowania czekolady, która w wyniku prawidłowo przeprowadzonego procesu, cechuje się dużą twardością i powoduje charakterystyczny trzask podczas przełamywania. Wzrost wartości pozostałych parametrów jest najprawdopodobniej związany z większym ograniczeniem dostępu powietrza do tych produktów, co z kolei

wpływa na spowalnianie procesów wysychania produktów (o czym świadczą wyższe wyniki adhezyjności i aktywności wody) (Wykres 1a,b).



a)



b)

Wykres 1 (a-b). Wpływ rodzaju białka na aktywność wody batonów wysokobiałkowych **(a)** bez czekolady, **(b)** w czekoladzie. Dane przedstawiono jako średnie ± SD (odchylenie standardowe). [a–f] Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

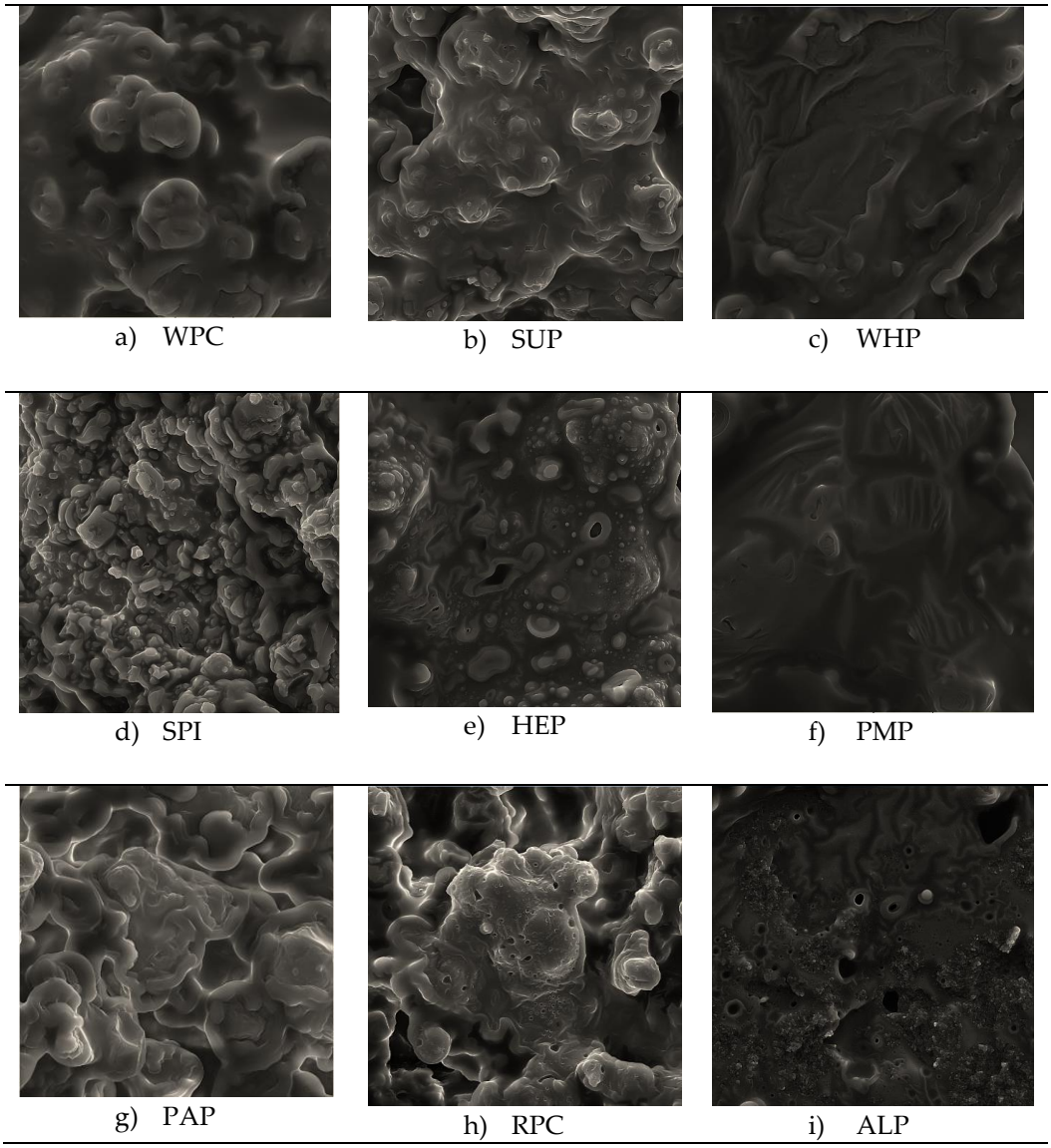
Tabela 3. Odporność na siłę cięcia batonów wysokobiałkowych wykonanych z różnego rodzaju białka.

Rodzaj białka zastosowany w batonach wysokobiałkowych pokrytych czekoladą	Odporność na cięcie	Rodzaj białka zastosowany w batonach wysokobiałkowych bez czekolady	Odporność na cięcie
	Siła potrzebna do przecięcia [N]		Siła potrzebna do przecięcia [N]
WPC – białka serwatkowe	79,31 ^{f} ± 0,298	WPC – białka serwatkowe	128,39 ^{h} ± 0,393
RPC – białka ryżowe	25,75 ^{d} ± 0,198	RPC – białka ryżowe	25,36 ^{e} ± 0,084
SPI – białka sojowe	109,69 ^{g} ± 0,112	SPI – białka sojowe	98,21 ^{g} ± 0,162
SUP – białka słonecznika	22,35 ^{c} ± 0,298	SUP – białka słonecznika	14,38 ^{d} ± 0,149
WHP – białka pszenne	10,54 ^{a} ± 0,073	WHP – białka pszenne	8,43 ^{b} ± 0,020
HEP – białka konopne	15,59 ^{b} ± 0,271	HEP – białka konopne	10,58 ^{c} ± 0,126
PAP – białka grochu	75,34 ^{e} ± 0,222	PAP – białka grochu	81,45 ^{f} ± 0,194
PMP – białka dyni	22,70 ^{c} ± 0,143	PMP – białka dyni	7,69 ^{a} ± 0,148
ALP – białka alg morskich	235,45 ^{h} ± 0,366	ALP – białka alg morskich	166,82 ^{i} ± 0,138

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–i}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Stwierdzono dość dużą liczbę podobieństw pomiędzy mikrostrukturą białek (Rysunek 2a,i) SUP, PAP, WPC i RPC. Na zdjęciach białka te posiadały znaczną liczbę wgłębień i przetłoczeń. Biorąc pod uwagę parametry tekstury, taka struktura prawdopodobnie ma istotny wpływ na zmniejszenie twardości i siły potrzebnej do przecięcia (Tabela 3). Wyjątkiem były próbki wykonane z SUP, cechujące się znacznie większą twardością. Może to być związane z powstawaniem dużych skupisk (aglomeratów) białek, co skutkuje powstaniem zwartej i twardej struktury oraz bezpośrednio przekłada się na wysokie wartości parametrów twardości, kruchości i adhezyjności. Zaobserwowano również, że wszystkie powyższe próby charakteryzowały się dość dużą podatnością na działanie siły trzpienia przecinającego w teście cięcia. Warto wspomnieć, że batony z białek WHP i PMP, posiadające strukturę falistą, pozbawione są dużej ilości wypustek i porów powietrznych. Charakteryzowały się również stosunkowo małą twardością oraz dużą podatnością na siłę cięcia. Wszystkie batony wykonane z wyżej wymienionych białek wykazywały podobną, akceptowalną technologicznie, aktywność wody ($a_w < 0,735$).

Rysunek 2 (a-i). Mikrostruktura badanych batonów wysokobiałkowych wykonana za pomocą skaningowego mikroskopu elektronowego (SEM HV: 30 kV, 271 μm, SEM powiększenie: 800x).



a) WPC b) SUP c) WHP

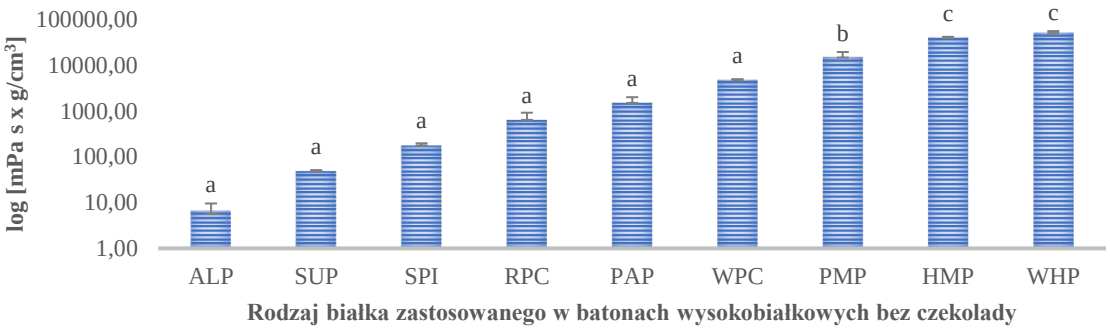
d) SPI e) HEP f) PMP

g) PAP h) RPC i) ALP

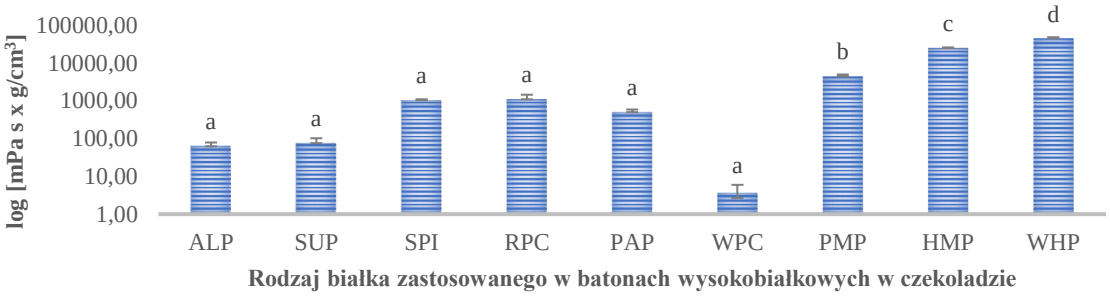
Batony wykonane z białek ALP cechowały się bardzo nieregularną budową. Na jego powierzchni zaobserwowano liczne powietrzne pory i nierównomiernie rozmieszczone aglomeraty cząsteczek białka w postaci krzaczastych wypustek. Co ciekawe, białkowe wypukłości były również przeplatane przez pofalowane, stosunkowo gładkie struktury białkowo-tłuszczowe. Odnosząc się do pracy Bleakleya i Hayesa (Bleakley & Hayes, 2017), powstawanie charakterystycznych aglomeratów w przypadku białka alg może być związane z obecnością lektyn w tym typie białka. Lektyny są glikoproteinami posiadającymi tendencję do agregacji i wysokiej specyficzności wiązania z węglowodanami bez inicjowania modyfikacji poprzez związaną z nimi aktywnością enzymatyczną. Zupełnie inna

mikrostruktura prób z ALP była zatem prawdopodobnie przyczyną ich największej twardości. Wykorzystanie w badaniach białek różnego pochodzenia botanicznego ma istotny wpływ na sposób pęcznienia, reorganizację struktur molekularnych czy agregację białek w produkcie. Jednak kontrola mikro- i makrostruktur jest nadal bardzo trudna ze względu na ograniczoną ilość informacji dotyczących tego zagadnienia (Purwanti et al., 2010).

Kolejnymi badanymi parametrami była lepkość dynamiczna oraz analiza barwy. Najwyższe wartości lepkości (Wykres 2a,b) odnotowano dla batonów wykonanych z białek WHP i HEP (>10000 mPa s g/cm^3), natomiast najniższe - dla ALP, WPC, PAP i SUP (<10000 mPa s g/cm^3). Niskie wartości lepkości, w szczególności dla ALP, można skorelować z wysokimi wynikami twardości i siły cięcia. Warto również zwrócić uwagę na mikrostrukturę batonów otrzymanych z wyżej wymienionych białek, w której widoczne były liczne skupiska szerokich porów (prawdopodobnie pory tłuszczowo-powietrzne) oraz zwarta i nieregularna struktura.



a)



b)

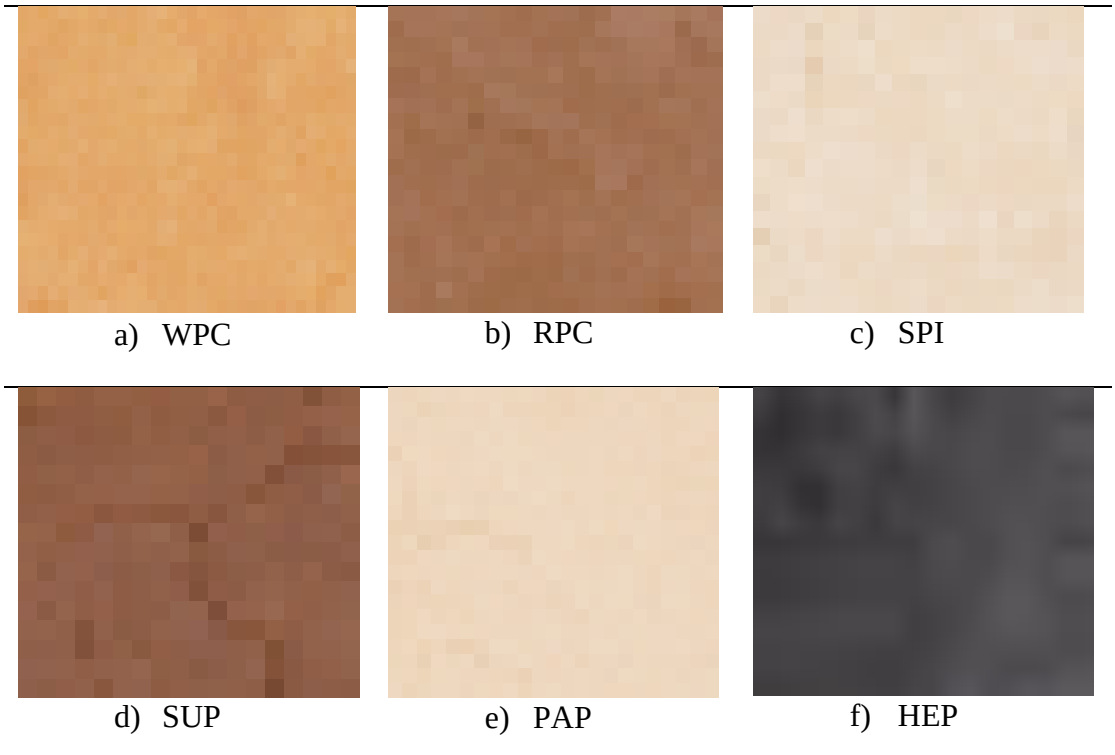
Wykres 2 (a-b). Wpływ rodzaju białka na lepkość ultradźwiękową batonów wysokobiałkowych bez czekolady **(a)** oraz w czekoladzie **(b)**. Dane przedstawiono jako średnie ± SD (odchylenie standardowe). a–d Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Tabela 4 (a-b). (a) Wpływ rodzaju białka na zmianę barwy batonów wysokobiałkowych mierzony za pomocą metody CVS (Komputerowy System Wizyjny), **(b)** Wizualizacja otrzymanej barwy.

a)

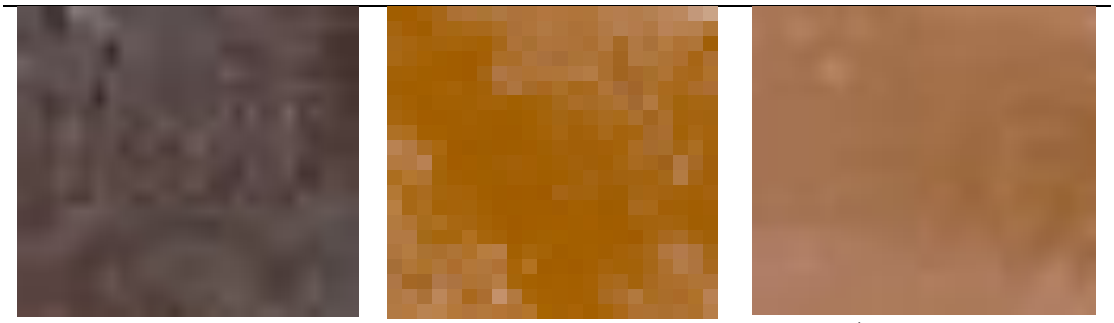
Rodzaj białka wykorzystany w produkcie (bez czekolady)	**Badana cecha**			
	L *	**a ***	**b ***	**NBS Units**
WPC – białka serwatkowe	63,86 ^{f} ± 1,069	17,29 ^{d} ± 0,488	44,43 ^{f} ± 0,976	-
RPC – białka ryżowe	43,71 ^{c} ± 0,488	10,00 ^{c} ± 0,000	21,14 ^{b} ± 0,690	29,12
SPI – białka sojowe	79,43 ^{h} ± 0,787	5,29 ^{a} ± 0,488	19,43 ^{a} ± 0,976	29,26
SUP – białka słonecznika	34,14 ^{a} ± 0,378	11,00 ^{c} ± 0,000	22,29 ^{b} ± 0,756	34,58
WHP – białka pszenne	40,57 ^{b} ± 0,976	10,00 ^{c} ± 0,000	31,71 ^{c} ± 1,113	25,32
HEP – białka konopne	50,57 ^{e} ± 0,976	47,43 ^{f} ± 1,272	50,29 ^{g} ± 1,704	30,78
PAP – białka grochu	78,00 ^{g} ± 0,000	8,00 ^{b} ± 0,000	23,00 ^{b} ± 0,000	25,12
PMP – białka dyni	49,43 ^{e} ± 1,134	40,71 ^{e} ± 1,113	34,14 ^{d} ± 2,116	27,02
ALP – białka alg morskich	47,71 ^{d} ± 0,488	10,86 ^{c} ± 0,378	39,71 ^{e} ± 0,488	16,57

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–h}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$). b)



a) WPC b) RPC c) SPI

d) SUP e) PAP f) HEP

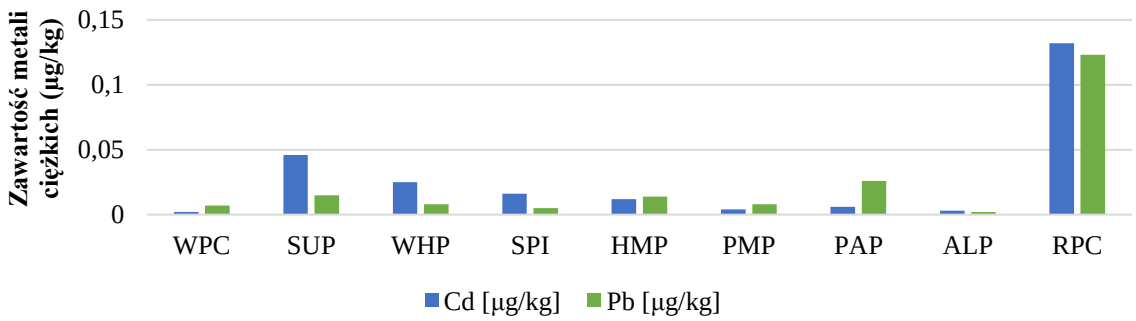


g) PMP h) ALP i) WHP

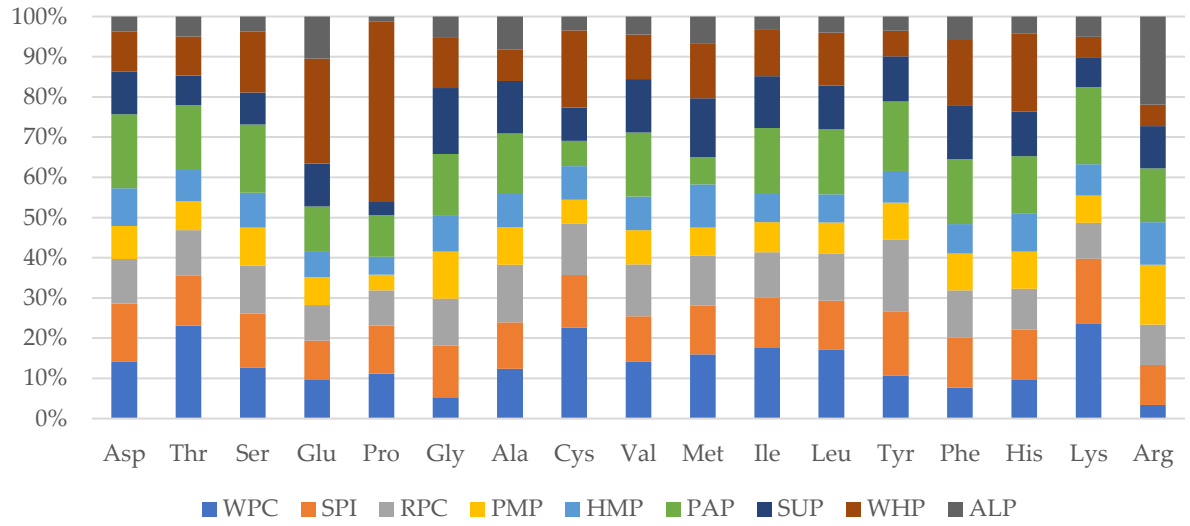
Wyniki analizy barwy przedstawiono w Tabeli 4a,b. Biorąc pod uwagę badania innych naukowców (Inami et al., 2015), wszystkie różnice kolorystyczne wyrażone wartościami NBS (National Bureau of Standards Units) > 6 są znaczne. Rozbieżności świadczą o dużym wpływie zastosowanych białek na różnice barwy batonów wysokobiałkowych. Białka z różnych źródeł charakteryzowały się inną barwą w porównaniu do próby kontrolnej wykonanej z WPC. Najwyższą jasnością charakteryzowało się białko SPI, co może świadczyć o wolniejszej zdolności do wiązania tłuszczu niż inne badane białka. Tłuszcz na powierzchni batoników prawdopodobnie powoduje zwiększoną zdolność odbijania światła. Pozostałe różnice w parametrach a^* i b^* są prawdopodobnie bezpośrednio związane z pochodzeniem składnika (białka roślinne i zwierzęce). Nie badano barwy batonów oblanych czekoladą, gdyż powierzchnia zewnętrzna każdej z prób, oblewana była tym samym rodzajem czekolady. Można jednak przypuszczać, że próby oblane czekoladą miałyby jaśniejsze barwy rdzenia ze względu na lepszą ochronę przed dostępem światła i powietrza (spowolnienie reakcji Maillarda). Porównując wyniki z pracami innych badaczy (McMahon et al., 2009) można przypuszczać, że batony wykonane z syropów wysokofruktozowych i glukozowych są podatniejsze na procesy ciemnienia niż w przypadku innych rodzajów syropów. W związku z tym, następny etap rozprawy doktorskiej dotyczył badań wpływu użytego rodzaju syropu na cechy reologiczne, różnice w barwie, aktywność wody, aspekty żywieniowe i sensoryczne batonów wysokobiałkowych.

Jako ostatnie, wykonano badania dotyczące zawartości metali ciężkich (Wykres 3), zawartości aminokwasów (Wykres 4), wartości energetycznej i odżywczej (Tabela 5) oraz przeprowadzono analizę sensoryczną (Wykres 5a,b). Wszystkie badane rodzaje batonów spełniły normy Unii Europejskiej określone w Rozporządzeniu Komisji (WE) nr 1881/2006 z dnia 19 grudnia 2006 r., pod względem zawartości metali ciężkich (Gallo et al., 2021). W wyniku analiz zawartości aminokwasów, zaobserwowano, że batony zbudowane z białek SPI, RPC i PAP wykazywały dość wyrównane zawartości całego spektrum aminokwasów.

Wśród nich na szczególną uwagę zasługują aminokwasy egzogenne, które zostały określone w znacznych ilościach, jak na białka pochodzenia roślinnego. Wysoką zawartość aminokwasów egzogennych w izolatach białek soi i ryżu potwierdził również Kalman (Kalman, 2014). Można więc przypuszczać, że te rodzaje białek mogą stawać się coraz bardziej popularne, zwłaszcza wśród wegan i wegetarian ze względu na możliwość zaspokajania niedoborów aminokwasów, w przypadku stosowania diet z udziałem tych białek. W odniesieniu do analizy wartości energetycznej i odżywczej warto zwrócić uwagę na zawartość błonnika w batonach wykonanych z HEP i SUP, w których zawartość tego składnika była znacznie wyższa niż w innych próbkach. Ponadto taka ilość błonnika (> 6 g/100 g) pozwala na umieszczenie oświadczenia żywieniowego „wysoka zawartość błonnika" na opakowaniach tych produktów zgodnie z rozporządzeniem (WE) nr 1924/2006 Parlamentu Europejskiego i Rady z dnia 20 grudnia 2006 r. (Martínez-Sanz et al., 2017). Jednak pomimo znaczącej zawartości błonnika, batony wykonane z tych rodzajów białek (HEP, SUP) nie zostały zakwalifikowane do dalszej części badań, przede wszystkim ze względu na przeciętną atrakcyjność sensoryczną oraz niewielką zdolność obniżania aktywności wody.



Wykres 3. Zawartość metali ciężkich (kadm i ołów) w opracowanych batonach wysokobiałkowych.

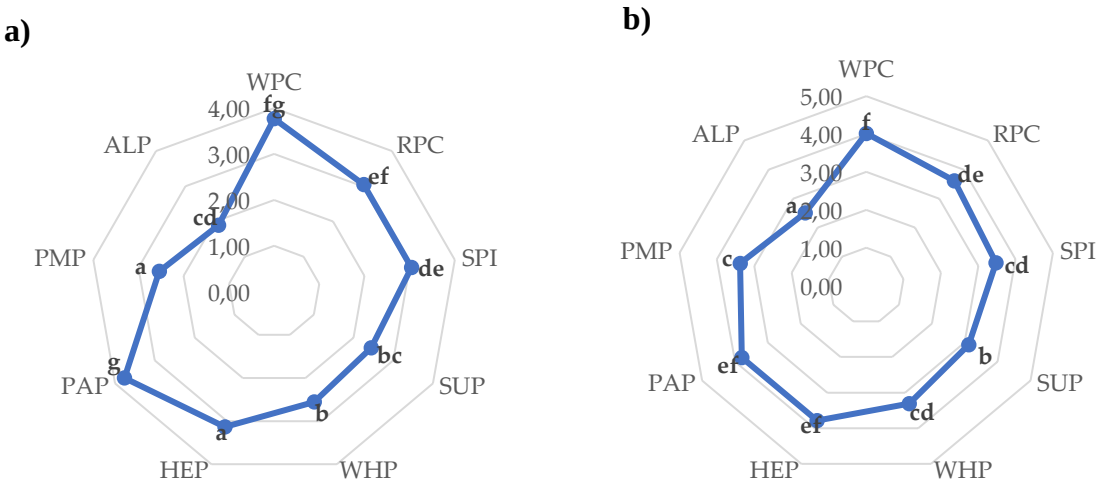


Wykres 4. Udział poszczególnych aminokwasów w opracowanych batonach wysokobiałkowych.

Tabela 5. Różnice w wartości energetycznej i odżywczej badanych batonów wysokobiałkowych na podstawie metody obliczeniowej.

Wartość energetyczna i odżywcza w 100 g wyrobu gotowego (bez czekolady)									
Rodzaj użytego syropu	**Energia [kJ]**	**Energia [kcal]**	**Tłuszcz [g]**	**Kw. tł. nasycone [g]**	**Węglowodany [g]**	**Cukry [g]**	**Błonnik [g]**	**Białko [g]**	**Sól [g]**
WPC	1762	419	15	1,4	40	15	0,03	31	0,12
RPC	1771	421	15	0,96	38	9,2	3,2	32	0
SPI	1728	411	15	1,3	35	9,5	0,03	34	0,81
SUP	1620	386	15	1,2	38	11	7,7	21	0
WHP	1811	431	16	1,3	41	11	1,5	30	0,02
HEP	1663	397	18	1,6	36	11	7,7	19	0,02
PAP	1739	414	16	1,2	35	9,2	0,95	32	1,4
PMP	1757	420	20	2	35	9,8	3,9	23	0,39
ALP	1801	429	18	1,9	42	9,2	1,6	24	0,62
Wartość energetyczna i odżywcza w 100 g wyrobu gotowego (w czekoladzie)									
Rodzaj użytego syropu	**Energia [kJ]**	**Energia [kcal]**	**Tłuszcz [g]**	**Kw. tł. nasycone [g]**	**Węglowodany [g]**	**Cukry [g]**	**Błonnik [g]**	**Białko [g]**	**Sól [g]**
WPC	1833	437	18	4,9	43	23	1,4	25	0,09
RPC	1853	442	18	4,6	42	19	3,9	26	0
SPI	1836	438	19	4,8	39	19	1,4	27	0,64
SUP	1709	408	17	3,7	41	18	7,5	19	0
WHP	1879	448	19	4,9	44	20	2,5	24	0,02
HEP	1789	428	21	5,1	40	20	7,5	16	0,02
PAP	1826	435	19	4,8	39	19	2,2	26	1,1
PMP	1852	443	22	5,4	40	19	4,4	19	0,3
ALP	1903	454	21	5,4	45	19	2,6	20	0,49

Najwyższe oceny w analizie sensorycznej uzyskano dla batonów wykonanych z białek WPC i PAP. Oceniający zwracali szczególną uwagę na wygląd zewnętrzny, barwę i doznania smakowe. Zdaniem osób poddanych badaniu, wysokie oceny dla tego typu białek wiązały się z przyjemną konsystencją, smakiem i kolorem. Batony najgorzej oceniane (ALP), zdaniem oceniających, odznaczały się zbyt dużą twardością, nieprzyjemnym posmakiem i zielono-żółtą barwę, co spowodowało najniższe oceny. Negatywne oceny smaku batona ALP mogą być również spowodowane zbyt dużym dozowaniem tego typu białka w przypadku zadanej aplikacji. Na podstawie badań Halla i in. (Hall et al., 2012), w której dodatek białka alg w pieczywie wynosił 4%, można więc przypuszczać, że niskie oceny batonów z białek alg mogły być spowodowane zbyt wysokim udziałem tego składnika w produkcie końcowym (30%). Biorąc pod uwagę wyniki analizy sensorycznej, można również wnioskować, że pokrycie produktów wysokobiałkowych czekoladą znacznie poprawia ich smakowitość. Oceny poszczególnych prób oblanych czekoladą były wyraźnie lepiej oceniane niż ich nieoblane odpowiedni. Pozostałe batony wysokobiałkowe zostały ocenione na średnim poziomie z tendencją do bardziej pozytywnych.



Wykres 5 (a-b). Analiza sensoryczna batonów wysokobiałkowych **(a)** bez czekolady **(b)** w czekoladzie. [a–g] Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

6.3. Badania dotyczące wpływu zastosowanego rodzaju syropu na właściwości fizykochemiczne, strukturalne oraz wartość odżywczą batonów wysokobiałkowych (publikacja III)

Firmy działające w branży przemysłu spożywczego nieustannie opracowują wiele nowych propozycji produktów wysokobiałkowych, a w tym przede wszystkim batonów białkowych, wychodząc naprzeciw wymaganiom i oczekiwaniom współczesnych konsumentów. Niestety, przede wszystkim ze względu na niską cenę standardowych surowców niezbędnych do stworzenia batonów wysokobiałkowych tj. syropy wysokofruktozowe, cukrowe czy tłuszcze cukiernicze, większość producentów nie decyduje się na modyfikację tych elementów w swoich recepturach, zwłaszcza jeśli chodzi o syropy (Nadeem et al., 2012). Syrop pełni w przypadku tych produktów rolę elementu pozwalającego na zlepienie zastosowanych w recepturze składników i prawidłowe uformowanie wyrobu, a także wpływa na trwałość produktu. Najczęstsze formuły batonów wysokobiałkowych składają się z trzech głównych składników: preparatu białkowego, syropu i formy tłuszczu (oleje i/lub tłuszcze zestalone) (Imtiaz et al., 2012). Po pierwsze, składniki te w największym stopniu warunkują utworzenie właściwych cech produktu wysokobiałkowego, począwszy od procesu produkcji (cechy decydujące o przydatności technologicznej pozwalającej na wysoką wydajność procesu produkcyjnego), a kończąc na zachowaniu określonej przez producenta jakości produktu finalnego, który trafi na półkę sklepową oraz w rezultacie do konsumenta.

Wciąż zwiększające się wymagania współczesnego konsumenta, wzrost świadomości, stosowanie diet, aktywny tryb życia oraz przywiązanie uwagi do produktów prozdrowotnych powodują, że właściwe wydaje się poszukiwanie odpowiednich alternatyw dla wspomnianych, powszechnie stosowanych składników, jednocześnie zwracając uwagę na zachowanie parametrów technologicznych procesu produkcyjnego oraz jego dużej wydajności (Jabeen et al., 2020; Małecki et al., 2020).

Wyniki przeprowadzonych badań, polegających na próbie określenia możliwych ekwiwalentów syropów wysokofruktozowych w aplikacji batonów wysokobiałkowych, zawarto w **publikacji III (Małecki J.; Tomasevic I.; Sołowiej B.G., 2022, The Influence of the Syrup Type on Rheology, Color Differences, Water Activity, Nutritional and Sensory Aspects of High-Protein Bars for Sportsmen. *Journal of Food Quality*, 1(1), 2317676)**. Ze względu na aktualny stan wiedzy oraz dostępność poszczególnych składników, do badań zakwalifikowano: syrop glukozowy (GS) - zastosowany jako próba kontrolna, płynny błonnik z tapioki (TF), oligofruktozę (OF), płynny błonnik grochowo-kukurydziany (PM) oraz alkohol polihydroksylowy – maltitol (ML). Badania, jakim poddano syropy oraz batony z nich wykonane dotyczyły: analizy profilowej tekstury (TPA), aktywności wody, lepkości dynamicznej, wartości odżywczej i energetycznej, ekstruzji wstecznej, analizy barwy (CVS) oraz analizy modułów: zachowawczego (G′ - wynik naprężeń wynikających z cech sprężystych materiału), oraz modułu stratności (G″ – określającego naprężenia związane z cechami lepkimi badanego materiału) i kąta fazowego ((δ) – określającego czy mamy do czynienia z produktami lepkimi czy elastycznymi).

Tabela 6 (a-b). Wpływ syropów na cechy tekstury batonów wysokobiałkowych **(a)** bez czekolady, **(b)** w czekoladzie.

a)

Rodzaj syropu zastosowany w batonach wysokobiałkowych bez czekolady	**Badana cecha tekstury**				
	Twardość [N]	**Kruchość [N]**	**Adhezyjność / Przylegalność [J]**	**Spójność**	**Odporność na cięcie / Siła potrzebna do przecięcia [N]**
OF – Błonnik z korzenia cykorii	26,75 ^{a} ± 0,893	0,13 ^{b} ± 0,017	13,47 ^{c} ± 1,320	0,34 ^{bc} ± 0,009	133,25^{a} ± 3,622
TF – Błonnik z tapioki	53,06 ^{b} ± 1,981	0,21 ^{d} ± 0,011	16,13 ^{d} ± 2,000	0,34 ^{bc} ± 0,015	163,25^{c} ± 3,999
ML – Syrop maltitolowy	62,44 ^{c} ± 0,692	0,20 ^{cd} ± 0,007	28,22 ^{e} ± 1,518	0,36 ^{c} ± 0,020	167,56^{c} ± 1,337
PM – Błonnik grochowo – kukurydziany	81,97 ^{d} ± 1,261	0,19 ^{c} ± 0,009	3,01 ^{a} ± 0,446	0,17 ^{a} ± 0,005	135,49^{a} ± 2,808

GS – Syrop glukozowy	91,43 ^{e} ± 0,250	0,04 ^{a} ± 0,002	8,68 ^{b} ± 0,299	0,32 ^{b} ± 0,017	156,16^{b} ± 2,947

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–e}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

b)

Rodzaj syropu zastosowany w batonach wysokobiałkowych w czekoladzie	**Badana cecha tekstury**				
	Twardość [N]	**Kruchość [N]**	**Adhezyjność / Przylegalność [J]**	**Spójność**	**Odporność na cięcie / Siła potrzebna do przecięcia [N]**
OF – Błonnik z korzenia cykorii	38,79 ^{a} ± 0,432	0,10 ^{cb} ± 0,013	145,32 ^{b} ± 15,302	0,27 ^{b} ± 0,010	70,10^{a} ± 0,803
TF – Błonnik z tapioki	81,61 ^{b} ± 1,167	0,12 ^{c} ± 0,011	214,53 ^{c} ± 14,285	0,23 ^{a} ± 0,015	124,95^{b} ± 0,566
ML – Syrop maltitolowy	73,36 ^{b} ± 0,672	0,09 ^{b} ± 0,007	236,99 ^{c} ± 24,602	0,30 ^{b} ± 0,009	132,01^{c} ± 2,145
PM – Błonnik grochowo – kukurydziany	311,65 ^{d} ± 10,401	0,12 ^{c} ± 0,012	54,71 ^{a} ± 3,596	0,28 ^{b} ± 0,013	124,12^{b} ± 0,928
GS – Syrop glukozowy	106,26 ^{c} ± 2,149	0,04 ^{a} ± 0,009	571,75 ^{d} ± 23,101	0,34 ^{c} ± 0,033	148,68^{d} ± 4,688

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–d}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Wykonane badania związane z parametrami tekstury (Tabela 6a,b) wykazały, że batony wykonane z syropu glukozowego (GS) i syropu grochowo-kukurydzianego (PM) cechowały się największą twardością, odpowiednio 91,43 N - GS i 81,97 N - PM dla batonów bez czekolady oraz 311,65 N - PM i 106,26 N - GS dla batonów oblanych czekoladą. Natomiast, najniższą twardość odnotowano przy wariancie wykorzystującym oligofruktozę (OF) jako substancję syropową, w obydwu przypadkach - bez czekolady (26,75 N) i z warstwą czekolady (38,79 N). Podobną prawidłowość zauważono w przypadku testu cięcia, gdzie ponownie baton wykonany z syropu OF (bez pokrycia czekoladą) charakteryzował się najmniejszym oporem (70,10 N) na działającą siłę elementu roboczego urządzenia. Jednocześnie próby wykonane z syropów ML i TF bez czekolady (167,56 N - ML; 163,25 N - PM) oraz GS w czekoladzie (148,68 N) wykazywały największy opór podczas testu cięcia.

Tabela 7. Wartości siły ekstruzji wstecznej oraz modułów G′, G″ i δ (°) badanych syropów stosowanych w opracowanych batonach wysokobiałkowych.

Rodzaj syropu	Siła [N]	G′ [Pa]	G″ [Pa]	δ [°]
OF - Oligofruktoza	1,515 ^{a} ± 0,058	0,104 ^{a} ± 0,102	2,484 ^{a} ± 0,133	90,919 ^{b} ± 3,207
TF – Błonnik z tapioki	10,536 ^{b} ± 0,420	0,801 ^{a} ± 0,141	16,915 ^{b} ± 1,825	90,028 ^{ab} ± 5,330
ML - Maltitol	36,520 ^{c} ± 1,219	0,124 ^{a} ± 0,115	2,325 ^{a} ± 0,182	88,472 ^{a} ± 4,094
PM – Błonnik grochowo-kukurydziany	309,583 ^{e} ± 3,247	48,340 ^{b} ± 10,697	158,417 ^{d} ± 23,573	98,582 ^{c} ± 18,856
GS – Syrop glukozowy	295,730 ^{d} ± 2,993	0,798 ^{a} ± 0,641	32,292 ^{c} ± 1,043	89,390 ^{ab} ± 1,475

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–e}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Odnosząc się do Tabeli 8, syropy OF (1,515 N), TF (10,536 N) i ML (36,520 N) wykazały najniższe wartości siły potrzebnej do przeciśnięcia substancji przez szczelinę podczas testu ekstruzji wstecznej (N). Syropami posiadającymi największą tendencję do obklejania się na końcówce sondy badawczej, oraz związana z tym konieczność zastosowania dużej siły, widoczna była w przypadku syropów PM (309,583 N) i GS (295,730 N). Przypuszczalnie podstawowym uzasadnieniem różnic w tym badaniu była konsystencja stosowanych syropów oraz poszczególnych części będących składowymi tych substancji. W przypadku cieczy newtonowskich (w tym przede wszystkim woda, która jest podstawowym segmentem wszystkich stosowanych syropów), konsystencja nie zależy od szybkości ścinania, jednak opiera się na właściwościach substancji kształtujących ciecz i jej granicach termodynamicznych, tj. temperatura i współczynnik nacisku. Natomiast substancje zawarte w zastosowanych syropach (alkohole wielowodorotlenowe, polisacharydy itp.) mogą powodować zmianę charakteru substancji syropowej, sprawiając że syropy te nie zachowują się jak płyny newtonowskie. Może być to jedno z wyjaśnień różnego zachowania zastosowanych syropów podczas przeprowadzonego badania ekstruzji wstecznej (Hoshino et al., 2013; Ionescu et al., 2020). Pozostałe wyniki w Tabeli 8, wskazują, iż wartości G′ znacznie zwiększały się w przypadku syropu PM, co świadczyło o wzmocnieniu struktury żelowej wytworzonych z niego batonów wysokobiałkowych ($p < 0,05$). Jednakże wartości modułu zachowawczego (G′) były niższe niż modułu stratności (G″) we wszystkich testowanych próbkach. Oznacza to, że badane syropy, podczas pomiaru wykazywały właściwości lepkie. Stwierdzono pewną korelację pomiędzy G′, G″ oraz wartościami twardości batonów wysokobiałkowych, która wskazuje, że struktura otrzymanego produktu

staje się twardsza i bardziej zwarta wraz z zastosowaniem syropu PM. Ponadto, gdy $\delta < 45°$, wyrób wykazuje właściwości elastyczne (żelowe); w przeciwnym razie (tj. $\delta > 45°$) produkt wykazuje właściwości lepkie. W każdym badanym syropie wartość δ była wyższa niż 45°, więc badane syropy można zakwalifikować jako lepkie.

Biorąc pod uwagę dostępne dane literaturowe oraz analizowane różnice w barwie opracowanych batonów wysokobiałkowych (Tabela 8a,b), ukazują one pewną tendencję (przede wszystkim w przypadku produktów wykonanych z WPC połączonych z syropem GS), iż odcień batonów wysokobiałkowych po 20-tym dniu przechowywania, przy niewielkim wpływie rodzaju stosowanego syropu, uległ zmianie, objawiając się wyczuwalną dla obserwatora zmianą granicy parametru b* (odcień żółty). Barwa uległa pociemnieniu i przybrała odcienie brązowe. W tym etapie badań nie analizowano batonów pokrytych czekoladą, lecz można przypuszczać, że wykazywałyby się one mniejszą tendencją do ciemnienia ze względu na lepszą ochronę przed dostępem światła i powietrza, a w wyniku tego utrudnianie reakcji Maillarda (Inami et al., 2015; Li et al., 2008).

Tabela 8 (a-b). (a) Wpływ syropów na zmianę barwy batonów wysokobiałkowych mierzony za pomocą metody CVS (Komputerowy System Wizyjny), (b) Wizualizacja otrzymanej barwy.

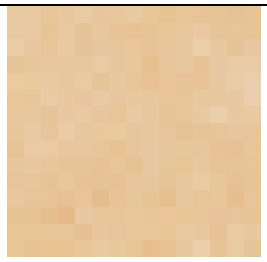
a)

Rodzaj białka wykorzystany w produkcie (bez czekolady)	**Badana cecha**			
	L *	**a ***	**b ***	**NBS Units**
OF - Oligofruktoza	58,86 ^{a} ± 0,388	19,71 ^{a} ± 0,488	49,71 ^{d} ± 0,488	20,44
TF – Błonnik z tapioki	60,29 ^{b} ± 0,488	20,29 ^{a} ± 0,756	52,14 ^{e} ± 1,069	21,58
ML - Maltitol	65,57 ^{c} ± 0,787	15,43 ^{d} ± 0,535	44,57 ^{c} ± 0,787	11,98
PM – Błonnik grochowo-kukurydziany	70,00 ^{d} ± 0,000	12,86 ^{c} ± 0,378	40,43 ^{b} ± 0,535	6,23
GS – Syrop glukozowy	72,14 ^{e} ± 0,378	10,57 ^{b} ± 0,535	34,43 ^{a} ± 1,134	-

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–e}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

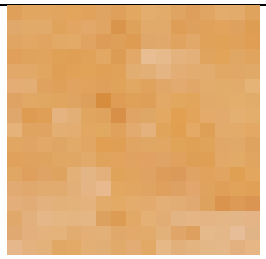
b)

a) TF – Błonnik z tapioki (NBS 21,58)



b) GS – Syrop glukozowy (Próba kontrolna)

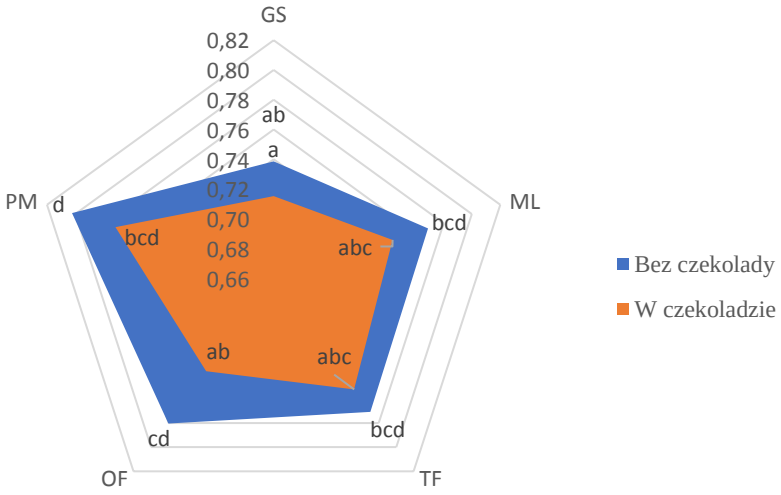
c) PM - Błonnik grochowo-kukurydziany (NBS 6,23)



d) ML – Maltitol (NBS 11,68)

e) OF – Oligofruktoza (NBS 20,44)

Otrzymane wyniki analizy aktywności wody (a_w) przedstawiono na Wykresie 6. Najwyższą wartością a_w cechowały się batony bez czekolady, wykonane z syropu PM (0,802), natomiast najniższą batony w czekoladzie wykonane z GS (0,715) oraz OF (0,737). Produkty żywnościowe o aktywności wody poniżej 0,85 są uznawane za umiarkowanie bezpieczne mikrobiologicznie (Tapia et al., 2020). Należy zaznaczyć, że wszystkie opracowane batony posiadały aktywność wody niższą niż 0,85. Można jednak przypuszczać, że produkt wykonany z syropu PM w porównaniu do pozostałych batonów będzie wykazywał większą tendencję do rozwoju takich form drobnoustrojów jak: *Staphyloccocus*, *Saccharomyces* czy *Debaryomyces* (Schiraldi et al., 2012).

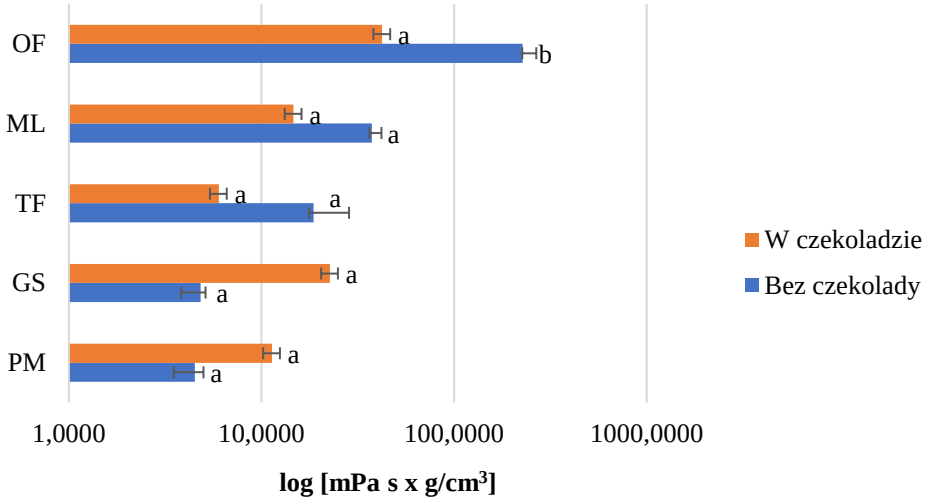


Wykres 6. Wpływ syropów na aktywność wody batonów wysokobiałkowych bez czekolady i z pokrywą czekoladową. Różne litery (a-d) wskazują na istotne różnice przy p <0,05.

Wysokie wyniki aktywności wody produktu wykonanego z PM mogą więc wskazywać na wysoką zawartość wody niezwiązanej w tym syropie (Labuza & Altunakar, 2020). Zauważalnie niższe wartości parametru aktywności wody w przypadku batonów pokrytych czekoladą mogą wynikać z ograniczenia dostępu powietrza do wnętrza produktu (Esbelin et al., 2018).

Różnice w wynikach lepkości dynamicznej (Wykres 7) dla testowanych w tym badaniu batonów nie były znaczące (z wyjątkiem jednej próby dla syropu OF bez czekolady). Najbardziej podwyższone wyniki dla tego parametru odnotowano jednak dla batonów wykonanych z syropów OF, ML, a najniższe dla PM i TF. Wyniki batoników z syropu GS były niejednoznaczne. W przypadku batonów bez czekolady próbka wykazywała niską lepkość, natomiast w przypadku batonów pokrytych czekoladą była to zdecydowanie jedna

z wyższych w pomiarach. Prawdopodobnie wpływ na ten wynik ma czekolada, która wykazuje wyższą lepkość niż mieszanka syropowo-białkowa stosowana w tym batonie w przypadku gdy czekolada użyta do procesu podlegała procesowi temperowania, w wyniku czego cechowała się odpowiednią twardością i charakterystycznym trzaskiem podczas przełamywania. Zmniejszenie lepkości większości badanych batonów w czekoladzie (OF, ML, TF) można utożsamiać z wolniejszym wysychaniem batonów wysokobiałkowych przez ograniczenie dostępu powietrza do wewnętrznych części produktu (Chanasattru et al., 2008).



Wykres 7. Wpływ syropów na lepkość dynamiczną batonów wysokobiałkowych bez czekolady i z pokrywą czekoladową. Różne litery (a-b) wskazują na istotne różnice przy p <0,05.

Niskie wartości parametru lepkości, szczególnie dla PM i GS, korelują natomiast z wysokimi wynikami parametrów twardości w batonach bez pokrywy czekoladowej oraz wysokimi parametrami modułu G" dla tych syropów. Z drugiej jednak strony, stosunkowo wysoka lepkość dynamiczna batoników wykonanych z syropów OF, ML i TF można powiązać z ich stosunkowo niską twardością oraz niskimi wartościami siły cięcia. Biorąc pod uwagę uzyskane wyniki oraz analizy innych badaczy można przypuszczać, że na uzyskane wyniki mogły mieć również wpływ takie czynniki, jak stopień napowietrzenia masy batonika oraz konsystencja i stężenie białka, z którego został wykonany dany produkt (Tomczyńska-Mleko & Ozimek, 2013).

Dokonana analiza wartości energetycznej i odżywczej (Tabela 9) badanych produktów pokazała, iż największe odchylenia dotyczyły wartości energetycznej i zawartości błonnika w stosunku do batonów wykonanych z syropu GS (próba kontrolna). Najmniejszą wartością

energetyczną cechowały się batony wykonane z syropów TF i PM. Wiązało się to dodatkowo z najwyższymi poziomami błonnika przy stosowaniu tych syropów. Istotne jest, aby stosowanie składników błonnikowych, tj. zastosowane w tej aplikacji syropy TF, OF i PM, powodowały zwiększenie zawartości błonnika w gotowych produktach na poziomie większym niż 6 g na 100 g.

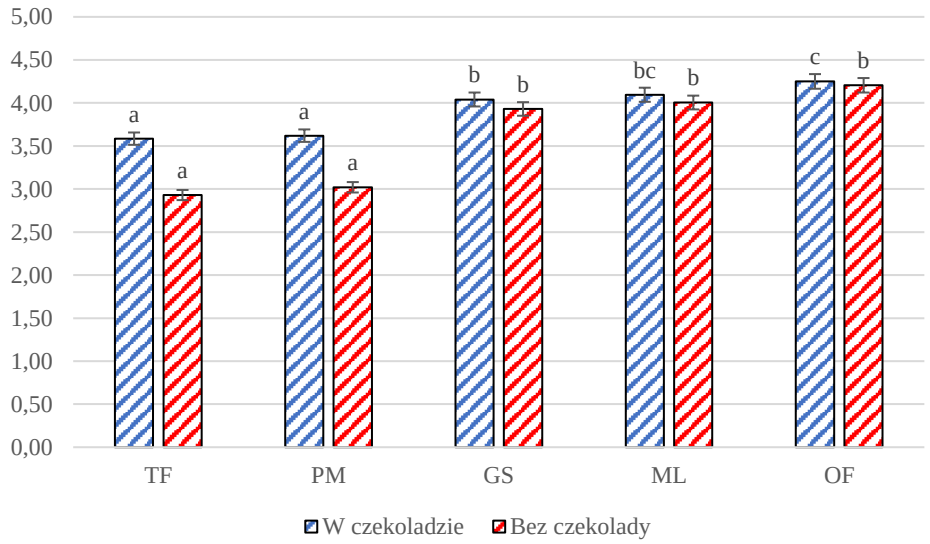
Tabela 9. Różnice w wartości energetycznej i odżywczej badanych batonów wysokobiałkowych na podstawie metody obliczeniowej.

Wartość energetyczna i odżywcza w 100 g wyrobu gotowego (bez czekolady)									
Rodzaj użytego syropu	**Energia [kJ]**	**Energia [kcal]**	**Tłuszcz [g]**	**Kw. tł. nasycone [g]**	**Węglowodany [g]**	**Cukry [g]**	**Błonnik [g]**	**Białko [g]**	**Sól [g]**
GS	1748	416	16	1,2	37	10	0,03	31	0,31
TF	1524	366	16	1,2	13	3,5	23	31	0,31
PM	1561	375	17	1,2	12	3,2	23	32	0,31
ML	1595	380	16	1,2	28	3,2	0,03	31	0,31
OF	1578	378	16	1,2	19	9,9	17	31	0,33
Wartość energetyczna i odżywcza w 100 g wyrobu gotowego (w czekoladzie)									
Rodzaj użytego syropu	**Energia [kJ]**	**Energia [kcal]**	**Tłuszcz [g]**	**Kw. tł. nasycone [g]**	**Węglowodany [g]**	**Cukry [g]**	**Błonnik [g]**	**Białko [g]**	**Sól [g]**
GS	1836	438	19	4,7	41	20	1,4	25	0,24
TF	1654	397	19	4,7	22	14	19	25	0,24
PM	1699	408	20	4,7	21	14	20	26	0,24
ML	1717	410	19	4,7	34	14	1,4	25	0,24
OF	1707	409	19	4,7	27	19	15	25	0,26

Taka ilość błonnika (> 6 g/100 g) pozwala bowiem na umieszczanie oświadczenia żywieniowego „wysoka zawartość błonnika” na opakowaniu tych produktów zgodnie z Rozporządzeniem (WE) nr 1924/2006 Parlamentu Europejskiego i Rady z dnia 20 grudnia 2006 r. (Reuterswärd, 2007). Jest to szczególnie istotne, ponieważ przyjmowanie błonnika pokarmowego wiąże się m.in. ze zmniejszonym ryzykiem zachorowań na choroby układu sercowo-naczyniowego. Analizując prace innych badaczy (Jovanov et al., 2021), w których opracowywano batony wysokobiałkowe będące substytutami posiłków dla sportowców, z mieszaniną glicerolu, maltodekstryny i inuliny jako składników syropowych, można przypuszczać, że otrzymane w opisywanej pracy wyroby wpasowują się w ten trend. Ponadto w przypadku zastosowania syropów TF, OF oraz PM, produkty z nich wykonywane nie wymagają umieszczania na opakowaniu żadnych informacji ostrzegawczych przed możliwym działaniem przeczyszczającym. Zgodnie z obowiązującym prawem unijnym, stosowanie alkoholi wielowodorotlenowych oraz ich pochodnych w ilości powyżej 10% wymaga takiej deklaracji (Carocho et al., 2017). Zaobserwowano także zmniejszoną zawartość tłuszczów nasyconych w opracowanych batonach. Jest to kluczowa cecha żywności, zwłaszcza dla osób

aktywnie uprawiających sport bądź aktywnych fizycznie. Kwasy tłuszczowe nasycone i typu „trans" uważane są za najbardziej szkodliwe dla zdrowia. Ich wysokie spożycie sprzyja rozwojowi m.in. ryzyka chorób układu krążenia i cukrzycy typu 2 (Astrup et al., 2020).

Analiza sensoryczna przeprowadzona na badanych batonach (Wykres 8) wykazała, że najgorzej ocenianymi batonami były te wykonane z syropów TF i PM. Według badanych, posiadały dużą twardość oraz niewyraźny, nieprzyjemny i długotrwały posmak, co spowodowało uzyskanie gorszych ocen.



Wykres 8. Wpływ syropów na ocenę sensoryczną batonów wysokobiałkowych bez czekolady i z pokrywą czekoladową. Różne litery (a-c) wskazują na istotne różnice przy p <0,05.

Przypuszczalnie, taki wynik oceny można utożsamiać z niezwykle wysoką zawartością błonnika w tego rodzaju syropach. Tapioka, która jest dobrym źródłem witaminy C, wapnia i fosforu, może ponadto pobudzać trawienie i wzmacniać układ odpornościowy u ludzi. Zgodnie z dostępną wiedzą, ten rodzaj błonnika może być również wykorzystywany jako składnik obniżający zawartości tłuszczu w produktach spożywczych (San José et al., 2018; Yadav et al., 2020). Uzyskane wyniki sugerują, że batony wysokobiałkowe pokryte warstwą czekolady były lepiej oceniane. Można zatem przypuszczać, że pokrywa czekoladowa znacznie poprawia smakowitość tego typu produktów. Nawiązując do badań przeprowadzonych przez innych badaczy, które dotyczyły badań nad wykorzystaniem polioli w kształtowaniu właściwości fizykochemicznych izolatów sojowych, wysokie oceny batonika z syropu ML można wiązać z wpływem polioli na właściwości strukturalne i powierzchniowe w wyrobach wysokobiałkowych. Oddziaływanie białek z poliolami indukuje zwiększone uporządkowanie strukturalny i koncentrację cząsteczek białek (Pan et al., 2017).

6.4. Badania dotyczące wpływu wyselekcjonowanych na podstawie poprzednich badań kombinacji najlepiej rokujących rodzajów białek i syropów na właściwości fizykochemiczne, strukturalne oraz wartość odżywczą batonów wysokobiałkowych (publikacja IV)

Preparaty białek roślinnych, pozyskiwane głównie z soi, grochu i ryżu, które są alternatywą dla powszechnie stosowanych białek zwierzęcych (białka serwatkowe, białko jaja, albuminy itp.), wykazują również szereg właściwości podobnych do białek zwierzęcych tj. zdolność do żelowania podczas obróbki cieplnej, stabilizacja emulsji, emulgacja tłuszczu, kontrola procesu krystalizacji, zagęszczanie, tworzenie pian, wiązanie składników płynnych czy zdolność kształtowania tekstury w połączeniu przede wszystkim z węglowodanami (modyfikacja twardości produktu i innych parametrów tekstury) (Zhao et al., 2020). Ze względu na neutralny smak i zapach, a także dobre właściwości użytkowe i stosunkowo niską cenę, przede wszystkim preparaty białek sojowych wykorzystywane są na szeroką skalę w różnych gałęziach przemysłu spożywczego np. w suplementach diety, zupach, sosach, majonezach, wyrobach piekarniczych i cukierniczych (Nishinari et al., 2018). Wykorzystywane są również jako składniki panierek, głównie w przemyśle mięsnym. W produktach dla wegetarian i wegan, białka ryżu i grochu są stosowane jako substancje wzbogacające w produkcji wędlin bezmięsnych i analogów mięsa, a także coraz częściej w branży piekarniczo-cukierniczej, które w ostatnich latach cieszą się coraz większym zainteresowaniem na rynku (Zhang et al., 2019; Zhao et al., 2020). Płynne błonniki roślinne, w szczególności oligofruktoza oraz szereg innowacyjnych syropów, zawierających podobne do fruktooligosacharydów (FOS) frakcje błonnika pochodzącego z różnych roślin m.in. płynne błonniki z kukurydzy lub tapioki, są jednymi z najczęściej stosowanych prebiotycznych substancji mogących być ekwiwalentami dla rozpowszechnionych syropów glukozowych i glukozowo-fruktozowych. Wspomniane substancje wysokobłonnikowe, wykazują odporność na działanie enzymów trawiennych w przewodzie pokarmowym człowieka, przechodząc do jelita grubego, gdzie są wykorzystywane przez pożyteczną mikroflorę jako pożywka, wpływając znacząco na jej namnażanie, a w rezultacie poprawę stanu zdrowia gospodarza (Man et al., 2021). Oligofruktoza wpływa na profil lipidowy i redukuje poziom cholesterolu w surowicy krwi, zwiększa biodostępność składników mineralnych, zapobiega i wspomaga leczenie cukrzycy, wykazuje działanie przeciwnowotworowe i redukuje poziom metabolitów. W przemyśle spożywczym umożliwiają znaczną redukcję lub całkowitą eliminację cukru, syropów glukozowych

i tłuszczu, pozwalając na tworzenie innowacyjnych produktów spożywczych o walorach dietetycznych (Carocho et al., 2017). Poliole to grupa półsyntetycznych słodzików, znanych również jako alkohole polihydroksylowe, alkohole wielowodorotlenowe, alkohole cukrowe itp. Występują one naturalnie w roślinach i owocach, m.in. w śliwkach, gruszkach, brzoskwiniach, jabłkach, oliwkach, figach, truskawkach i malinach. Do polioli należą takie substancje jak: maltitol, ksylitol, sorbitol, laktitol, mannitol i izomalt. Cechują się mniejszą słodyczą niż sacharoza, przez co mogą być stosowane w żywności w większych ilościach niż substancje intensywnie słodzące (Saraiva et al., 2020). Składniki tego typu mogą pełnić funkcję substancji wypełniających, wiążących (zastępniki dla syropów glukozowych), zmniejszając jednocześnie wartość energetyczną w porównaniu z konwencjonalnie wykonanymi produktami. Poliole zaliczane są także do substancji obojętnych na działanie enzymów trawiennych i trudno fermentujących, które wykazują stosunkowo dużą stabilność chemiczną. Alkohole wielowodorotlenowe są w niewielkich ilościach wchłaniane w układzie pokarmowym w wyniku dyfuzji biernej. Proces ten jest natomiast stosunkowo powolny, więc nie powoduje gwałtownego wzrostu stężenia glukozy we krwi i wydzielania insuliny przez komórki trzustki (Sahin et al., 2018).

Badania mające na celu podsumowanie i wybór najlepiej rokujących połączeń białek i syropów w aplikacji batonów wysokobiałkowych, zawarto w **publikacji IV (Małecki J., Terpiłowski K., Nastaj M., Sołowiej B. G., 2022, Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used. *International Journal of Environmental Research and Public Health, 19, 3923*)**. Na podstawie uzyskanych w poprzednich badaniach wyników do analiz zostały zakwalifikowane syropy: oligofruktoza (OF), syrop maltitolowy (ML), płynny błonnik z tapioki (TF) oraz białka ryżu (RPC), grochu (PEA) i soi (SOY). Próbą kontrolną stanowił produkt wykonany z syropu glukozowego (GS) i koncentratu białek serwatkowych (WPC). Z wyselekcjonowanych do ostatniej części badań białek i syropów, tworzono wszystkie możliwe połączenia w obrębie tych składników (10 wariantów wraz z próbą kontrolną). Wyniki zastosowanych połączeń białkowo-syropowych nie były analizowane i publikowane we wcześniej opisywanych artykułach naukowych. Wszystkie rodzaje powtórzeń zostały wykonane w wariantach bez pokrycia czekoladą, ze względu na profil prowadzonych analiz. Otrzymane batony wysokobiałkowe poddano badaniom profilowej tekstury (TPA), aktywności wody, mikrostruktury powierzchni (mikroskopia optyczna), lepkości dynamicznej, wartości odżywczej i energetycznej, stopnia chropowatości i suchości powierzchni (analiza kąta

zwilżania). Badaniom na stabilność przy zmiennej temperaturze poddawano natomiast zastosowane syropy (współczynnik TSI – *ang. Turbiscan Stability Index*).

Wpływ zastosowania różnych kombinacji białkowo-syropowych na parametry tekstury i siłę oporu podczas próby cięcia przedstawiono w Tabeli 10. Zdjęcia mikrostruktury powierzchni opracowanych batonów, wykonane za pomocą mikroskopu optycznego przedstawiono w Tabeli 11a,j. Na podstawie przeprowadzonych analiz zaobserwowano istotne ($p < 0,05$) różnice pomiędzy przeprowadzonymi badaniami. Z analiz wynika, że największą twardością (281,90 N) charakteryzowały się batony wykonane z powszechnie stosowanych składników (WPC+GS – próba kontrolna). Najniższe parametry twardości stwierdzono natomiast w próbkach sporządzonych z białka sojowego (18,76 N) i ryżowego (19,92 N) w połączeniu z syropem maltitolowym (SOY+ML i RPC+ML). Warto zauważyć, że mała twardość poszczególnych typów badanych batonów wysokobiałkowych korelowała z równie małą odpornością na cięcie.

Tabela 10. Wpływ określonej kombinacji białka i syropu na cechy tekstury i odporność na przecinanie batonów wysokobiałkowych.

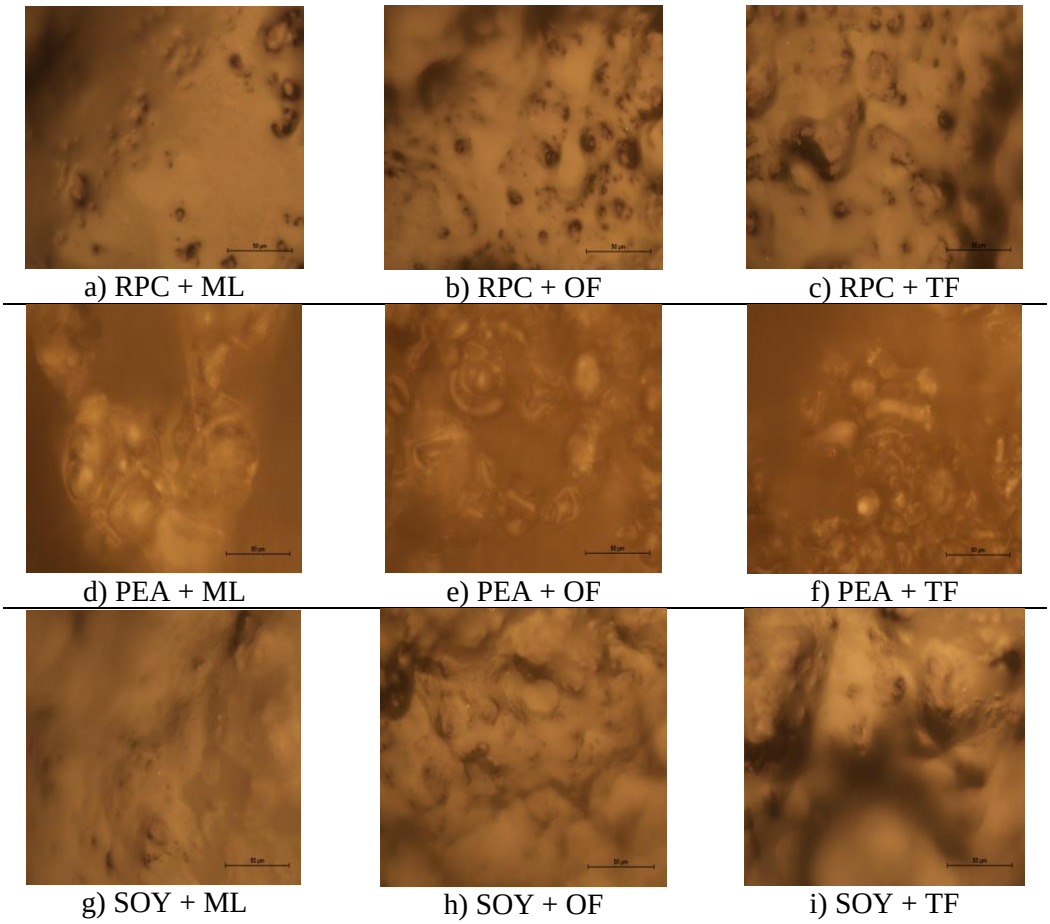
Połączenie białka i syropu	Parametry tekstury				Odporność na cięcie / Siła potrzebna do przecięcia [N]
	Twardość [N]	Kruchość [N]	Adhezyjność (Przylegalność) [J]	Spójność	
WPC + GS	281,90 ^{h} ± 1,32	0,32 ^{ab} ± 0,13	1,66 ^{f} ± 0,11	0,28 ^{h} ± 0,01	49,27 ^{i} ± 0,15
RPC + ML	19,92 ^{a} ± 0,48	0,16 ^{a} ± 0,02	1,53 ^{e} ± 0,05	0,14 ^{e} ± 0,01	8,27 ^{a} ± 0,03
RPC + OF	27,67 ^{b} ± 0,18	0,27 ^{ab} ± 0,02	3,34 ^{g} ± 0,03	0,12 ^{de} ± 0,01	11,51 ^{b} ± 0,14
RPC + TF	35,53 ^{c} ± 0,49	0,47 ^{ab} ± 0,02	0,10 ^{a} ± 0,01	0,10 ^{cd} ± 0,01	15,73 ^{d} ± 0,16
PEA + ML	56,22 ^{d} ± 0,30	89,13 ^{c} ± 0,43	0,14 ^{a} ± 0,01	0,02 ^{a} ± 0,01	29,79 ^{f} ± 0,05
PEA + OF	106,68 ^{f} ± 0,22	141,45 ^{d} ± 0,79	0,17 ^{ab} ± 0,01	0,07 ^{bc} ± 0,01	48,55 ^{h} ± 0,23
PEA + TF	71,76 ^{e} ± 0,29	157,33 ^{e} ± 1,08	0,25 ^{b} ± 0,03	0,06 ^{b} ± 0,01	49,94 ^{j} ± 0,07
SOY + ML	18,76 ^{a} ± 0,62	0,13 ^{a} ± 0,01	1,51 ^{e} ± 0,03	0,25 ^{gh} ± 0,03	14,26 ^{c} ± 0,15
SOY + OF	136,46 ^{g} ± 2,97	1,14 ^{b} ± 0,10	1,21 ^{d} ± 0,06	0,24 ^{fg} ± 0,01	46,58 ^{g} ± 0,21
SOY + TF	34,82 ^{c} ± 0,65	0,30 ^{ab} ± 0,02	0,48 ^{c} ± 0,01	0,23 ^{f} ± 0,02	21,53 ^{e} ± 0,21

Dane przedstawiono jako średnie ± SD (odchylenie standardowe). $^{a–j}$ Średnie w tej samej kolumnie z różniącymi się literami są istotnie różne ($p < 0,05$).

Testowane batony wysokobiałkowe wykazywały zróżnicowane wartości. Zauważono pewną zależność - duża twardość skutkowała również tendencją do przyklejania się batonów

wysokobiałkowych do powierzchni, a tym samym powodowała mniejszą adhezyjność i spójność. Potwierdzają to również informacje i doniesienia innych naukowców (Banach et al., 2017). Na podstawie dostępnych w literaturze badań (Hogan et al., 2012) można przypuszczać, że duża twardość jest powiązana z mikrostrukturą cząsteczek danego typu białka i ich zdolnością do agregacji wewnątrz produktu. Różnice w parametrach tekstury i odporności na cięcie różnych typów białek można powiązać również z wielkością porów i fragmentacją cząsteczek białka, co wpływa na zmianę stopień migracji wilgoci w produktach tego typu (białka o mniejszych porach i fragmentacji), przez co procesy twardnienia ulegają spowolnieniu, jak również zmniejsza się odporność na przecięcie i zwiększona skłonność do przywierania produktu do powierzchni (McMahon et al., 2009; Zhou et al., 2008; Zhou & Labuza, 2010).

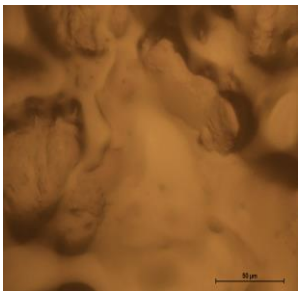
Rysunek 3 (a-j). Mikrostruktura powierzchni badanych batonów wysokobiałkowych. Mikroskopia optyczna (MAG: 400x).



a) RPC + ML b) RPC + OF c) RPC + TF

d) PEA + ML e) PEA + OF f) PEA + TF

g) SOY + ML h) SOY + OF i) SOY + TF

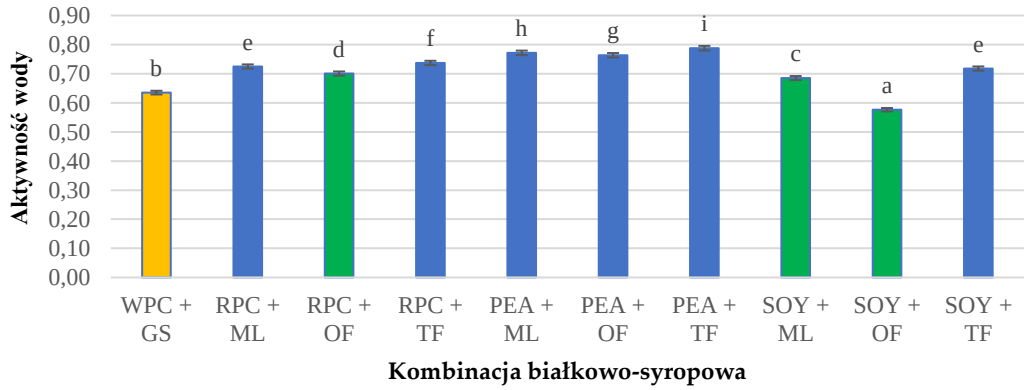


j) WPC + GS

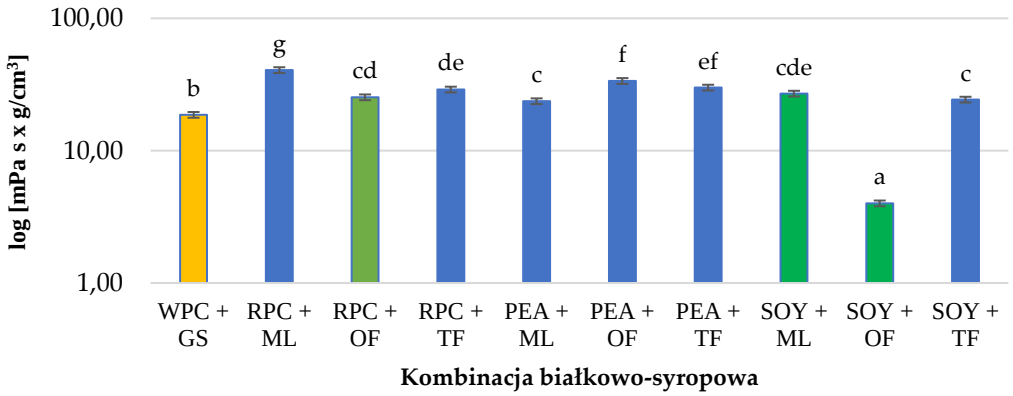
Na podstawie zdjęć mikrostruktury batonów wysokobiałkowych (Rysunek 3a,j) można stwierdzić, że istnieją duże powinowactwa w wielkości porów i pofałdowaniu struktury badanych białek roślinnych, co prawdopodobnie zmniejsza parametry TPA i odporność na przecięcie w porównaniu z próbką kontrolną (WPC + GS). Dodatkowo zaobserwowano istotny wpływ syropów stosowanych w aplikacji batonów wysokobiałkowych na redukcję parametrów tekstury oraz odporności na przecięcie (Hogan et al., 2016; Nadeem et al., 2012). Można przypuszczać, że zastosowanie alternatywnych syropów może wpływać na zmniejszanie twardości produktów wysokobiałkowych poprzez osłabienie wiązań powierzchniowych, oddziaływania kowalencyjne między białkami i syropami, które obejmują wiązania wodorowe, van der Waalsa lub siły jonowe (Hassan, 2020).

Wyniki przeprowadzonych badań aktywności wody oraz lepkości (określonej za pomocą wiskozymetru ultradźwiękowego) wykonanych batonów wysokobiałkowych przedstawiono na Wykresie 9a,b.

a)



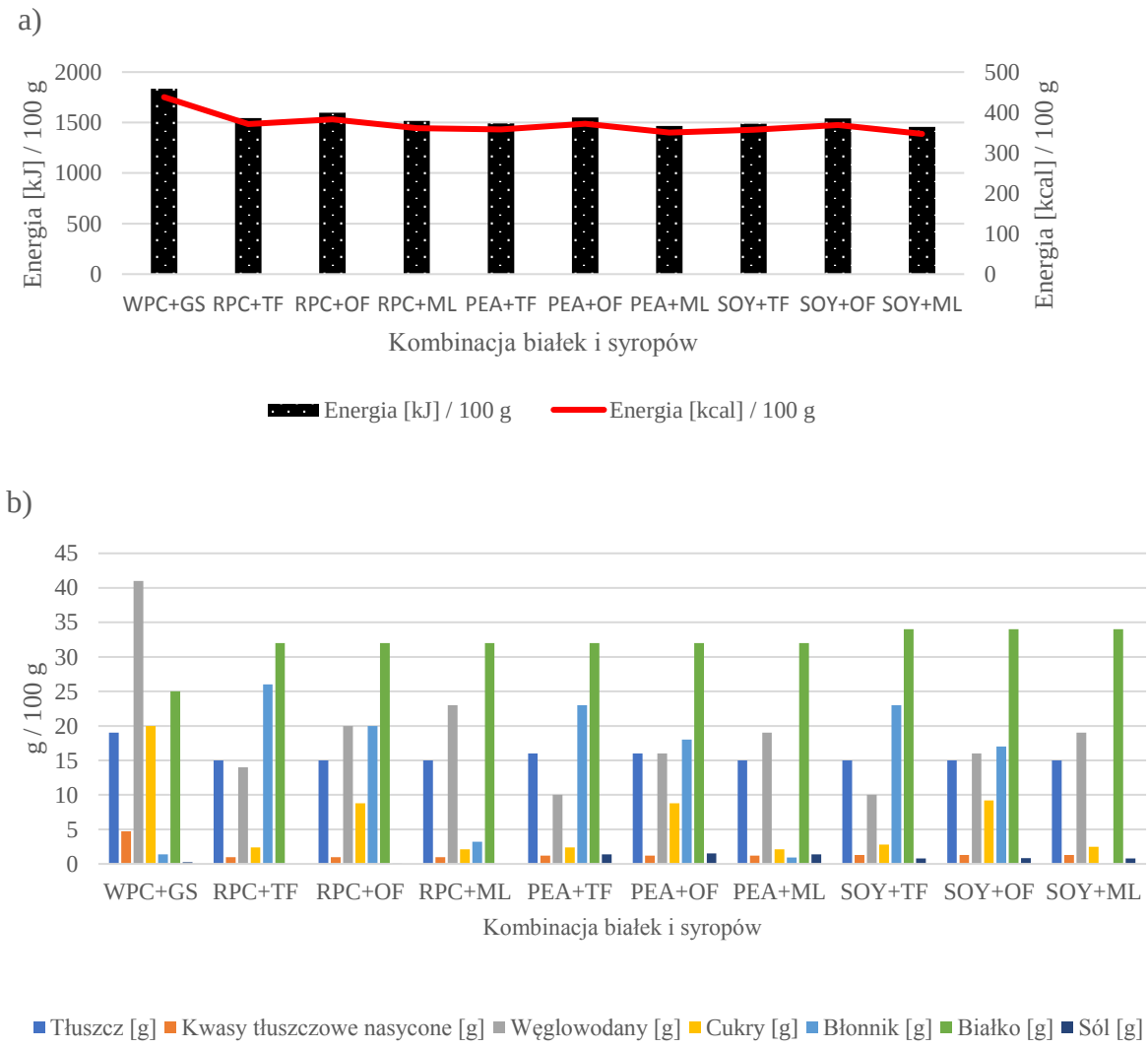
b)



Wykres 9 (a-b). Wpływ określonej kombinacji białka i syropu na **(a)** aktywność wody (a_w) i **(b)** lepkość opracowanych batonów wysokobiałkowych. Litery (a–i) wskazują na istotne różnice przy $p < 0,05$. Próbki z najlepszymi wynikami dla obydwu oznaczeń zostały oznaczone na zielono; próba kontrolna – na żółto.

Stwierdzono pewną zależność pomiędzy uzyskanymi wynikami aktywności wody i lepkości dynamicznej. Największą aktywnością wody (0,79) charakteryzował się baton wysokobiałkowy PEA + TF i jednocześnie był on najbardziej lepki (30 mPa·s·g/cm^3). Z kolei próba wykonana z SOY + OF miała najmniejszą aktywność wody (0,58) oraz cechowała się najmniejszą lepkość dynamiczną (4,0 mPa·s·g/cm^3). Ta zależność dotyczyła wszystkich badanych próbek. Na podstawie wcześniejszych analiz oraz badań przeprowadzonych przez innych badaczy (Loveday et al., 2009; Tomczyńska-Mleko & Ozimek, 2013), różnice w aktywności wody i lepkości ultradźwiękowej mogą wynikać z mikrostruktury poszczególnych rodzajów białek, ich stężenia w produkcie, tendencji do ich aglomeracji w czasie lub ilości porów powietrznych powstających w produkcie podczas procesu mieszania i napowietrzania masy. W literaturze naukowej brakuje danych dotyczących oznaczania lepkości za pomocą wiskozymetrów ultradźwiękowych, dlatego trudno jest znaleźć wyniki badań do porównania.

Przeprowadzoną analizę wartości energetycznej i odżywczej badanych próbek przedstawiono na Wykresie 10a,b. Uzyskane wyniki wskazują, iż w przypadku próby kontrolnej wzrost wartości energetycznej spowodowany był głównie przez wyższą zawartość węglowodanów, co skutkowało negatywnym bilansem poszczególnych składników. Pozostałe próby charakteryzowały się zbliżoną wartością energetyczną oraz zwiększoną zawartością białka, przede wszystkim dzięki redukcji zawartości węglowodanów poprzez zastosowanie ekwiwalentów syropu glukozowego.

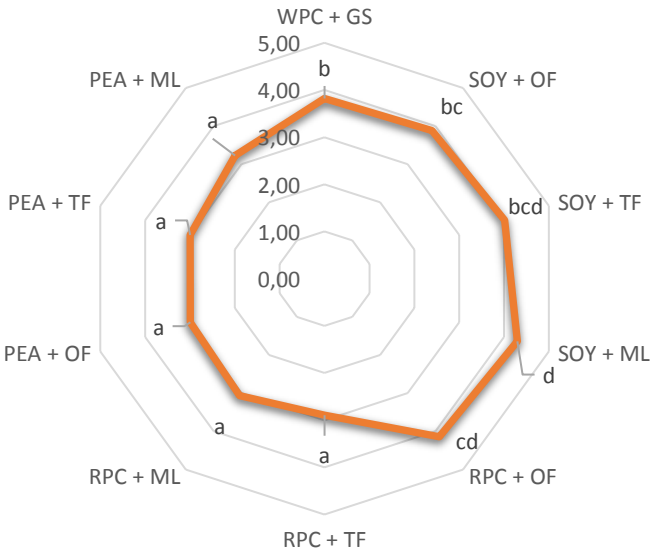


Wykres 10 (a-b). Wpływ określonej kombinacji białka i syropu na wartość energetyczną **(a)** i odżywczą **(b)** opracowanych batonów wysokobiałkowych.

W odpowiednich proporcjach, składniki odżywcze tj. białka, tłuszcze i węglowodany są źródłem ATP (Adenozyno-5′-trifosforan), który podczas pracy mięśni rozkłada się na ADP (Adenozyno-5′-difosforan) z jednoczesnym uwalnianiem energii. Ich ilość i odpowiednio dobrane proporcje muszą stymulować odpowiednią dawkę energii w zależności od rodzaju uprawianej dyscypliny sportu, czasu trwania wysiłku i zmian jego intensywności (Lun et al., 2012). Wszystkie przeprowadzone testy dobrze wpisują się w ten trend i mogą być wykorzystywane jako uzupełnienie diety dla osób aktywnych fizycznie. Należy jednak zauważyć, że próba wytworzona z SOY + ML charakteryzowała się najniższą wartością energetyczną. Wynika to prawdopodobnie ze zmniejszonej kaloryczności maltitolu (2,4 kcal/g). Ten sam baton charakteryzował się najniższą zawartością błonnika, ze względu na

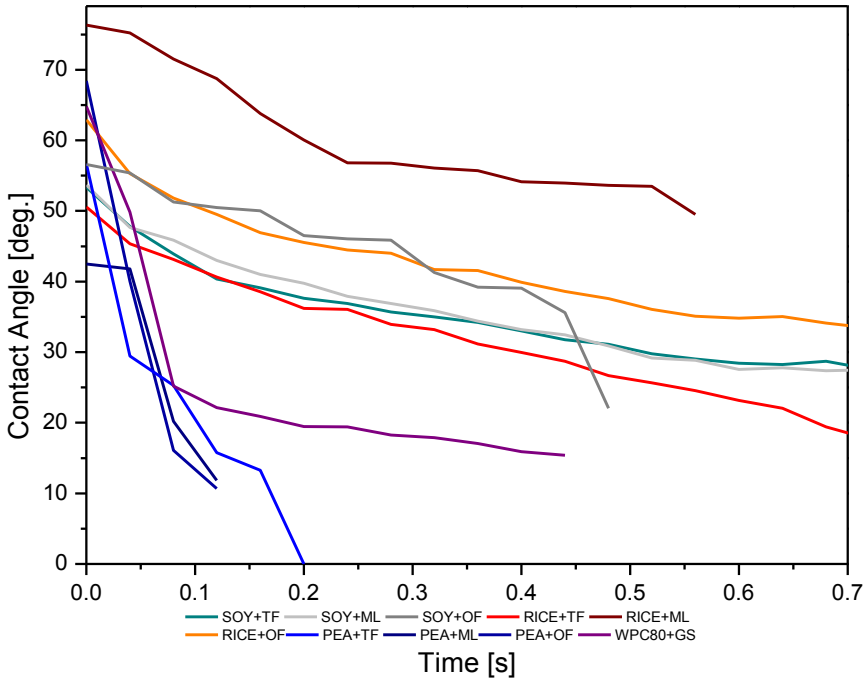
konieczność zadeklarowania polioli jako alkoholi wielowodorotlenowych, których nie można zadeklarować jako błonnik. Warto zwrócić szczególną uwagę na zawartość błonnika pokarmowego w uzyskanych próbkach wykonanych z RPC + TF (26 g/100 g), PEA + TF (23 g/100 g) oraz SOY + TF (23 g/100 g), które miały najwyższy poziom zawartości tego składnika. Produkty, do których w procesie produkcyjnym zostały dodane płynne, błonnikowe substancje, charakteryzowały się „wysoką zawartością błonnika" (w rozumieniu aktualnych legislacji prawnych) w produkcie końcowym i mogą stanowić dodatkowe kryterium wyboru tych produktów dla potencjalnych konsumentów (Khedkar et al., 2016).

Przeprowadzona analiza sensoryczna wykazała, iż najwyżej ocenianymi próbami były batony z białek sojowych i ryżowych, ze szczególnym uwzględnieniem wariantów prób zawierających oligofruktozę i błonnik z tapioki (RPC+OF, SOY+OF i SOY+TF) (Wykres 11). Wysoko oceniona została również próbka wytworzona z białka sojowego z dodatkiem syropu maltitolowego (SOY+ML). Wysokie wyniki tych testów można skorelować ze stosunkowo niskimi parametrami lepkości oraz parametrami tekstury tych samych wyrobów, co mogło znacząco przyczynić się do pozytywnych ocen panelistów. Biorąc pod uwagę wyniki wcześniejszych analiz (publikacja II), batony z białek ryżowych i sojowych zostały wysoko ocenione podczas analizy sensorycznej, co również zostało potwierdzone w niniejszym badaniu. Z kolei według innych badaczy (Gunyaphan et al., 2020), batony proteinowe z białek grochu są oceniane przez konsumentów bardzo pozytywnie. Można przypuszczać, że różnice w tych wynikach mogą wynikać z zawartości białka w gotowym produkcie oraz stopnia ich rozdrobnienia i dezodoryzacji.



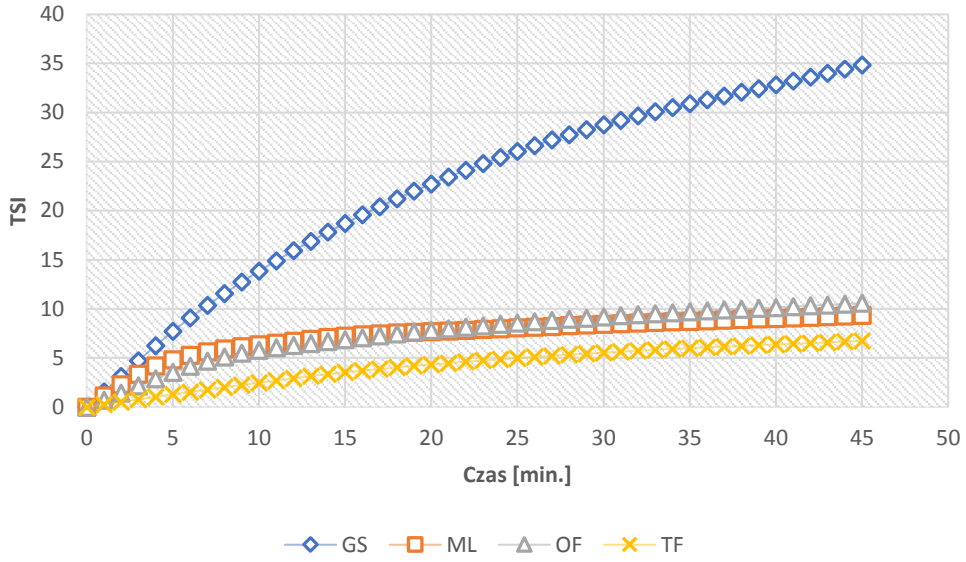
Wykres 11. Analiza sensoryczna opracowanych produktów z wykorzystaniem różnych kombinacji białka i syropu. Litery (a–d) wskazują na istotne różnice przy $p < 0,05$.

Przeprowadzono również badania zwilżalności powierzchni za pomocą analizy kąta zwilżania. Zwilżalność to ważna właściwość fizyczna charakteryzująca powierzchnię materiałów. Jego wartość determinuje podstawowe funkcje produktów spożywczych i innych materiałów, w tym przyleganie do powierzchni czy smarowność (Kayaoğlu & Öztürk, 2013). Miarą zwilżalności powierzchni ciała stałego cieczą (najczęściej jest to woda) o małej masie cząsteczkowej jest kąt (nazywany kątem zwilżania) pomiędzy styczną do kropli w punkcie kontaktu z badaną powierzchnią. Pomiaru dokonuje się poprzez umieszczenie kropli cieczy o małej masie cząsteczkowej na powierzchni badanego materiału, mierząc kąt nachylenia stycznej do obrysu powierzchni kropli w miejscu jej zetknięcia z danym podłożem (Ojogbo et al., 2018). Wyniki uzyskanych kątów zwilżania (Wykres 12) wskazują na różnice w otrzymanych parametrach w zależności od kombinacji białek i syropów. Wykonane badania wskazują, iż największą hydrofobowością powierzchni charakteryzowała się próbka składająca się z RPC + ML, gdyż kąty zwilżania były największe (bliskie 80°). Najmniejszymi kątami zwilżania charakteryzował się produkt wykonany z PEA + TF, dzięki czemu powierzchnia tego produktu wykazywała największe właściwości hydrofilowe. Warto też zaznaczyć, że w przypadku wszystkich analizowanych prób, kąt z czasem bardzo szybko zmniejszał się. Na podstawie badań przeprowadzanych przez innych naukowców (Ojogbo et al., 2018; Pérez-Huertas et al., 2020) można przypuszczać, że na różnice kątów zwilżania może mieć wpływ chropowatość danej powierzchni badanych wyrobów, wynikająca z substancji ją tworzących. Testowane batony miały zdolność szybkiego wchłaniania kropli wody na powierzchni w porównaniu z produktami innych badaczy. Biorąc pod uwagę przeprowadzone analizy, może to mieć związek ze stosunkowo małą aktywnością wody prezentowanych produktów oraz dużą zawartością suchych składników o dużej wodochłonności (białka, słód jęczmienny, maltodekstryna), co potwierdzają również doniesienia innych badaczy (Ojogbo et al., 2018), w których testowano wyroby o suchej strukturze.



Wykres 12. Porównanie kinetyki poszczególnych kropel wody w zależności od rodzaju białka i syropu użytego do produkcji opracowanych batoników wysokobiałkowych.

Otrzymane wyniki Turbiscan Stability Index (TSI) przeprowadzone dla poszczególnych rodzajów syropów stosowanych do produkcji badanych batonów wysokobiałkowych przedstawiono na Wykresie 13. Turbiscan Stability Index mierzy globalną stabilność produktu i służy do porównania stabilność substancji płynnych. Wyższe wartości TSI oznaczają większą niestabilność układu. W związku z tym parametr TSI nazywany jest współczynnikiem niestabilności (Wiśniewska, 2010). Zgodnie z tą metodologią, syrop TF charakteryzował się największą stabilnością w pełnym zakresie badań. Najbardziej niestabilną próbką okazał się syrop GS, powszechnie stosowany w przemyśle spożywczym. Z badań innych naukowców (Schellart, 2011) wynika, że duża niestabilność tego syropu może wynikać z jego bardzo dużej zdolności do zmiany lepkości w zależności od temperatury. Syropy glukozowe w niskiej temperaturze charakteryzują się bardzo dużą lepkością, a wraz ze wzrostem temperatury ich lepkość ulega znacznemu zmniejszeniu. Ma to kluczowe znaczenie podczas procesu dozowania syropu dla różnych rodzajów produktów, zwykle syrop jest podgrzewany w celu ułatwienia procesu pompowania i zmniejszenia obciążenia pomp. Można przyjąć, że tak duża lepkość GS w temperaturach zbliżonych do 20-30 °C może być przyczyną zwiększonej twardości produktów wysokobiałkowych, co nie jest pożądane w szczególności w przypadku produktów wysokobiałkowych (Domian et al., 2021).



Wykres 13. Zmiany TSI w czasie, podczas podgrzewania poszczególnych syropów wykorzystywanych do produkcji batonów wysokobiałkowych.

Syrop TF charakteryzował się dużą płynnością i małą lepkością w całym zakresie pomiarowym. Biorąc pod uwagę inne przeprowadzone analizy, niskie TSI dla syropu TF może być przyczyną tendencji wytwarzanych z niego batonów wysokobiałkowych do większej aktywności wody i przyspieszonego ryzyka wysychania powierzchni z powodu migracji wilgoci do wnętrza struktur batonów, co mogło mieć również wpływ na kruchość powierzchni. Biorąc pod uwagę wyniki TSI uzyskane dla syropów OF i ML, posiadały one zbilansowane wartości TSI. Zgodnie z danymi literaturowymi, również rodzaj i zawartość białka mogą mieć wpływ na ten parametr (Nastaj et al., 2020).

7. Stwierdzenia i Wnioski

1. Na podstawie wykonanych analiz można stwierdzić, że zastosowanie alternatyw koncentratu białek serwatkowych, oraz syropu glukozowego miało wpływ na właściwości fizykochemiczne oraz cechy sensoryczne i funkcjonalne batonów wysokobiałkowych.
2. Wszystkie badane syropy wykazywały właściwości lepkie ($\delta > 45°$), a wartości modułu zachowawczego (G′) oraz stratności (G″) badanych syropów były powiązane z parametrami teksturalnymi końcowych produktów - batonów wysokobiałkowych.
3. Analiza barwy opracowanych batonów wysokobiałkowych, oceniana na podstawie Komputerowego Systemu Wizyjnego (CVS), wskazywała na to, iż rodzaj użytego białka oraz syropu wywierały znaczący wpływ na barwę wyrobu gotowego.
4. Zastosowanie białek z alg morskich (ALP) oraz płynnego błonnika z tapioki (TF) w znacznym stopniu zwiększyły stopień twardości otrzymanych batonów wysokobiałkowych.
5. Zastosowanie określonych rodzajów białek i syropów istotnie wpłynęło na cechy sensoryczne batonów wysokobiałkowych. Najwyższe oceny dotyczyły batonów wykonanych z białek sojowych i ryżowych w połączeniu z oligofruktozą i błonnikiem z tapioki oraz maltitolem (RPC+OF, SOY+OF, SOY+TF, SOY+ML).
6. Badania dotyczące aktywności wody (a_w) wskazywały na odpowiednią stabilność mikrobiologiczną produktów (przede wszystkim wykonanych z białek sojowych i ryżowych oraz oligofruktozy), w związku z czym, nie ma konieczności przechowywania batonów w warunkach chłodniczych.
7. Zastosowane alternatywy białek serwatkowych oraz syropu glukozowego w znacznym stopniu wpłynęły na wzrost wartości odżywczej i obniżenie wartości energetycznej opracowanych produktów.
8. Wszystkie rodzaje opracowanych batonów, w których fazę płynną stanowiły płynne błonniki roślinne (OF, TF, PM), zgodnie z obowiązującymi przepisami UE mogą posiadać oświadczenie żywieniowe „wysoka zawartość błonnika” (atrakcyjność marketingowa).
9. Wyniki uzyskane w przeprowadzonych badaniach wskazują, iż batony wysokobiałkowe pokryte czekoladą były lepiej oceniane przez konsumentów pod względem sensorycznym niż ich nieoblane czekoladą odpowiedniki.

10. Przeprowadzone analizy dowodzą, że wszystkie wykonane warianty batonów wysokobiałkowych (zawierające alternatywy dla białek serwatkowych i syropu glukozowego) są potencjalnie możliwe do wdrożenia w warunkach przemysłowych.

Bibliografia

1. Abd El-Salam, M. H., & El-Shibiny, S. (2020). Hardness of high protein nutrition bars based on milk protein concentrates: A review. *Biointerface Research in Applied Chemistry*, *10*(1), 4914–4921. https://doi.org/10.33263/BRIAC101914921
2. Abdulmumeen, H. A., Risikat, A. N., & Sururah, A. R. (2012). Food: its preservatives, additives and applications. *International Journal of Chemical and Biochemical Sciences*, *1*(1), 36–47.
3. Adámek, M., Adámková, A., Mlček, J., Borkovcová, M., & Bednářová, M. (2018). Acceptability and sensory evaluation of energy bars and protein bars enriched with edible insect. *Potravinarstvo Slovak Journal of Food Sciences*, *12*(1), 431–437. https://doi.org/10.5219/925
4. Alemayehu, F. R., Bendevis, M. A., & Jacobsen, S. E. (2015). The Potential for Utilizing the Seed Crop Amaranth (Amaranthus spp.) in East Africa as an Alternative Crop to Support Food Security and Climate Change Mitigation. *Journal of Agronomy and Crop Science*, *201*(5), 321–329. https://doi.org/10.1111/JAC.12108
5. Anand, S., & Sati, N. (2013). Artificial preservatives and their harmful effects: looking toward nature for safer alternatives. *International Journal of Pharmaceutical Sciences and Research*, *4*(7), 2496–2501. https://doi.org/10.13040/IJPSR.0975-8232.4(7).2496-01
6. Aneja, K. R., Dhiman, R., Aggarwal, N. K., & Aneja, A. (2014). Emerging preservation techniques for controlling spoilage and pathogenic microorganisms in fruit juices. *International Journal of Microbiology*, *1*(1), 1–14. https://doi.org/10.1155/2014/758942
7. Astrup, A., Magkos, F., Bier, D. M., Brenna, J. T., de Oliveira Otto, M. C., Hill, J. O., King, J. C., Mente, A., Ordovas, J. M., Volek, J. S., Yusuf, S., & Krauss, R. M. (2020). Saturated Fats and Health: A Reassessment and Proposal for Food-Based Recommendations: JACC State-of-the-Art Review. *Journal of the American College of Cardiology*, *76*, 844–857. https://doi.org/10.1016/j.jacc.2020.05.077
8. Banach, J. C., Clark, S., & Lamsal, B. P. (2016). Instrumental and Sensory Texture Attributes of High-Protein Nutrition Bars Formulated with Extruded Milk Protein Concentrate. *Journal of Food Science*, *81*(5), S1254–S1262. https://doi.org/10.1111/1750-3841.13270
9. Banach, J. C., Clark, S., & Lamsal, B. P. (2017). Particle Size of Milk Protein Concentrate Powder Affects the Texture of High-Protein Nutrition Bars During

Storage. *Journal of Food Science*, *82*(4), 913–921. https://doi.org/10.1111/1750-3841.13684

10. Bleakley, S., & Hayes, M. (2017). Algal Proteins: Extraction, Application, and Challenges Concerning Production. *Foods*, *6*(5), 33. https://doi.org/10.3390/foods6050033
11. Calligaris, S., Pieve, S. D., Kravina, G., Manzocco, L., & Nicoli, C. M. (2008). Shelf life prediction of bread sticks using oxidation indices: a validation study. *Journal of Food Science*, *73*(2), 51–56. https://doi.org/10.1111/J.1750-3841.2007.00624.X
12. Carocho, M., Morales, P., & Ferreira, I. C. F. R. (2017). Sweeteners as food additives in the XXI century: A review of what is known, and what is to come. *Food and Chemical Toxicology*, *107*(1), 302–317. https://doi.org/10.1016/J.FCT.2017.06.046
13. Chanasattru, W., Decker, E. A., & Julian McClements, D. (2008). Impact of cosolvents (polyols) on globular protein functionality: Ultrasonic velocity, density, surface tension and solubility study. *Food Hydrocolloids*, *22*(8), 1475–1484. https://doi.org/10.1016/j.foodhyd.2007.09.007
14. Cho, M. J. (2010). Soy Protein Functionality and Food Bar Texture. In *Chemistry, Texture, and Flavor of Soy*. https://doi.org/doi:10.1021/bk-2010-1059.ch019
15. Clary, D., Van de Bussche, T., Janis, M., & Gossip, M. (2010). Sloan, A.E. (2002). The top 10 functional food trends. The next generation, . *Food Technology*, *56*(1), 32–57. https://doi.org/10.1016/j.amj.2009.03.008
16. Clemens, R. A., Jones, J. M., Kern, M., Lee, S. Y., Mayhew, E. J., Slavin, J. L., & Zivanovic, S. (2016). Functionality of Sugars in Foods and Health. *Comprehensive Reviews in Food Science and Food Safety*, *15*(3), 433–470. https://doi.org/10.1111/1541-4337.12194
17. Coda, R., Varis, J., Verni, M., Rizzello, C. G., & Katina, K. (2017). Improvement of the protein quality of wheat bread through faba bean sourdough addition. *LWT - Food Science and Technology*, *82*(1), 296–302. https://doi.org/10.1016/J.LWT.2017.04.062
18. Corradini, M. G., & Peleg, M. (2007). Shelf-life estimation from accelerated storage data. *Trends in Food Science and Technology*, *18*(1), 37–47. https://doi.org/10.1016/J.TIFS.2006.07.011
19. De Oliveira Sousa, A. G., Fernandes, D. C., Alves, A. M., de Freitas, J. B., & Naves, M. M. V. (2011). Nutritional quality and protein value of exotic almonds and nut from the Brazilian Savanna compared to peanut. *Food Research International*, *44*(7), 2319–2325. https://doi.org/10.1016/J.FOODRES.2011.02.013

20. Domian, E., Marzec, A., & Kowalska, H. (2021). Assessing the effectiveness of colloidal microcrystalline cellulose as a suspending agent for black and white liquid dyes. *International Journal of Food Science & Technology*, *56*(5), 2504–2515. https://doi.org/10.1111/IJFS.14889
21. Erickson, S., & Carr, J. (2020). The technological challenges of reducing the sugar content of foods. *Nutrition Bulletin*, *45*(3), 309–314. https://doi.org/10.1111/NBU.12454
22. Ermiş, E., & Karasu, E. N. (2020). PÜSKÜRTMELİ Kurutucuİle Yağı AlinmiAyçiçeğiProtein Ekstrakti TozÜretimi:FonksiyoneÖzellikleri Ve TozKarakterizasyonu. *Gida / the Journal of Food*, *45*, 39–49. https://doi.org/10.15237/gida.gd19096
23. Esbelin, J., Santos, T., & Hébraud, M. (2018). Desiccation: An environmental and food industry stress that bacteria commonly face. *Food Microbiology*, *69*(1), 82–88. https://doi.org/10.1016/J.FM.2017.07.017
24. Gallo, P., Imbimbo, S., Alvino, S., Castellano, V., Arace, O., Soprano, V., Esposito, M., Serpe, F. P., & Sansone, D. (2021). Contamination by aflatoxins b/g in food and commodities imported in southern italy from 2017 to 2020: A risk-based evaluation. *Toxins*, *13*(6), 368–381. https://doi.org/10.3390/TOXINS13060368/S1
25. Giménez, A., Ares, F., & Ares, G. (2012). Sensory shelf-life estimation: A review of current methodological approaches. *Food Research International*, *49*(1), 311–325. https://doi.org/10.1016/J.FOODRES.2012.07.008
26. Gokoglu, N. (2019). Novel natural food preservatives and applications in seafood preservation: a review. *Journal of the Science of Food and Agriculture*, *99*(5), 2068–2077. https://doi.org/10.1002/JSFA.9416
27. Gomes, A., Sá, A., Moreno, M. F., Augusto, B., & Carciofi, M. (2020). Plant proteins as high-quality nutritional source for human diet. *Trends in Food Science & Technology*, *97*(1), 170–184. https://doi.org/10.1016/j.tifs.2020.01.011
28. Goodbody, A. (2013). Raise the bar. *Mining Magazine*, *SEP*, 73–78. https://doi.org/10.2139/ssrn.2852866
29. Gunyaphan, S., On-Nom, N., Suttisansanee, U., Nana, A., Chamchan, R., Khemthong, C., & Chupeerach, C. (2020). Product qualities and sensory evaluation of high protein snack bar incorporated with pea protein isolate. *Food Research*, *4*(4), 51–55. https://doi.org/10.26656/FR.2017.4(S4).008
30. Hall, A. C., Fairclough, A. C., Mahadevan, K., & Paxman, J. R. (2012). Ascophyllum

nodosum enriched bread reduces subsequent energy intake with no effect on post-prandial glucose and cholesterol in healthy, overweight males. A pilot study. *Appetite*. https://doi.org/10.1016/j.appet.2011.11.002

31. Hassan, S. K. (2020). Quantitative and qualitative effects of proteins and natural sugars on hardening and color of high-protein nutrition bars during storage. *EurAsian Journal of BioSciences, 14*(1), 915–932.
32. Hassoun, A., Carpena, M., Prieto, M. A., Simal-Gandara, J., Özogul, F., Özogul, Y., Çoban, Ö. E., Guðjónsdóttir, M., Barba, F. J., Marti-Quijal, F. J., Jambrak, A. R., Maltar-Strmečki, N., Kljusurić, J. G., & Regenstein, J. M. (2020). Use of Spectroscopic Techniques to Monitor Changes in Food Quality during Application of Natural Preservatives: A Review. *Antioxidants, 9*, 882–912. https://doi.org/10.3390/ANTIOX9090882
33. Hogan, S. A., Chaurin, V., O'Kennedy, B. T., & Kelly, P. M. (2012). Influence of dairy proteins on textural changes in high-protein bars. *International Dairy Journal, 26*(1), 58–65. https://doi.org/10.1016/j.idairyj.2012.02.006
34. Hogan, S. A., O'Loughlin, I. B., & Kelly, P. M. (2016). Soft matter characterisation of whey protein powder systems. *International Dairy Journal, 52*, 1-9. https://doi.org/10.1016/j.idairyj.2015.07.005
35. Hoshino, T., Kawai, K., & Hagura, Y. (2013). Proposal of Short Back Extrusion Method for Enabling Consecutive Viscosity Measurements of High-viscosity Newtonian Fluid. *Nippon Shokuhin Kagaku Kogaku Kaishi*, *60*(2), 100–109. https://doi.org/10.3136/nskkk.60.100
36. Iannario, M., Manisera, M., Piccolo, D., & Zuccolotto, P. (2012). Sensory analysis in the food industry as a tool for marketing decisions. *Advances in Data Analysis and Classification*, *6*(4), 303–321. https://doi.org/10.1007/S11634-012-0120-4
37. Imtiaz, S. R., Kuhn-Sherlock, B., & Campbell, M. (2012). EFfect of dairy protein blends on texture of high protein bars. *Journal of Texture Studies*, *43*(4), 275–286. https://doi.org/10.1111/j.1745-4603.2011.00337.x
38. Inami, T., Tanimoto, Y., Minami, N., Yamaguchi, M., & Kasai, K. (2015). Color stability of laboratory glass-fiber-reinforced plastics for esthetic orthodontic wires. *Korean Journal of Orthodontics*, *45*(3), 130. https://doi.org/10.4041/kjod.2015.45.3.130
39. Ionescu, C. M., Birs, I. R., Copot, D., Muresan, C. I., & Caponetto, R. (2020). Mathematical modelling with experimental validation of viscoelastic properties in

non-Newtonian fluids. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2172), 1–21. https://doi.org/10.1098/rsta.2019.0284

40. Jabeen, S., Huma, N., Sameen, A., & Zia, M. A. (2020). Formulation and characterization of protein-energy bars prepared by using dates, apricots, cheese and whey protein isolate. *Food Science and Technology*, *41*(1), 197–207. https://doi.org/10.1590/FST.12220
41. Jovanov, P., Sakač, M., Jurdana, M., Pražnikar, Z. J., Kenig, S., Hadna Dev, M., Jakus, T., Petelin, A., Škrobot, D., & Marić, A. (2021). High-Protein Bar as a Meal Replacement in Elite Sports Nutrition: A Pilot Study. *Foods*, *10*(11), 1–12. https://doi.org/10.3390/FOODS10112628
42. Kalman, D. (2014). Amino Acid Composition of an Organic Brown Rice Protein Concentrate and Isolate Compared to Soy and Whey Concentrates and Isolates. *Foods*, *3*(3), 394-402. https://doi.org/10.3390/foods3030394
43. Kayaoğlu, B. K., & Öztürk, E. (2013). Imparting hydrophobicity to natural leather through plasma polymerization for easy care effect. *Fibers and Polymers*, *14*(10), 1706–1713. https://doi.org/10.1007/S12221-013-1706-Y
44. Kelly, P. (2019). Whey Protein Ingredient Applications. *Whey Proteins: From Milk to Medicine*, *9*(1), 335–375. https://doi.org/10.1016/B978-0-12-812124-5.00010-2
45. Mirza, S.K., Asema, U., & Sultan Kasim, S. (2017). To study the harmful effects of food preservatives on human health. *Journal of Medicinal Chemistry and Drug Discovery*, *2*(2), 610–616. www.jmcdd.orgwww.jmcdd.org
46. Khedkar, S., Bröring, S., & Ciliberti, S. (2016). Exploring the Nutrition and Health Claims Regulation (EC) No. 1924/2006: What is the impact on innovation in the EU food sector? *International Journal of Food Sciences and Nutrition, 68*(1), 10–17. https://doi.org/10.1080/09637486.2016.1212818
47. Kumar, A., Mohanty, V., & Yashaswini, P. (2018). Development of high protein nutrition bar enriched with spirulina plantensis for undernourished children. *Current Research in Nutrition and Food Science*, *6*(3), 835–844. https://doi.org/10.12944/CRNFSJ.6.3.26
48. Labuza, T. P., & Altunakar, B. (2020). Water Activity Prediction and Moisture Sorption Isotherms. *Water Activity in Foods*, *1*(1), 161–205. https://doi.org/10.1002/9781118765982.CH7
49. Leistner, L. (2000). Basic aspects of food preservation by hurdle technology.

International Journal of Food Microbiology, *55*(3), 181–186. https://doi.org/10.1016/S0168-1605(00)00161-6

50. Li-Chan, E. C. Y., & Lacroix, I. M. E. (2018). Properties of proteins in food systems: An introduction. In *Proteins in Food Processing: Second Edition* (pp. 1–25). https://doi.org/10.1016/B978-0-08-100722-8.00002-4
51. Li, Y., Szlachetka, K., Chen, P., Lin, X., & Ruan, R. (2008). Ingredient characterization and hardening of high-protein food bars: An NMR state diagram approach. *Cereal Chemistry*, *85*(6), 780–786. https://doi.org/10.1094/CCHEM-85-6-0780
52. Loveday, S. M., Hindmarsh, J. P., Creamer, L. K., & Singh, H. (2009). Physicochemical changes in a model protein bar during storage. *Food Research International*, *42*(7), 798–806. https://doi.org/10.1016/J.FOODRES.2009.03.002
53. Lun, V., Erdman, K. A., Fung, T. S., & Reimer, R. A. (2012). Dietary Supplementation Practices in Canadian High-Performance Athletes. *International Journal of Sport Nutrition and Exercise Metabolism*, *22*(1), 31–37. https://doi.org/10.1123/IJSNEM.22.1.31
54. Małecki, J., Tomasevic, I., Djekic, I., & Sołowiej, B. G. (2020). The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People. *Foods*, *9*(10), 1467. https://doi.org/10.3390/foods9101467
55. Man, S., Liu, T., Yao, Y., Lu, Y., Ma, L., & Lu, F. (2021). Friend or foe? The roles of inulin-type fructans. *Carbohydrate Polymers*, *252*(1), 117155. https://doi.org/10.1016/J.CARBPOL.2020.117155
56. Manzocco, L., Calligaris, S., & Nicoli, M. C. (2010). Methods for food shelf life determination and prediction. *Oxidation in Foods and Beverages and Antioxidant Applications: Understanding Mechanisms of Oxidation and Antioxidant Activity*, *3*(5), 196–222. https://doi.org/10.1533/9780857090447.1.196
57. Martínez-Sanz, J. M., Sospedra, I., Baladía, E., Arranz, L., Ortiz-Moncada, R., & Gil-Izquierdo, A. (2017). Current Status of Legislation on Dietary Products for Sportspeople in a European Framework. *Nutrients*, *9*(11), 1225–1241. https://doi.org/10.3390/NU9111225
58. Mattila, P., Mäkinen, S., Eurola, M., Jalava, T., Pihlava, J. M., Hellström, J., & Pihlanto, A. (2018). Nutritional Value of Commercial Protein-Rich Plant Products. *Plant Foods for Human Nutrition*, *73*(2), 108–115. https://doi.org/10.1007/S11130-

018-0660-7/TABLES/4

59. McMahon, D. J., Adams, S. L., & Mcmanus, W. R. (2009). Hardening of high-protein nutrition bars and sugar/polyol-protein phase separation. *Journal of Food Science*, *74*(6), 312-321. https://doi.org/10.1111/j.1750-3841.2009.01225.x
60. Mojet, J., & Köster, E. P. (2005). Sensory memory and food texture. *Food Quality and Preference*, *16*(3), 251–266. https://doi.org/10.1016/J.FOODQUAL.2004.04.017
61. Molina-Rubio, M. P., Casas-Alencáster, N. B., & Martínez-Padilla, L. P. (2010). Effect of formulation and processing conditions on the rheological and textural properties of a semi-liquid syrup model. *Food Research International*, *43*(3), 678–682. https://doi.org/10.1016/j.foodres.2009.10.023
62. Mota, M. C., Silva, C. M., Balieiro, L. C. T., Gonçalves, B. F., Fahmy, W. M., & Crispim, C. A. (2019). Association between social jetlag food consumption and meal times in patients with obesity-related chronic diseases. *PLOS ONE*, *14*(2), 1–14. https://doi.org/10.1371/JOURNAL.PONE.0212126
63. Muñoz, A. M. (2002). Sensory evaluation in quality control: an overview, new developments and future opportunities. *Food Quality and Preference*, *13*(6), 329–339. https://doi.org/10.1016/S0950-3293(02)00014-9
64. Nadeem, M., Salim-Ur-Rehman, Muhammad Anjum, F., Murtaza, M. A., & Mueen-Ud-Din, G. (2012). Development, Characterization, and Optimization of Protein Level in Date Bars Using Response Surface Methodology. *The Scientific World Journal*, *2*(1), 1–11. https://doi.org/10.1100/2012/518702
65. Nastaj, M., Terpiłowski, K., & Sołowiej, B. G. (2020). The effect of native and polymerised whey protein isolate addition on surface and microstructural properties of processed cheeses and their meltability determined by Turbiscan. *International Journal of Food Science & Technology*, *55*(5), 2179–2187. https://doi.org/10.1111/IJFS.14471
66. Nishinari, K., Fang, Y., Nagano, T., Guo, S., & Wang, R. (2018). Soy as a food ingredient. *Proteins in Food Processing: Second Edition*, *6*(1), 149–186. https://doi.org/10.1016/B978-0-08-100722-8.00007-3
67. Ojogbo, E., Blanchard, R., & Mekonnen, T. (2018). Hydrophobic and Melt Processable Starch-Laurate Esters: Synthesis, Structure–Property Correlations. *Journal of Polymer Science, Part A: Polymer Chemistry*, *56*(23), 2611–2622. https://doi.org/10.1002/POLA.29237
68. Pan, M., Meng, X., Jiang, L., Yu, D., & Liu, T. (2017). Effect of cosolvents (polyols)

on structural and foaming properties of soy protein isolate. *Czech Journal of Food Sciences*, *35*(1), 57–66. https://doi.org/10.17221/35/2016-CJFS

69. Pérez-Huertas, S., Terpiłowski, K., Tomczyńska-Mleko, M., & Mleko, S. (2020). Surface modification of albumin/gelatin films gelled on low-temperature plasma-treated polyethylene terephthalate plates. *Plasma Processes and Polymers*, *17*(3), 1–9. https://doi.org/10.1002/PPAP.201900171
70. Piernas, C., & Popkin, B. M. (2010). Snacking Increased among U.S. Adults between 1977 and 2006. *The Journal of Nutrition*, *140*(2), 325–332. https://doi.org/10.3945/JN.109.112763
71. Potes, N., Kerry, J. P., & Roos, Y. H. (2014). Protein Modifications in High Protein-Oil and Protein-Oil-Sugar Systems at Low Water Activity. *Food Biophysics*, *9*(1), 49–60. https://doi.org/10.1007/s11483-013-9316-1
72. Purwanti, N., van der Goot, A. J., Boom, R., & Vereijken, J. (2010). New directions towards structure formation and stability of protein-rich foods from globular proteins. *Trends in Food Science and Technology*, *21*(2), 85-94. https://doi.org/10.1016/j.tifs.2009.10.009
73. Rao, Q., Klaassen Kamdar, A., & Labuza, T. P. (2016). Storage Stability of Food Protein Hydrolysates-A Review. *Critical Reviews in Food Science and Nutrition*, *56*(7), 1169–1192. https://doi.org/10.1080/10408398.2012.758085
74. Rawat, N., & Darappa, I. (2015). Effect of ingredients on rheological, nutritional and quality characteristics of fibre and protein enriched baked energy bars. *Journal of Food Science and Technology*, *52*(5), 3006–3013. https://doi.org/10.1007/S13197-014-1367-X
75. Reuterswärd, A. L. (2007). The new EC Regulation on nutrition and health claims on foods. *Scandinavian Journal of Food & Nutrition*, *51*(3), 100–106. https://doi.org/10.1080/17482970701685625
76. Rolls, E. T. (2012). Mechanisms for Sensing Fat in Food in the Mouth. *Journal of Food Science*, *77*(3), 140–142. https://doi.org/10.1111/J.1750-3841.2011.02584.X
77. Sá, A. G. A., Moreno, Y. M. F., & Carciofi, B. A. M. (2020). Plant proteins as high-quality nutritional source for human diet. *Trends in Food Science & Technology*, *97*, 170–184. https://doi.org/10.1016/J.TIFS.2020.01.011
78. Sahin, A. W., Axel, C., Zannini, E., & Arendt, E. K. (2018). Xylitol, mannitol and maltitol as potential sucrose replacers in burger buns. *Food & Function*, *9*(4), 2201–2212. https://doi.org/10.1039/C8FO00066B

79. San José, F. J., Collado-Fernández, M., & López, R. (2018). Sensory evaluation of biscuits enriched with artichoke fiber-rich powders (Cynara scolymus L.). *Food Science and Nutrition*, *6*(1), 160–167. https://doi.org/10.1002/fsn3.541
80. Saraiva, A., Carrascosa, C., Raheem, D., Ramos, F., & Raposo, A. (2020). Maltitol: Analytical Determination Methods, Applications in the Food Industry, Metabolism and Health Impacts. *International Journal of Environmental Research and Public Health*, *17*(14), 5227–5255. https://doi.org/10.3390/IJERPH17145227
81. Schellart, W. P. (2011). Rheology and density of glucose syrup and honey: Determining their suitability for usage in analogue and fluid dynamic models of geological processes. *Journal of Structural Geology*, *33*(6), 1079–1088. https://doi.org/10.1016/J.JSG.2011.03.013
82. Schiraldi, A., Fessas, D., & Signorelli, M. (2012). Water activity in biological system. *Polish Journal of Food and Nutrition Sciences*, *62*(1), 5–13. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.agro-7f55bc61-085d-4ed4-b15f-4392a479cff0
83. Sharp, M. A., & Harris, G. (2020). A Method for Determination of Unbound Fats in Protein Bar Formulations Compared with Isolated Fat/Protein Combinations to Optimize Shelf Life. *Current Developments in Nutrition*, *4*(3), 776–780. https://doi.org/10.1093/CDN/NZAA052_045
84. Sherwin, C. P., & Labuza, T. P. (2003). Role of Moisture in Maillard Browning Reaction Rate in Intermediate Moisture Foods: Comparing Solvent Phase and Matrix Properties. *Journal of Food Science*, *68*(2), 588–593. https://doi.org/10.1111/J.1365-2621.2003.TB05715.X
85. Singh-Ackbarali, D., & Maharaj, R. (2014). Sensory Evaluation as a Tool in Determining Acceptability of Innovative Products Developed by Undergraduate Students in Food Science and Technology at the University of Trinidad and Tobago. *Journal of Curriculum and Teaching*, *3*(1), 10–27. https://doi.org/10.5430/jct.v3n1p10
86. Smith, A. A. (2011). Preservatives in Food Products – Review. *International Journal of Pharmaceutical & Biological Archive*, *2*(2), 583–599. https://www.ijpba.info/ijpba/index.php/ijpba/article/view/236
87. Srebernich, S. M., Gonçalves, G. M. S., Ormenese, R. de C. S. C., & Ruffi, C. R. G. (2016). Physico-chemical, sensory and nutritional characteristics of cereal bars with addition of acacia gum, inulin and sorbitol. *Food Science and Technology*, *36*(3), 555–562. https://doi.org/10.1590/1678-457X.05416

88. Stanner, S. A., & Spiro, A. (2020). Public health rationale for reducing sugar: Strategies and challenges. *Nutrition Bulletin*, *45*(3), 253–270. https://doi.org/10.1111/NBU.12460
89. Sun-Waterhouse, D., Zhao, M., & Waterhouse, G. I. N. (2014). Protein Modification During Ingredient Preparation and Food Processing: Approaches to Improve Food Processability and Nutrition. *Food and Bioprocess Technology*, *7*(7), 1853–1893. https://doi.org/10.1007/S11947-014-1326-6
90. Szydłowska, A., Zielińska, D., Łepecka, A., Trząskowska, M., Neffe-Skocińska, K., & Kołożyn-Krajewska, D. (2020). Development of Functional High-Protein Organic Bars with the Addition of Whey Protein Concentrate and Bioactive Ingredients. *Agriculture*, *10*(9), 390–409. https://doi.org/10.3390/AGRICULTURE10090390
91. Tapia, M. S., Alzamora, S. M., & Chirife, J. (2020). Effects of Water Activity (aw) on Microbial Stability as a Hurdle in Food Preservation. In *Water Activity in Foods* (pp. 323–355). Wiley. https://doi.org/10.1002/9781118765982.ch14
92. Tomczyńska-Mleko, M., & Ozimek, L. (2013). Ultrasound viscosity measurements allow determination of gas volume fraction in foamed gels. *Journal of Food Process Engineering*, *36*, 572-578. https://doi.org/10.1111/jfpe.12019
93. Trinh, T., & Glasgow, S. (2012). On the texture profile analysis test. In *Quality of Life Through Chemical Engineering* (pp. 1-12).
94. Tuśnio, A., Taciak, M., Barszcz, M., Święch, E., Bachanek, I., & Skomiał, J. (2017). Effect of Replacing Soybean Meal by Raw or Extruded Pea Seeds on Growth Performance and Selected Physiological Parameters of the Ileum and Distal Colon of Pigs. *PLOS ONE*, *12*(1), 1–16. https://doi.org/10.1371/JOURNAL.PONE.0169467
95. Vivek, K., Subbarao, K. V., Routray, W., Kamini, N. R., & Dash, K. K. (2019). Application of Fuzzy Logic in Sensory Evaluation of Food Products: a Comprehensive Study. *Food and Bioprocess Technology*, *13*(1), 1–29. https://doi.org/10.1007/S11947-019-02337-4
96. Walia, A., Gupta, A. K., & Sharma, V. (2019). Role of Bioactive Compounds in Human Health. *Acta Scientific Medical Sciences*, *3*(9), 25–33.
97. Wang, Q., & Xiong, Y. L. (2019). Processing, Nutrition, and Functionality of Hempseed Protein: A Review. *Comprehensive Reviews in Food Science and Food Safety*, *18*, 936-952. https://doi.org/10.1111/1541-4337.12450
98. Weeks, E. R. (2007). Soft jammed materials. *Statistical Physics of Complex Fluids*, 1–87. http://laplace.ucv.cl/Patterns/Referencias/soft-materials-sendai2007.pdf

99. Wiśniewska, M. (2010). Influences of polyacrylic acid adsorption and temperature on the alumina suspension stability. *Powder Technology*, *198*(2), 258–266. https://doi.org/10.1016/J.POWTEC.2009.11.016

100. Yadav, G., David Professor, J., Thakur Assistant Professor, S., Shukla Associate Professor, S., Kumari Assistant Professor, A., Yadav, V., David, J., Thakur, S., Shukla, S., & Kumari, A. (2020). Evaluation of sensory attributes in different levels of Tapioca in pro-biotic Ice cream. *The Pharma Innovation Journal*, *9*(1), 404–407. https://doi.org/10.22271/tpi.2020.v9.i1g.4313

101. Zainal Abidin, N. A., Mohd Zin, Z., Abdullah, M. A. A., Rusli, N. D., & Zainol, M. K. (2020). Physicochemical properties and sensory acceptance of canavalia ensiformis tempeh energy bar. *Food Research*, *4*(5), 1637–1645. https://doi.org/10.26656/FR.2017.4(5).150

102. Zhang, Y., Chen, C., Chen, Y., & Chen, Y. (2019). Effect of rice protein on the water mobility, water migration and microstructure of rice starch during retrogradation. *Food Hydrocolloids*, *91*(1), 136–142. https://doi.org/10.1016/J.FOODHYD.2019.01.015

103. Zhao, H., Shen, C., Wu, Z., Zhang, Z., & Xu, C. (2020). Comparison of wheat, soybean, rice, and pea protein properties for effective applications in food products. *Journal of Food Biochemistry*, *44*(4), 1–12. https://doi.org/10.1111/JFBC.13157

104. Zhou, P., Liu, X., & Labuza, T. P. (2008). Moisture-Induced Aggregation of Whey Proteins in a Protein/Buffer Model System. *Journal of Agricultural and Food Chemistry*, *56*(6), 2048–2054. https://doi.org/10.1021/jf073151v

105. Zhou, D., & Labuza, T. P. (2010). Effect of Cysteine on Lowering Protein Aggregation and Subsequent Hardening of Whey Protein Isolate (WPI) Protein Bars in WPI/Buffer Model Systems. *Journal of Agricultural and Food Chemistry*, *58*(13), 7970–7979. https://doi.org/10.1021/jf100743z

8. Publikacje wchodzące w skład rozprawy doktorskiej

polymers

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Review

Proteins in Food Systems—Bionanomaterials, Conventional and Unconventional Sources, Functional Properties, and Development Opportunities

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Abstract: Recently, food companies from various European countries have observed increased interest in high-protein food and other products with specific functional properties. This review article intends to present proteins as an increasingly popular ingredient in various food products that frequently draw contemporary consumers' attention. The study describes the role of conventional, unconventional, and alternative sources of protein in the human body. Furthermore, the study explores proteins' nutritional value and functional properties, their use in the food industry, and the application of proteins in bionanomaterials. Due to the expected increase in demand for high-protein products, the paper also examines the health benefits and risks of consuming these products, current market trends, and consumer preferences.

Keywords: health; plant protein; animal protein; food

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1. Introduction

It is estimated that the ever-increasing population growth will reach around nine billion people by 2050 (Figure 1), resulting in huge demand for protein-rich food worldwide. This estimation indicates the potential insufficiency of conventional protein sources in the future, resulting in increased interest in unconventional proteins [1]. Proteins are the basic macronutrient of the human diet. In terms of chemical structure, proteins consist of carbon, oxygen, nitrogen, hydrogen, sulfur, and phosphorus. The properties and functions of proteins depend on their structure [2]. We can distinguish between simple proteins, consisting mainly of amino acids, and complex proteins with other components attached to the amino acids. Proteins are large biomolecules and macromolecules comprising one or more long chains of amino acid residues. A linear chain of amino acid residues is called a polypeptide. A protein contains at least one long polypeptide. The individual amino acid residues are bonded together by peptide bonds and adjacent amino acid residues [3,4]. Protein is considered a key ingredient in the human diet for assessing the body's needs due to the complex metabolic changes required to run two processes constantly, such as the synthesis and breakdown of the body's proteins [5]. This essential process is the function of the multithreaded protein metabolism and is commonly known as protein turnover. Proteins are cell molecules that power virtually every function and development program in biology. Surprisingly, many of these critical molecules easily aggregate and accumulate inside living cells through interactions between developed and complex domains. Aggregation may occur incorrectly and lead to disease, but there is growing evidence that the aggregation phenomenon can be regulated by the cell and used to perform important and beneficial biological functions, from molecular scaffolding to memory [6,7].

In industry, proteins are widely used, depending on their specific functional properties. The main functional differences observed in proteins are their varying structural properties [8]. Polypeptide chain modifications and changes in environmental conditions affect the conformation of protein molecules and, thus, their solubility and ability to form or stabilize emulsions and foams [9]. This review article presents the role of proteins in the human body, characteristic of conventional, unconventional, or alternative sources of proteins. In addition, the nutritional value of proteins, their functional properties, and their use in the food industry are examined.

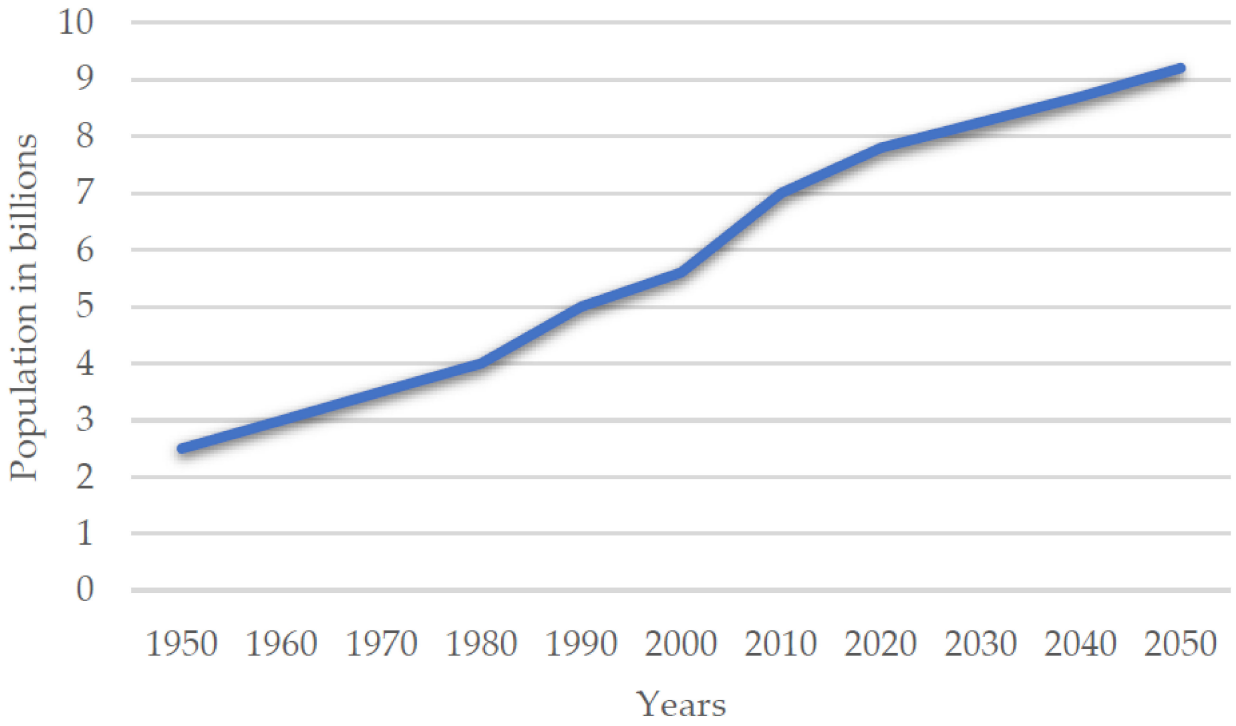

Figure 1. World population growth 1950–2019 with projections to 2050 based on Jensen et al., 2020 [10].

Based on FAO Food Balance Sheet data, it is clear that global meat consumption has increased significantly in recent decades due to the growing population. Henchion et al. 2014 [11] found that overall meat consumption increased by almost 60% between 1990 and 2009. This trend is expected to continue, driven by income growth in countries such as Asia, South America, and the Middle East. While the United Nations and governments are implementing campaigns to reduce the amount of meat consumed [12], global meat consumption is expected to increase by 76% by 2050 compared to 2017 [13]. The global plant-based protein market is projected to grow from USD 10.3 billion in 2020 to USD 14.5 billion by 2025, recording a compound annual growth rate (CAGR) of 7.1% during the forecast period. The major factors driving the growth of the plant-based protein market include growing demand in the food industry, increasing demand for pea-based protein, and the opportunity to expand in potential high-growth markets [14,15]. Consumers make food choices based on traditional food values such as taste and price. However, other food values, such as health, environmental impact, and ethical concerns, now influence consumer decisions. Due to these influences, increasing interest in unconventional proteins (including plant and insect proteins) is expected in the coming years [16].

Proteins are subject to constant interactions related to the influence of other nutrients and energy metabolism. They are the basic structural and functional components of every human body cell, responsible for gene expression control, and essential for the young organism's proper growth and development. They are part of many enzymatic systems (as biocatalysts) [14]. Proteins perform the function of transporting oxygen (hemoglobin),

iron (transferrin), and retinol (eight-stranded β-barrel proteins that bind extracellular retinoids, such as retinol-binding protein 4 and epididymal retinoic acid-binding protein). Furthermore, actin and myosin are muscle-contractile elements participating in tissue repair and regeneration. Proteins (as antibodies) participate in cellular and humoral immunity processes [17,18]. Proteins function as substrates in synthesizing many hormones and biologically active compounds, such as adrenaline, noradrenaline, thyroid hormones (thyroxine, triiodothyronine), histamine, and serotonin. In addition, they participate in creating biologically active compounds such as purine and pyrimidine bases (components of nucleotides and nucleic acids), choline (phospholipids component), glutathione, creatine, and many other components involved in physiological processes [19]. The unique characteristics of their pure enzyme forms make proteins highly applicable to several chemical transformation reactions in the pharmaceutical industry, such as group protection and deprotection, selective acylation and deacylation, selective hydrolysis, deracemization, kinetic resolution of racemic mixtures, esterification, and transesterification [20].

2. Functional Properties of Proteins

Proteins can have surface properties such as the ability to form or stabilize emulsions (interfacial oil/water interface), the ability to create or stabilize foams (interfacial air/water interface), or solubility (combining the connections between water and proteins). In addition, proteins have hydrodynamic properties based on intermolecular interactions, including gelation, texture, and molding sensory properties (taste and smell) [21]. The functional properties of proteins (Figure 2) depend directly on the specific properties of their molecules, such as size, shape, susceptibility to denaturation, flexibility, amino acid composition, hydrophilicity and hydrophobicity, the charge distribution in the molecule, the nature and number of microdomain structures, the ability of the entire molecule or its constituent domains to adapt to changing environmental conditions, and the nature of the interrelationships between different proteins and other food components [22]. The functional properties of proteins are affected by important environmental factors in the protein's location, such as pH, temperature, pressure, and ionic strength [8]. Proteins form complex systems with other food ingredients that affect the formation of their functional properties, and additionally, technological processes play a significant role in shaping proteins' functional properties [23]. In most proteins, the majority of hydrophilic functional groups are located on the surface of the molecules. However, the hydrophobic groups are not entirely located inside them. In globular proteins, 40–50% of the molecule's surface may be occupied by hydrophobic amino acid residues [24]. Their specific distribution in the polypeptide chains affects the surface formation of protein molecules, the ability to create oligomers and micellar structures, and functional properties [25].

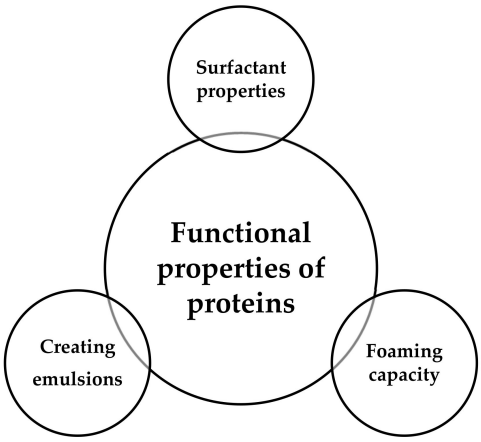

Figure 2. Classification of the main functional properties of proteins.

Sulfuric amino acids play a significant role in shaping the structure and function of proteins [26], and thiol groups can be oxidized to form intra- and intermolecular disulfide bridges. These interactions change the structure and function performed by the proteins. Cross-bending disulfide bridges stabilize proteins' tertiary structure and affect their functional properties [27].

2.1. Functional Properties of Proteins

Among proteins' functional properties, solubility deserves special attention. Solubility is considered the basic functional property of food proteins. This property largely determines the applicability of protein preparations in food technology. High solubility is often associated with the protein's good functional properties, enabling producers to create food products with desired, repeatable, and predictable characteristics [28]. Loss of solubility due to food processing under harsh conditions is often an indicator of denaturation and subsequent protein cross-linking [29]. The solubility of proteins depends on the structure and properties of the solvent, temperature, pH of the environment, concentration and charge of ions, and the nature of interactions with other molecules [30]. Surface hydrophobicity and the resultant electric charge are the most important characteristics of the protein molecule, determining its behavior towards the solvent. Surface hydrophobicity is an indicator of the character of the diverse electrostatic potential of various protein surface fragments, decisive for the protein's spatial shape and behavior towards polar and apolar solvents [31]. One method for modifying hydrophobic/hydrophilic surface protein molecules is chemical modification such as glycosylation, and enzymatic modification (density cargo), such as dephosphorylation [32]. Protein use helps to maintain high solubility in an environment. This property is particularly significant in an acidic environment. For example, using proteins as additives to juices and beverages prevents coagulation [33].

2.2. Surface Properties of Proteins

The phenomenon of proteins stabilizing emulsions or foam is caused by their ability to adsorb at the interface, reduce surface tension, and create a coherent layer around oil droplets or air bubbles [34]. If the surface of the particles is entirely hydrophilic, phase interface adsorption may not occur. However, if it contains only a few hydrophobic residues and interacts with the phases' surface, adsorption may occur. In other words, adsorption at the interface between air/water and oil/water depends on the statistical probability of collisions of hydrophobic groups located on the surfaces of protein molecules with a phase boundary. Conformational stability, the ability to rearrange at the interface, and symmetry/asymmetry in distributing polar and apolar functional groups influence the membrane adsorption and formation amphiphilicity of protein structures [35]. Due to these properties and their greater ability to provide satiety than carbohydrates and fats, proteins can act as a regulator of gastrointestinal hormones to increase the feeling of saturation and reduce the calories absorbed from meals [36]. The addition of foams with bubbles to food products such as chocolate, cheese puffs, and gelatin foams introduces innovation and reduces the products' calorific value by increasing their bulk compared to their standard counterparts [37].

Furthermore, aerated gels have applications in the formation of capsular products, the release of taste, the selective supply of bioactive particles, satiety control (similar to foams), and the creation of gastronomic structures [38]. Therefore, proteins can shape the desired texture of a food product, improve water absorption, and prevent syneresis. The gel matrix is retained; immobilized water molecules and other food ingredients such as carbohydrates, polyhydric alcohols, and fibers help to create a stable gel structure for food products [39].

2.3. Foaming Capacity

Foams are created by dispersing air bubbles in the liquid phase. Adding protein increases the aqueous phase's viscosity, increasing the interfacial film's durability and

producing foam [40]. Proteins reduce the surface tension by interacting with the water molecules and air, allowing foam bubbles to form. After adsorption on the surface of the air bubbles, polar amino acid residues on the surfaces of the protein molecules react with the liquid, and non-polar amino acids react with the air, resulting in the formation of a coherent, flexible film around the air bubble's interphase. The bubbles remain separate from each other because unchanged fragments of the protein molecules connect with them. The 0.1–1 mm diameter air bubbles can comprise up to 99% of the foam's total volume [41]. The factors influencing foam formation include surface hydrophobicity, the location of hydrophobic amino acid residues on the protein's surface, thiol groups, cations and anions, carbohydrates, and lipids. The stability of the formed foam depends on the protein's ability to protect the foam from the effects of gravity and mechanical interactions [42]. Stable foam is usually created at a pH close to the protein's isoelectric point, when electrostatic interaction forces are the smallest. Processes that increase hydrophobicity improve foaming properties. The protein's foaming properties can be increased with short periods of heating. For example, thermal denaturation for 30 min at a temperature range of 40–60 °C improves the foaming properties of whey proteins. Optimal heating conditions depend on the type and concentration of protein [43].

2.4. Creating Emulsions

Emulsions are dispersion systems consisting of two or more immiscible liquids in the form of a continuous and a dispersed phase (small droplets). When mixing oil and solutions with aqueous proteins, it is preferable to limit contact between them and phase separation. Initially, minimal contact is achieved due to spherical droplets' formation with energy input from the outside. A stabilizing agent is introduced to facilitate the emulsion's formation and improve its stability. Proteins, as an emulsifying agent, can be used as a stabilizer [43,44]. Protein-stabilized emulsions ensure minimal contact between hydrophobic groups and water and are energy-efficient as they do not require high energy expenditure during emulsion formation [44]. The time required to form a coherent layer around the oil droplets and establish thermodynamic equilibrium depends on the protein type. With loose, elastic-structured proteins, these phenomena proceed quickly, at medium speed using globular proteins, and slowly with proteins with a compact structure. The droplet size of the dispersed phase characterizes the basic size of the emulsion. The diameter of these drops in food product emulsions varies between 0.2 and 10 mm. The size depends on the emulsion production method, the difference in viscosity between the two phases, the emulsifier used, and the energy input during emulsion formation [45]. Low-quality products contain drops of approximately 10 mm diameter and above. In high-quality products such as mayonnaise, the drops are 2–4 mm [46]. Industry commonly uses the proteins lysozyme, β-lactoglobulin, β-casein, α-lactalbumin, and ovalbumin for emulsifying [47].

In contrast to low-molecular-weight emulsifiers, the structure of proteins may be affected by adsorption. Therefore, a good emulsifier should not only create but also stabilize the newly formed interface. Protein-stabilized emulsions are more stable at a pH other than the isoelectric point values of the proteins. The emulsion's stability depends on the continuous phase's viscosity, gravity forces, the resultant charge, and the protein's structure. In the emulsion preparation device, the energy provided during emulsification mainly determines the extent and nature of changes to the emulsion over time [48]. Furthermore, environmental factors, such as protein concentration, active acidity, oil/water phase ratio, and ionic strength, determine the emulsion's stability [49]. Changing the protein's structure can lead to conformational changes and affect its ability to create and stabilize emulsions. The increase in hydrophilicity can play a positive role in shaping the emulsifying properties [50].

2.5. Protein-Based Bionanomaterials

In nature, we find many examples of solid and functional bionanomaterials understood as a combination of bio-macromolecules (mainly proteins) with small organic molecules or materials, providing the basis for the production of advanced and highly efficient hybrids (photosystems, metalloenzymes, antenna systems, and bionanocomposites) [51]. Nanomaterials are significant in the developing field of science and economy. Size reduction could result in several new physicochemical properties and many potential applications. Nanotechnology is an innovative technology that uses methods and techniques to obtain materials, elements, and devices with at least one controlled dimension in the nanoscale range of 1–100 nm [52]. Two techniques are used in the production of nanomaterials: top-down and bottom-up. The top-down method consists of reducing the particle size. The bottom-up method considers the construction of new structures based on existing nanoparticles [53]. Using this method, the nanostructures' building blocks can be atoms, molecules, or nanoparticles, depending on the properties of the final product.

It is possible to obtain a material with the desired properties by changing the size of the building material, controlling the features of its surface and interior, and imposing specific conditions for joining particles into a nanomaterial [54]. Nanotechnology applications apply to all areas of food science (Figure 3), including agriculture, food processing, packaging, safety, nutrition, and nutraceuticals [55]. New approaches are being applied to the development and design of new protein-based bionanomaterials. The significance of using proteins in the production of bionanomaterials goes beyond their intrinsic functionality, as proteins can also be used as highly tunable platforms as a basis for accommodating and binding synthetic materials, suggesting new functions for the hybrid system. In addition to functional and versatile structural proteins as building blocks for design, it should be noted that, compared to other platforms, protein-based materials are ecological, durable, biodegradable, and biocompatible [51].

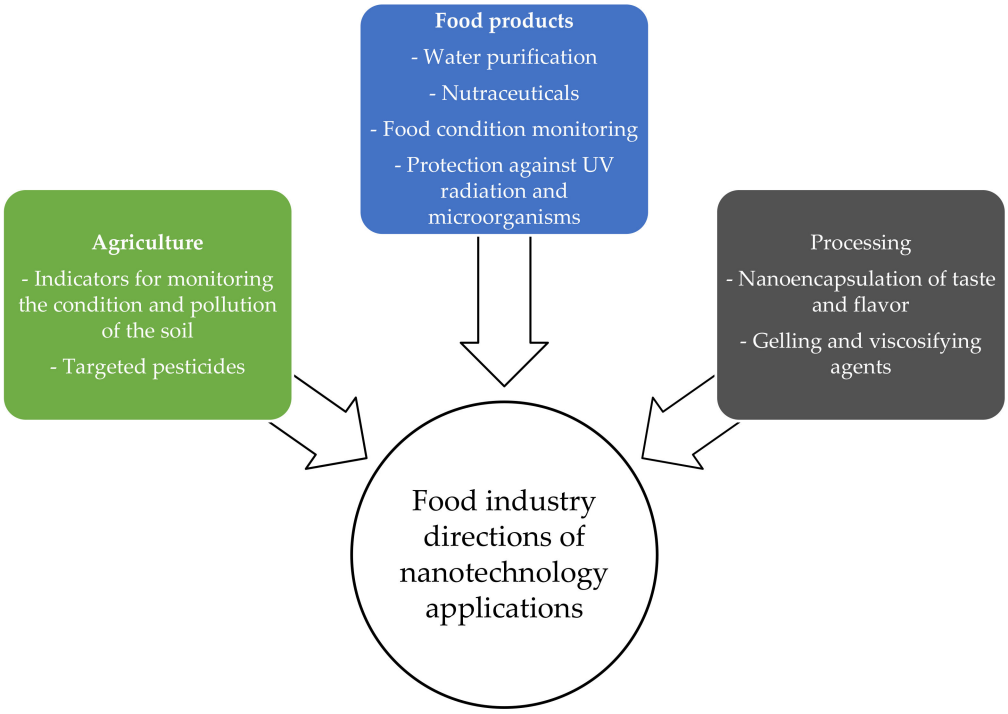

Figure 3. Directions of nanotechnology applications in the food industry based on [52].

3. The Most Common Sources of Plant and Animal Proteins

Food proteins are essential nutrients required for maintaining various bodily functions and human health. Proteins, especially some traditional plant- and animal-derived protein sources (Figure 4), are essential food ingredients. They are listed and described in this section.

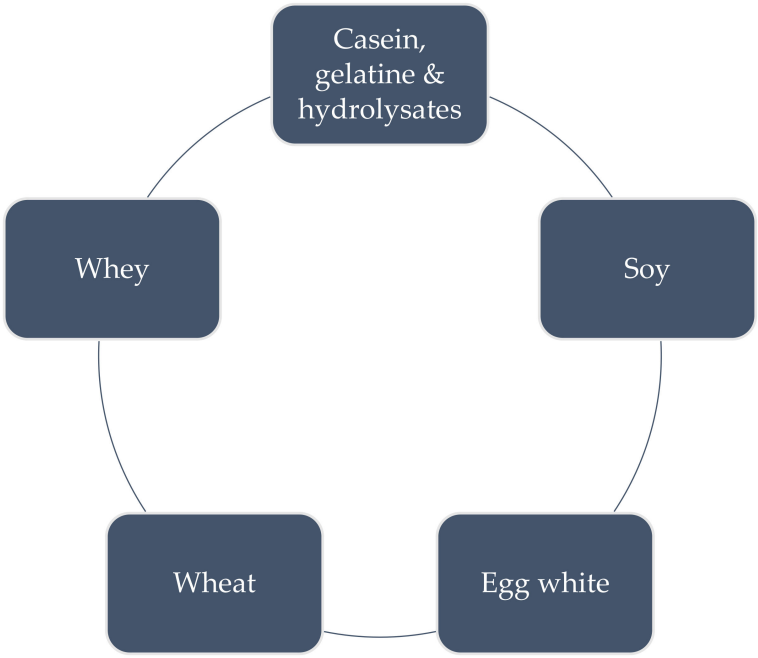

Figure 4. The most common sources of protein in food production.

3.1. Soy

Soy is the primary plant for protein production, with a global soybean harvest of around 300 million metric tons per year [56]. Soybean has been a food source for many years. It is the globally adopted GM crop, covering 80% of GM crop-growing areas worldwide, corresponding to approximately 100 million metric tons per year. The main threat associated with genetically modified organisms is biodiversity disturbance, resulting from the uncontrolled modification of transgenic organisms released into the environment [57]. Modified varieties can displace traditional plant varieties and reduce the number of certain species. The emergence of agricultural monocultures contributes to the resistance of plant species and insects to the chemical agents controlling them and a significant increase in their population. Crossing transgenic plants with rapid-growth wild plants can lead to the formation of "superweeds" [58]. Therefore, the safety of genetically modified crops and transgenic food products requires detailed analysis and clarification of issues such as the toxicity and health safety of GM plants, the impact of GM plants on other organisms, the allergenicity of food products made from GM plants, biological safety, and resistance to antibiotics [59].

The United States is the largest producer of soy and soy products [60]. Soybeans contain a naturally high protein content (35–40%); soy is widely used in oil production, and soy flour is generated during this process. A significant amount of defatted soy flour serves as animal feed. The remaining flour is used for various kinds of high-protein products intended for human consumption [61]. The relatively high protein content and preferably balanced amino acid composition make soy protein suitable as a substitute for meat and milk proteins in humans' daily diet [62]. The most common soy products are soy flour, soy protein concentrate, soy protein isolate, textured, and hydrolyzed soy protein. Soy protein concentrate (SPC), containing approximately 65% protein, is obtained from defatted soy flakes free of soluble parts of the cell walls. Soy protein isolate (SPI),

with approximately 90% protein, is the most highly refined soy product. It is formed by alkalic extraction and isoelectric precipitation. The textured soy protein produced by the extrusion method resembles the texture of meat [56]. This product's primary function is an alternative protein source for the complete or partial replacement of animal protein in various food products, particularly in the daily diet of vegans and vegetarians. Isolates, soy protein, concentrate, soy flour, and the textured products derived from them are commonly used in food industry preparations due to their functional properties, such as water and fat binding, emulsifying, foaming, and gelling [63].

3.2. Wheat

Wheat is the most cultivated and the most significant crop in the world. It is consumed by over a billion people around the world in various forms [64]. In 2017, the total global production of wheat was 772 million metric tons, with approximately 150 million metric tons used as animal feed. Based on 2017 data, the European Union is the largest wheat producer, with 150.2 million metric tons. China, India, and Russia account for around 41% of the world's total wheat production [65,66]. Wheat is a more frequent source of protein and calories than any other food due to the global consumption of wheat products [64]. The protein content in wheat varies from 8% to 15%, depending on the variety [67]. The amino acid composition of wheat is quite unbalanced, lacks essential amino acids such as lysine, threonine, and methionine, and processing wheat into various products further depletes essential amino acids [68].

The main reservoir of protein in wheat grains is gluten protein. Gluten has unique functional properties not found in other plant proteins. Gluten creates a coherent, slightly elastic, cross-linked protein structure that allows wheat to be used to produce products such as sourdough [67]. Commonly used gluten, with a protein content of around 80%, is obtained by simply rinsing the flour with water. This method was discovered in the second half of the 19th century. In addition to the conventional method of obtaining gluten, several other methods of obtaining and modifying this protein are used [69]—for example, the chemical and enzymatic modification used in eluted gluten to strengthen its structure. Thanks to available technologies, it is possible to achieve 90% protein content in wheat protein isolates. The main application of gluten is bakery products, pasta, and breakfast cereals. As gluten possesses an efficient ability to abstract fat and water, it is used in the meat and fish industry [70]. Gluten is commonly used as a substitute for meat proteins in foods for vegetarians and vegans. Textured wheat protein, obtained by extrusion, is increasingly used to imitate meat products' appearance and structure [71].

Gluten-related diseases such as celiac disease and gluten ataxia are rare conditions, affecting less than 1% of the population. Despite the rarity of these diseases, there has been a significant increase in the adoption of a gluten-free lifestyle and the consumption of gluten-free foods over the last three decades [72]. Individuals might restrict gluten from their diets for various reasons, such as improvement of gastrointestinal and non-gastrointestinal symptoms, and because of the perception that gluten is potentially harmful and, thus, restriction represents a healthy lifestyle. Emerging evidence shows that gluten avoidance may benefit some patients with gastrointestinal symptoms, such as those commonly encountered with irritable bowel syndrome [73].

3.3. Milk Proteins (Casein)

Protein is an important component of milk as it largely determines its nutritional value and suitability for processing. Cow's milk contains approximately 3.4% protein on average and is the sum of two main fractions, casein and whey proteins, constituting approximately 80% and 20% protein and nitrogen compounds, respectively [74], and differing in their physicochemical properties. The knowledge of these compounds and their practical use is the basis for producing various milk–protein preparations. The raw material casein is used to produce pasteurized skimmed milk and skimmed milk powder [75]. With either acid or rennet coagulation methods used, casein is distinguished. Acid casein contains,

on average, around 88% protein, 1.5% fat, 0.3% lactose, and 2.1% ash. The composition of rennet casein is approximately 82% protein, 1.4% fat, 0.5% lactose, and up to 8.5% ash [76]. Cow's milk casein contains all essential amino acids in greater amounts than the FAO/WHO standard. When comparing casein with whole hen egg protein, lower contents of isoleucine, lysine, threonine, tryptophan, valine, and sulfur amino acids are apparent [77]. A significant quality-distinguishing feature of caseinate preparations is their functional properties, characterizing how proteins interact with food ingredients to determine their potential practical application. In food processing, the important functional properties of caseinates are solubility, water absorption, viscosity, gelling, fat binding, emulsification, and foaming [78]. Due to their properties, caseinates are used in many food processing industries, such as meat processing, delicatessen production, cereal product production, baking, confectionery, dairy, beverage production, food concentrates, and the preparation of products for special nutritional purposes [79]. In a section of the population, milk proteins can trigger an allergic reaction. Cow's milk allergy (CMA) is an immunologically mediated reaction to cow's milk proteins, involving the gastrointestinal tract, skin, respiratory tract, or sometimes multiple systems (systemic anaphylaxis). Its prevalence in the general population is probably 1–3%, highest in infants and lowest in adults [80,81].

3.4. Whey Proteins

Due to their favorable physicochemical and biological properties, whey proteins are now perceived as nutrients in the production of dietetic food, physiologically active in the production of functional foods, and structure-forming in traditional and new generation food [82]. Intake of 14 g of whey proteins covers the daily requirement for essential amino acids of a person weighing 70 kg, equivalent to 23 g of casein or 17 g of egg white. Whey proteins are popular due to their biological activity and the possibility of using them to produce so-called functional food [83]. The composition of whey's dry matter justifies its use as a raw material for further processing. Ultrafiltration densification is increasingly used to reduce the costs of concentrated whey operations. In addition to their nutritional properties, whey proteins offer a wide range of functional properties [84]. The meat industry uses whey proteins to improve taste, texturing, emulsifying, gelling, binding water, and improving nutritional properties. Whey proteins enable partial replacement of meat proteins, or replace soy products and other non-meat additives such as modified starches [85]. Using an appropriate proportion of functional whey proteins (about 35%) and milk powder in yogurt production improves its rheological and taste properties and allows the resignation or restriction of non-dairy thickeners such as gelatin, modified starches, and pectin [86]. In confectionery, whey proteins can be substituted for skimmed milk powder. In addition, whey proteins are used for non-fat mayonnaise production, sauces, and soups. Their advantages are solubility in a broad spectrum of pH and the ability to form gels, bind water, and imitate the taste properties of fats [87].

3.5. Egg White Proteins

Eggs are of particular interest from a nutritional point of view, gathering essential lipids, proteins, vitamins, minerals, and trace elements while offering a moderate calorie source (approximately 140 kcal/100 g), great culinary potential, and low economic cost. Indeed, eggs have been identified as the lowest-cost animal source for proteins, vitamin A, iron, vitamin B_{12}, riboflavin, and choline, and the second-lowest-cost source for zinc and calcium [88,89]. Egg proteins are distributed equally between the egg white and egg yolk, while lipids, vitamins, and minerals are essentially concentrated in the egg yolk. The relative content of egg minerals, vitamins, and specific fatty acids varies between national references but remains globally comparable when considering major constituents such as water, proteins, lipids, and carbohydrates [90]. The major egg nutrients are very stable and depend on the ratio of egg white to yolk in contrast to minor components affected by several factors, including hen nutrition. As a whole, raw, freshly laid eggs' water,

protein, fat, carbohydrates, and ash represent approximately 76.1%, 12.6%, 9.5%, 0.7%, and 1.1%, respectively [91]. Egg white contains around 10% protein, with many functionally important proteins, including ovalbumin (54%), ovotransferrin (12%), ovomucoid (11%), ovomucin (3.5%), and lysozyme (3.5%), among the major proteins that have high potential for industrial applications, if separated [90]. Simplicity, high method reproducibility, non-toxic chemicals used for separation, and the sequential separation of many proteins are significant criteria for the commercial production and application of egg proteins. The separated proteins are used in the food and pharmaceutical industry, and they can be modified with enzymes to meet the needs of a given industry. Ovotransferrin is used as a metal transporter, antibacterial, or anti-cancer agent, while lysozyme is mainly used as a preservative in food applications [92,93]. Ovalbumin is widely used as a dietary supplement and ovomucin as a cancer inhibitory agent [90]. Ovomucoid is the major egg allergen, but it can inhibit the growth of tumors and therefore is used as an anti-cancer agent. Hydrolyzed peptides from these proteins show good angiotensin I converting enzyme inhibitory, anti-tumor, metal-binding, and antioxidant activity [94]. Therefore, egg proteins and the production of bioactive peptides from these proteins are new areas with many possible applications [95,96]. Furthermore, due to their functional properties, egg proteins are widely used in various branches of the food industry for gelling, coagulating, foam formation, stabilization, and water binding. In addition, they are used in cheese production (ripened cheeses), the meat industry (raw meat and fish, pates, baking, sausages, and canned meat), in confectionery (foam products and meringues), in the production of beer, wine, and mead, and in the fat industry [97].

3.6. Gelatin

Gelatin is an animal protein of high purity, produced from collagen and constituting approximately 30% of a protein substance found in high-collagen areas of the animal and human body, especially in bone, cartilage, connective tissue, and skin. The production process transforms collagen into water-soluble gelatin [98]. Collagen determines the physicochemical properties of gelatin, and in particular, the gel strength of the obtained proteins [99]. Collagen is a protein with an unusual amino acid composition. It contains significant amounts of glycine and proline and two amino acids not derived directly from translation in ribosomes: hydroxylysine and significant amounts of hydroxyproline [100]. Regardless of the gelatin production method, the ability to reversibly form gel is its most significant feature. Different species of gelatin have lower or higher gelling capacities. Gelatin serves as a gelling agent, stabilizer, protective colloid, emulsifier, foaming agent, carrier, and binder and is an important auxiliary material in pharmacy. It can be used to produce capsules, liquid medicines, dragées, and granulates [101]. In the food industry, gelatin is a good solution for the production of low-calorie semi-finished products. As a stabilizing and binding additive, it can be used in yogurts, jelly, meat, and fish products. Using gelatin improves the structure in the process of freezing and thawing confectionery products [102].

3.7. Protein Hydrolysates—Food and Feed Additive and Use in Other Industrial Products

All compounds showing biological activity can be used as natural additives in modeling food products' functional properties (Figure 5). Many groceries are susceptible to oxidative changes within unsaturated fatty acids [103]. These changes may harm product quality; sensory value can become significantly decreased with small oxidation changes. Additionally, lipid oxidation products (free radicals) may become toxic or carcinogenic [104]. Enzymatic protein hydrolysis is used to refine foods' raw materials. In addition to the role that enzymatic protein hydrolysis fulfills in high-fat products, it is applied in food preparation technology to improve product consistency. The ingredients of hydrolysates have better emulsifying, foaming, and dispersing properties and solubility than parental proteins. In addition, hydrolysates also improve products' taste and water absorption capacity [105]. Shortening protein chains usually improves nutritional value and enhances

taste qualities. However, intense protein degradation can cause a bitter taste [106]. Mixtures of known, established, advanced, and designed hydrolysate compositions can be obtained with peptides' size, quality, and share of free amino acids [107]. Additionally, using protein hydrolysates has economic justification, as treated products have a relatively extended shelf life. This method is often used in meat processing to increase the availability and attractiveness of the products for consumers [108]. However, protein hydrolysates have significantly wider use and are used in the feed industry for specific functions. They have a beneficial impact on performance traits and animal welfare due to their impact on gastrointestinal flora and feed digestibility. Protein hydrolysates are also used in the pharmaceutical and cosmetics industry (particularly in products with increased fat content) and the paper industry [109,110]. Protein hydrolysates are also increasingly used to produce paint, biodegradable materials, adhesives, binders, coatings, unique mechanical properties and barriers, nanomaterials, and biopolymers [111].

4. Unconventional and Alternative Sources of Proteins

Proteins obtained from alternative sources (Figure 6) such as plants and insects have attracted considerable interest in the formulation of new food products with a lower environmental footprint and offer a solution to feeding a growing world population. Unfortunately, there is little information available on these emerging protein sources, in contrast to the substantial amount of knowledge accumulated over the years regarding many established proteins and protein fractions.

4.1. Rice

Rice has the second-largest harvest and plant consumption in the world after wheat. Annual harvests oscillate around 480 million metric tons [112]. The highest consumption of rice is characteristic of Asian countries. Rice protein contains the second-highest lysine content (the limiting amino acid in cereal) [113] and is favored over other cereal proteins because of its amino acid structure. The protein content in rice is relatively low, at around 8%. However, it is one of the primary protein sources in southern countries and Southeast Asia due to high consumption [114]. In Europe and the United States, high-protein rice ingredients are increasingly used to produce gluten-free food due to their hypoallergenic properties [115]. The solubility of rice proteins is lowest at pH 4–5 and increases as the pH increases or decreases. Their high glutelin content mainly influences the ability of rice proteins to dissolve at certain pH values. Glutelin is the dominant protein fraction in endosperm and constitutes a significant proportion of all rice bran proteins [116]. Preparations based on rice proteins and their specific fractions also have antioxidant, antihypertensive, antineoplastic, and anti-obesity properties [117]. Rice proteins are becoming more and more popular in sports nutrition products and dietary supplements. This protein can be used as an alternative to the currently widely used casein, whey, or soy, and as an additive in the production of bread, biscuit, high-protein bars, or edible films, improving these products' nutritional and functional value [117,118].

4.2. Corn

Corn is one of the most significant plants used in industry, particularly in the United States. The protein content in maize varies between 9% and 12%. Approximately 50% of the United States' harvest is used as animal feed. The remaining percentage is used in spirits, syrup (glucose syrup production), maize flour, starch, oil, corn protein, and for many other applications. Additionally, in the food industry, maize is use intermediately in producing foodstuffs such as chips and tortillas [119]. Corn gluten flour is formed as a wet, milled maize product used for corn protein production. Corn gluten is one of the few vegetable proteins produced on an industrial scale, and is mainly used to produce polymers and food bags [120].

Zein is not popularly used as a source of protein in cornmeal and other products for human consumption. It exhibits poor water solubility and is deficient in certain essential

amino acids such as lysine and tryptophan, limiting its application in the food industry. Consequently, it is mainly utilized as animal feed. Zein contains a high proportion of non-polar and hydrophobic amino acid residues buried inside the protein structure, responsible for its poor aqueous solubility [121]. Zein is corn's major storage protein and comprises ≈45–50% of corn protein. The isolate obtained from zein is not used directly for human consumption due to its negative nitrogen balance and poor solubility in water. The ability of zein and its resins to form hard, glossy, hydrophobic, and fat-proof coatings and their resistance to microbial growth has attracted commercial interest. Potential applications of zein include fiber, adhesives, coatings, ceramics, ink, cosmetics, textiles, chewing gum, and biodegradable plastics. Zein has high potential in the specialty food, pharmaceutical, and biodegradable plastic industries, but only if manufacturing costs can be decreased [122]. Modifying this protein's amino acid composition to permit its utilization in the food industry would increase its market value and range of applications [121].

The structural property of corn peptides is responsible for improved solubility. This property is mainly reflected in high solubility across a wide pH range, the formation of homogenous solutions with no precipitation, and the flow phenomenon. In addition, corn peptides have good solubility even under extreme conditions, such as low pH, so they are widely used in the acidic beverage industry. Furthermore, corn peptide drinks have the advantages of low viscosity, high glutamate content, and a pleasant taste and can improve brain function, making corn peptide beverages popular [123].

4.3. Quinoa

Quinoa (*Chenopodium quinoa* Willd) is an annual plant species. The bran fraction content in quinoa seeds is higher than in cereals such as wheat or corn, providing high protein and fat content in this plant's seeds [124]. The amino acid composition of quinoa proteins is well-balanced and has a higher content of exogenous amino acids than most cereals [125]. Quinoa contains polyphenols, phytosterols, and flavonoids and is a rich source of dietary fiber, minerals, and vitamins. Due to its functional properties, solubility, emulsifying, foaming, and gelling properties, quinoa has various applications in the food and other, industry [126]. Quinoa oil is high in omega-6 and vitamin E content. Quinoa starch is used in many innovative industrial applications due to its functional properties, including the stability of its structure during freezing and the modification of solution viscosities [127].

4.4. Beans

Beans are a rich source of bioactive peptides, polysaccharides, oligosaccharides, and polyphenols. As a legume, beans have a naturally high protein content (up to approximately 30%). Bean protein is becoming more and more popular due to bioactive peptides, making it possible to use this protein to produce anti-diabetic, hypotensive, anti-inflammatory, and metal-chelating medicines [128]. In addition, beans contain a huge amount of dietary fiber and can improve exposure to irritation of the intestinal mucosa by facilitating the expulsion of toxic compounds in the intestines (especially in the large intestine). The high fiber content of beans can also help to reduce constipation and hemorrhoids and support easier defecation [129]. Legumes are a rich source of protein and dietary fiber. However, a wide variety of antinutritional factors, such as raffinose family oligosaccharides (RFOs), neurotoxins, proteinaceous compounds, lectins, goitrogenic factors, amylase inhibitors, and phytic acid, are present in them [130]. These factors influence their bioavailability and nutrient absorption in humans and animals eating beans as food [131]. Breeding crop varieties with a reduced concentration of antinutritional factors, using enzymes to reduce their concentration, and local methods such as cooking, germination, and soaking are all possible methods to reduce the antinutritional factors of beans [132].

4.5. Lupine

According to scientific research, lupine contains slightly higher protein content than other legumes commonly consumed by humans and is practically free of starch (up to 2%). Lupine's structure is typically dicotyledonous. Its thick skin is approximately 30%, by weight of seeds, much higher than most domesticated species of cereals and legumes. The shell consists of cellulose and hemicellulose, and lupine seed fibers consist of soluble and insoluble fractions in the ratio of 40:60% [133]. The crude protein content of lupine fluctuates from 28% to 42%, depending on the type, variety rounds, conditions of growth, and soil type. In fractional lupine, protein composition is dominated by albumin and globulins (38% and 35%, respectively), 4.3% glutelin, and 0.6% prolamine. This combination of proteins is easily digestible, giving lupine a significant advantage over its competitors (soy, peas, and beans) [134]. In addition, products containing lupine are more easily digested than products containing soy or peas in their composition, as the fractional protein comprises lower proteolytic enzyme content inhibitors than other legumes. In addition to the full protein composition, lupine is a good source of vitamins, containing fat-soluble oils and provitamins, including sterols, carotenoids, and tocopherol, and much lower inhibitor content and water-soluble vitamins including riboflavin, thiamine, pyridoxine, folic acid, and ascorbic acid [135]. Protein preparations from lupine are successfully used in sports food formulas, bakery and confectionery recipes, and meat or dairy production technology. Many lupine products have been developed in recent years, including lupine oil, lupine protein concentrates and isolates, low-fat lupine flour and malt, and lupine flour extrudate [136].

4.6. Sunflower

Sunflower is one of the most produced oilseed crops, alongside soybean, rapeseed, cottonseed, and peanut [137]. According to the FAO, the world production of sunflower seed in 2019 was 56.07 Mt [138]. In summary, the whole sunflower seed contains 10–27% protein. However, when producing sunflower meal, the percentage increases to 40% for mechanically extracted seeds and 50% when the oil is removed with an organic solvent. In dehulled seeds, the protein percentage can reach 53–66% [139]. Sunflower proteins are primarily located in protein bodies and protein storage vacuoles of embryo and endosperm cells. Approximately 87–99% of the nitrogen in sunflower seeds corresponds to intact proteins. The remaining 1–13% originates from peptides, amino acids, or other nitrogenous substances. Sunflower's total carbohydrate content ranges from 4% to 18%, and sunflower seed carbohydrates are characterized by a low starch content (around 0.42%) [140]. Sunflower protein composition complies with the FAO recommendations [141], except for its Lys content, and sunflower contains less sulfur-containing amino acids than rape protein, especially Met and Cys. The content of acidic amino acids (20%) and basic amino acids (18%) is relatively balanced. Unfortunately, using this protein in food products is limited due to its dark color and characteristic aftertaste. However, the uninteresting color can be easily masked by covering the product with chocolate or glaze. Similarly, the strength of the aftertaste depends on the concentration of sunflower protein. Therefore, mixing with other, better-tasting proteins can potentially reduce the negative aftertaste without lowering the protein content [118].

4.7. Insects

Insects are part of the traditional diet of approximately two billion people worldwide [142]. In some regions, insects have been part of the human diet for centuries, specifically as an alternative protein source, making them a subject of great interest. Human consumption of insects is associated with communities located in many parts of Asia, Latin America, and Africa [143]. Insects (invertebrates) possess huge biodiversity, and their biomass represents 95% of the animal kingdom [144]. They can be consumed in different life stages—eggs, larvae, pupae, or adults—and have been used as human food from prehistoric times. The main orders of consumed insects are Coleoptera (31%), Lepidoptera

(18%), Hymenoptera (14%), Orthoptera (13%), and Hemiptera (10%) [145]. In May 2021, the Committee on Plants, Animals, Food and Feed (Novel Food and Toxicological Safety section), composed of representatives from all EU countries, gave a positive opinion of a draft legal act authorizing the sale of yellow mealworm (*Tenebrio molitor*) as a novel food [146]. Insects' high protein levels are the main component of their nutrient composition, and they also possess significant amounts of other important nutrients such as lipids, beneficial fatty acids, vitamins, and minerals [147]. Compared to plant and meat proteins, insect proteins have high levels of high-quality nutritional protein, high total protein levels, and an essential amino acid profile of 50–80%. In general, insect lipids contain high amounts of unsaturated fatty acids relative to saturated fatty acids [148].

Furthermore, many minerals are found in insects, such as iron, zinc, potassium, sodium, calcium, phosphorus, magnesium, manganese, and copper. In addition, they contain a great variety of lipophilic vitamins and riboflavin, pantothenic acid, biotin, and, sometimes, folic acid [149]. Therefore, insect proteins are a promising raw material for further research and industrial use. Unfortunately, at this time, many doubts exist about using insects as food. Specifically considering safety concerns, the common hazards related to insect consumption are microbiological, parasitological, and allergenic. Therefore, the production technology and safety of their use require further research and testing [150].

4.8. Algae

Algae are a varied group of species described as oxygen-producing, photosynthetic, unicellular, or multicellular organisms, excluding embryophyte terrestrial plants and lichens. Depending on the type and place of harvest, marine algae may have a protein content of 20% to 60% of dry matter [151,152]. Due to their pigmentation, macroalgae can be divided into three main groups: *Chlorophyta* (green algae), *Phaeophyta* (brown algae), and *Rhodophyta* (red algae) [153]. Thus, microalgae are a hugely diverse group. Several species are exploited for various biotechnological purposes, such as biofuel and animal feed.

Furthermore, *Arthrospira platensis* (Spirulina) and *Chlorella vulgaris* (Chlorella) are sold as functional foods due to their high vitamin and mineral content [154]. Algae are generally regarded as a rich protein source, their composition meets FAO requirements, and they are often compared with other protein sources, such as soybean or egg [155]. Limiting amino acids in most algae species are tryptophan and lysine, whereas aspartic acid and glutamic acid constitute a relatively large proportion of total amino acids in many seaweed species, largely contributing to the distinctive "umami" taste associated with seaweed [156]. Today, microalgae are typically consumed as a dietary supplement in tablets, powder, and capsules. However, they are also incorporated into several functional foods, including pasta, bread, biscuits, drinks, sweets, high-protein bars, and beer. For example, AlgaVia® is a company offering algae products, producing a protein- and lipid-rich algal powder from *Chlorella protothecoides* [118,154]. High doses of algal protein in food cause a characteristic aftertaste and significant hardening of the product, especially high-protein bars, so may not have a use in similar products [118]. However, this type of protein functions efficiently as a feed additive, especially for poultry. Supplementing poultry feed with microalgae as a protein source can improve health, productivity, and value, demonstrated by various species, including *Chlorella* sp., *Arthrospira* sp., *Porphyridium* sp., and *Haematococcus* sp. Chickens fed with supplemented Spirulina were reported to have increased viability, improved overall health, and reduced cholesterol, triglyceride, and fatty acid plasma concentrations [157].

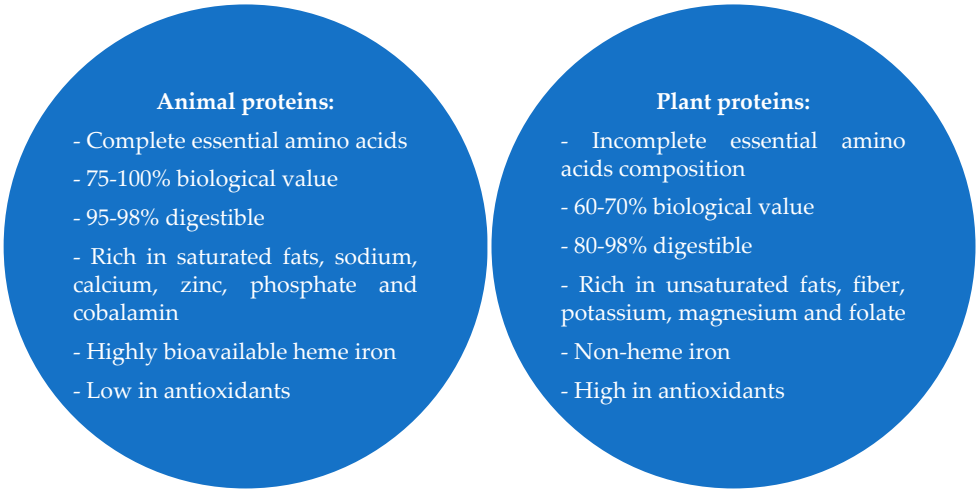

Figure 5. Animal and plant protein comparison based on Berrazaga et al., 2019 [158].

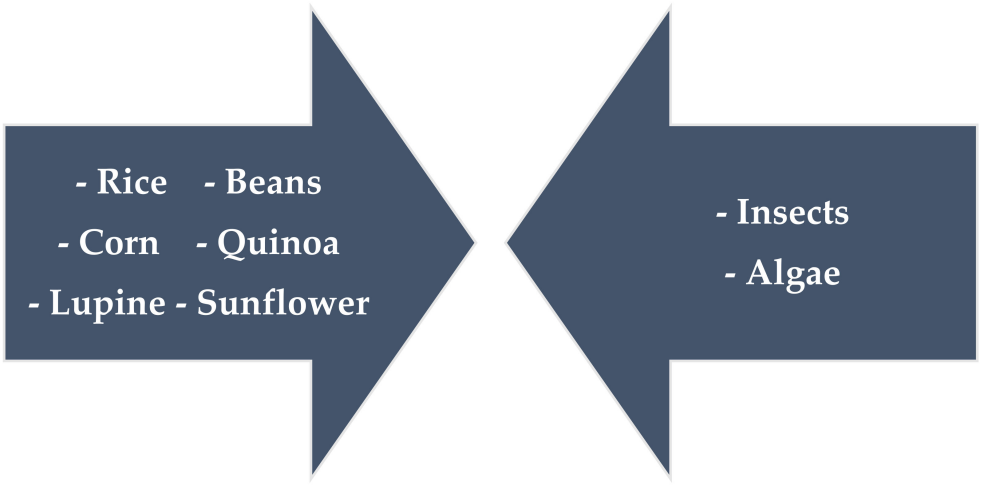

Figure 6. Unconventional and alternative protein sources are increasingly used in the food industry.

5. Conclusions

The human population is constantly increasing, and with it, the demand for protein. Therefore, we can expect an increasing demand for this nutrient in the coming years. In addition, the versatile, functional properties of proteins attract growing interest. Considering the increasing demand for proteins in the food industry and consumer trends for a healthy lifestyle, we can also expect an increase in interest in unconventional proteins such as lupine, bean, and other plant sources. However, an incomplete set of essential amino acids and issues with plants' aftertaste are problems often associated with plant proteins. These aspects are obstacles in the use of these proteins as substitutes for conventional proteins.

Further development required to expand our knowledge of bionanomaterial production, including the food industry and biodegradable packaging materials, is challenging various fields of science. With the discovery of new nanoscale materials, new fields of application will emerge.

Insects are a promising alternative to conventional protein sources, having great potential as a component of the human diet due to their high nutritional value. However, the problems of lack of acceptance of insects as a foodstuff in developed countries and difficulties with introducing food products containing insects to the market remain. Additionally, using insects in the food industry on a large scale is challenging due to consumer safety issues, which must be confirmed by further research. Undoubtedly, using alternative

sources of protein, especially edible insects, can solve the significant and growing issues of environmental and economic problems, and malnutrition. However, the globalization of insects and other unconventional protein sources in human nutrition undoubtedly requires efforts to increase public demand and acceptance and improve consumer awareness of the benefits of their consumption. Furthermore, the search for new insects and plants as sources of protein and the technology for their processing requires further research.

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References

1. Akhtar, Y.; Isman, M.B. Insects as an Alternative Protein Source. In *Proteins in Food Processing*, 2nd ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2018; pp. 263–288, ISBN 9780081007297.
2. Walia, A.; Gupta, A.K.; Sharma, V. Role of Bioactive Compounds in Human Health. *Acta Sci. Med. Sci.* **2019**, *3*, 25–33.
3. Dietzen, D.J. Amino acids, peptides, and proteins. In *Principles and Applications of Molecular Diagnostics*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 345–380, ISBN 9780128160619.
4. Bigman, L.S.; Levy, Y. Proteins: Molecules defined by their trade-offs. *Curr. Opin. Struct. Biol.* **2020**, *60*, 50–56. [CrossRef] [PubMed]
5. Jiang, L.; Wang, M.; Lin, S.; Jian, R.; Li, X.; Chan, J.; Dong, G.; Fang, H.; Robinson, A.E.; Aguet, F.; et al. A Quantitative Proteome Map of the Human Body. *Cell* **2020**, *183*, 269–283. [CrossRef]
6. Chiesa, G.; Kiriakov, S.; Khalil, A.S. Protein assembly systems in natural and synthetic biology. *BMC Biol.* **2020**, *18*, 1–18. [CrossRef]
7. Scognamiglio, P.L.; Platella, C.; Napolitano, E.; Musumeci, D.; Roviello, G.N. From Prebiotic Chemistry to Supramolecular Biomedical Materials: Exploring the Properties of Self-Assembling Nucleobase-Containing Peptides. *Molecules* **2021**, *26*, 3558. [CrossRef] [PubMed]
8. Wijaya, W.; Patel, A.R.; Setiowati, A.D.; Van der Meeren, P. Functional colloids from proteins and polysaccharides for food applications. *Trends Food Sci. Technol.* **2017**, *68*, 56–69. [CrossRef]
9. Aryee, A.N.A.; Agyei, D.; Udenigwe, C.C. Impact of processing on the chemistry and functionality of food proteins. In *Proteins in Food Processing*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 27–45, ISBN 9780081007297.
10. Jensen, J.T.; Creinin, M.D. Family planning, population growth, and the environment. *Contraception* **2020**, *101*, 145–147. [CrossRef]
11. Henchion, M.; McCarthy, M.; Resconi, V.C.; Troy, D. Meat consumption: Trends and quality matters. *Meat Sci.* **2014**, *98*, 561–568. [CrossRef] [PubMed]
12. Henchion, M.; De Backer, C.J.S.; Hudders, L. Ethical and Sustainable Aspects of Meat Production. *New Asp. Meat Qual.* **2017**, *26*, 649–666. [CrossRef]
13. Henchion, M.; Hayes, M.; Mullen, A.M.; Fenelon, M.; Tiwari, B. Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. *Foods* **2017**, *6*, 53. [CrossRef]
14. Sá, A.G.A.; Moreno, Y.M.F.; Carciofi, B.A.M. Plant proteins as high-quality nutritional source for human diet. *Trends Food Sci. Technol.* **2020**, *97*, 170–184. [CrossRef]
15. World Plant-Based Protein Industry Report 2020–2025. Available online: https://www.globenewswire.com/news-release/2020/08/20/2081186/0/en/World-Plant-based-Protein-Industry-Report-2020-2025.html (accessed on 19 July 2021).
16. Liñán, J.; Arroyo, P.; Carrete, L. Conceptualizing Healthy Food: How Consumer's Values Influence the Perceived Healthiness of a Food Product. *J. Food Nutr. Res.* **2019**, *7*, 679–687. [CrossRef]
17. Allison, T.M.; Bechara, C. Structural mass spectrometry comes of age: New insight into protein structure, function and interactions. *Biochem. Soc. Trans.* **2019**, *47*, 317–327. [CrossRef]
18. Redfern, C.P.F. Vitamin A and its natural derivatives. *Methods Enzymol.* **2020**, *637*, 1–25. [CrossRef] [PubMed]

19. Van Vranken, D.; Weiss, G.A. Protein Function. In *Introduction to Bioorganic Chemistry and Chemical Biology*; Garland Science: New York, NY, USA, 2020; pp. 504–547.
20. Meghwanshi, G.K.; Kaur, N.; Verma, S.; Dabi, N.K.; Vashishtha, A.; Charan, P.D.; Purohit, P.; Bhandari, H.S.; Bhojak, N.; Kumar, R. Enzymes for pharmaceutical and therapeutic applications. *Biotechnol. Appl. Biochem.* **2020**, *67*, 586–601. [CrossRef] [PubMed]
21. Foegeding, E.A.; Davis, J.P. Food protein functionality: A comprehensive approach. *Food Hydrocoll.* **2011**, *25*, 1853–1864. [CrossRef]
22. Li-Chan, E.C.Y.; Lacroix, I.M.E. Properties of proteins in food systems: An introduction. In *Proteins in Food Processing*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 1–25, ISBN 9780081007297.
23. Lam, R.S.H.; Nickerson, M.T. Food proteins: A review on their emulsifying properties using a structure-function approach. *Food Chem.* **2013**, *141*, 975–984. [CrossRef] [PubMed]
24. Gruner, P.; Riechers, B.; Semin, B.; Lim, J.; Johnston, A.; Short, K.; Baret, J.C. Controlling molecular transport in minimal emulsions. *Nat. Commun.* **2016**, *10392*, 1–9. [CrossRef] [PubMed]
25. Udgaonkar, J.B. Polypeptide chain collapse and protein folding. *Arch. Biochem. Biophys.* **2013**, *531*, 24–33. [CrossRef]
26. Wei, G.W. Multiscale, multiphysics and multidomain models I: Basic theory. *J. Theor. Comput. Chem.* **2013**, *12*, 1–34. [CrossRef]
27. Fass, D.; Thorpe, C. Chemistry and Enzymology of Disulfide Cross-Linking in Proteins. *Chem. Rev.* **2018**, *118*, 1169–1198. [CrossRef]
28. Kramer, R.M.; Shende, V.R.; Motl, N.; Pace, C.N.; Scholtz, J.M. Toward a molecular understanding of protein solubility: Increased negative surface charge correlates with increased solubility. *Biophys. J.* **2012**, *102*, 1907–1915. [CrossRef]
29. Haque, E.; Bhandari, B.R. Effects of protein conformational modifications, enthalpy relaxation, and interaction with water on the solubility of milk protein concentrate powder. In *Water Stress in Biological, Chemical, Pharmaceutical and Food Systems*; (Food Engineering Series); Springer: Berlin/Heidleberg, Germany, 2015; pp. 437–450.
30. Haque, E.; Bhandari, B.R.; Gidley, M.J.; Deeth, H.C.; Whittaker, A.K. Ageing-induced solubility loss in milk protein concentrate powder: Effect of protein conformational modifications and interactions with water. *J. Sci. Food Agric.* **2011**, *91*, 2576–2581. [CrossRef]
31. Nunes, L.; Tavares, G.M. Thermal treatments and emerging technologies: Impacts on the structure and techno-functional properties of milk proteins. *Trends Food Sci. Technol.* **2019**, *99*, 88–99. [CrossRef]
32. Takeuchi, H. Biochemical significance of regulation of protein stability by Oglucose glycans. *Seikagaku* **2018**, *90*, 519–523. [CrossRef]
33. López-Pedrouso, M.; Lorenzo, J.M.; Zapata, C.; Franco, D. Proteins and amino acids. In *Innovative Thermal and Non-Thermal Processing, Bioaccessibility and Bioavailability of Nutrients and Bioactive Compounds*; Woodhead Publishing: Sawston, UK, 2019; pp. 347–357, ISBN 9780128141748.
34. Martínez-Monteagudo, S.I.; Kamat, S.; Patel, N.; Konuklar, G.; Rangavajla, N.; Balasubramaniam, V.M. Improvements in emulsion stability of dairy beverages treated by high pressure homogenization: A pilot-scale feasibility study. *J. Food Eng.* **2017**, *193*, 42–52. [CrossRef]
35. Panagiotou, T.; Fisher, R. Improving Product Quality with Entrapped Stable Emulsions: From Theory to Industrial Application. *Challenges* **2012**, *3*, 84–114. [CrossRef]
36. Bendtsen, L.Q.; Lorenzen, J.K.; Bendsen, N.T.; Rasmussen, C.; Astrup, A. Effect of dairy proteins on appetite, energy expenditure, body weight, and composition: A review of the evidence from controlled clinical trials. *Adv. Nutr.* **2013**, *4*, 418–438. [CrossRef] [PubMed]
37. Sarkar, A.; Singh, H. Emulsions and foams stabilised by milk proteins. In *Advanced Dairy Chemistry: Volume 1B: Proteins: Applied Aspects*, 4th ed.; Springer: Berlin/Heidleberg, Germany, 2016; pp. 133–153, ISBN 9781493928002.
38. Chung, C.; McClements, D.J. Structure-function relationships in food emulsions: Improving food quality and sensory perception. *Food Struct.* **2014**, *1*, 106–126. [CrossRef]
39. Mleko, S.; Tomczyńska-Mleko, M.; Targoński, Z. Globular protein gels as carriers of active substances. *Agro Food Ind. Hi-Tech* **2010**, *21*, 26–28.
40. Liu, C.-M.; Peng, Q.; Zhong, J.-Z.; Liu, W.; Zhong, Y.-J.; Wang, F. Molecular and Functional Properties of Protein Fractions and Isolate from Cashew Nut (*Anacardium occidentale* L.). *Molecules* **2018**, *23*, 393. [CrossRef] [PubMed]
41. Huppertz, T. Foaming properties of milk: A review of the influence of composition and processing. *Int. J. Dairy Technol.* **2010**, *63*, 477–488. [CrossRef]
42. Karami, Z.; Akbari-adergani, B. Bioactive food derived peptides: A review on correlation between structure of bioactive peptides and their functional properties. *J. Food Sci. Technol.* **2019**, *56*. [CrossRef]
43. Karimi, M.; Ignasiak, M.T.; Chan, B.; Croft, A.K.; Radom, L.; Schiesser, C.H.; Pattison, D.I.; Davies, M.J. Reactivity of disulfide bonds is markedly affected by structure and environment: Implications for protein modification and stability. *Sci. Rep.* **2016**, *38572*, 1–12. [CrossRef]
44. Tavernier, I.; Wijaya, W.; Van der Meeren, P.; Dewettinck, K.; Patel, A.R. Food-grade particles for emulsion stabilization. *Trends Food Sci. Technol.* **2016**, *50*, 159–174. [CrossRef]
45. Xi, Z.; Liu, W.; McClements, D.J.; Zou, L. Rheological, structural, and microstructural properties of ethanol induced cold-set whey protein emulsion gels: Effect of oil content. *Food Chem.* **2019**, *291*, 22–29. [CrossRef]
46. Pérez-Andrés, J.M.; Charoux, C.M.G.; Cullen, P.J.; Tiwari, B.K. Chemical Modifications of Lipids and Proteins by Nonthermal Food Processing Technologies. *J. Agric. Food Chem.* **2018**, *67*, 2043–2051. [CrossRef]

47. Walstra, P. *Formation and Stability of Emulsions Made with Proteins and Peptides*; Wageningen Universiteit: Wageningen, The Netherlands, 2000.
48. Foegeding, E.A. Food Protein Functionality—A New Model. *J. Food Sci.* **2015**, *80*, 2670–2677. [CrossRef]
49. Bai, L.; Huan, S.; Gu, J.; McClements, D.J. Fabrication of oil-in-water nanoemulsions by dual-channel microfluidization using natural emulsifiers: Saponins, phospholipids, proteins, and polysaccharides. *Food Hydrocoll.* **2016**, *61*, 703–711. [CrossRef]
50. Tang, C.H. Globular proteins as soft particles for stabilizing emulsions: Concepts and strategies. *Food Hydrocoll.* **2020**, *103*, 1–15. [CrossRef]
51. Beloqui, A.; Cortajarena, A.L. Protein-based functional hybrid bionanomaterials by bottom-up approaches. *Curr. Opin. Struct. Biol.* **2020**, *63*, 74–81. [CrossRef] [PubMed]
52. Duncan, T.V. Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *J. Colloid Interface Sci.* **2011**, *363*, 1–24. [CrossRef]
53. Liu, Y.; Mai, S.; Li, N.; Yiu, C.K.Y.; Mao, J.; Pashley, D.H.; Tay, F.R. Differences between top-down and bottom-up approaches in mineralizing thick, partially-demineralized collagen scaffolds. *Acta Biomater.* **2011**, *7*, 1742–1751. [CrossRef] [PubMed]
54. Tadros, T.; Izquierdo, P.; Esquena, J.; Solans, C. Formation and stability of nano-emulsions. *Adv. Colloid Interface Sci.* **2004**, *108–109*, 303–318. [CrossRef]
55. Huang, Y.; Mei, L.; Chen, X.; Wang, Q. Recent Developments in Food Packaging Based on Nanomaterials. *Nanomaterials* **2018**, *8*, 830. [CrossRef]
56. Chatterjee, C.; Gleddie, S.; Xiao, C.W. Soybean bioactive peptides and their functional properties. *Nutrients* **2018**, *10*, 1211. [CrossRef]
57. Hirschi, K.D. Genetically Modified Plants: Nutritious, Sustainable, yet Underrated. *J. Nutr.* **2020**, *150*, 2628–2634. [CrossRef]
58. Haslberger, A.G. Codex guidelines for GM foods include the analysis of unintended effects. *Nat. Biotechnol.* **2003**, *21*, 739–741. [CrossRef] [PubMed]
59. Bawa, A.S.; Anilakumar, K.R. Genetically modified foods: Safety, risks and public concerns—A review. *J. Food Sci. Technol.* **2012**, *50*, 1035–1046. [CrossRef]
60. USDA. *Grain: World Markets and Trade*; USDA: Washington, DC, USA, 2019.
61. Nishinari, K.; Fang, Y.; Guo, S.; Phillips, G.O. Soy proteins: A review on composition, aggregation and emulsification. *Food Hydrocoll.* **2014**, *39*, 301–318. [CrossRef]
62. Fernandez-Cornejo, J.; Wechsler, S. Soybeans. In *Handbook on Agriculture, Biotechnology and Development*; Edward Elgar: Cheltenham, UK, 2014; pp. 1–880, ISBN 9780857938350.
63. Rizzo, G.; Baroni, L. Soy, soy foods and their role in vegetarian diets. *Nutrients* **2018**, *10*, 43. [CrossRef]
64. USDA. *World Agricultural Production Circular Series*; USDA: Washington, DC, USA, 2019.
65. Nuttall, J.G.; O'Leary, G.J.; Panozzo, J.F.; Walker, C.K.; Barlow, K.M.; Fitzgerald, G.J. Models of grain quality in wheat—A review. *Field Crop. Res.* **2017**, *202*, 136–145. [CrossRef]
66. Global Wheat Demand: Feeding the World by Milling and Feeding. Available online: https://research.rabobank.com/far/en/sectors/grains-oilseeds/global_wheat_demand_article_1.html (accessed on 19 July 2021).
67. Biesiekierski, J.R. What is gluten? *J. Gastroenterol. Hepatol.* **2017**, *32*, 78–81. [CrossRef] [PubMed]
68. Anjum, F.M.; Ahmad, I.; Butt, M.S.; Sheikh, M.A.; Pasha, I. Amino acid composition of spring wheats and losses of lysine during chapati baking. *J. Food Compos. Anal.* **2005**, *18*, 523–532. [CrossRef]
69. Day, L. Wheat gluten: Production, properties and application. In *Handbook of Food Proteins*; Woodhead Publishing: Sawston, UK, 2011; pp. 1–464, ISBN 9780857093639.
70. Samard, S.; Gu, B.Y.; Ryu, G.H. Effects of extrusion types, screw speed and addition of wheat gluten on physicochemical characteristics and cooking stability of meat analogues. *J. Sci. Food Agric.* **2019**, *99*, 4922–4931. [CrossRef]
71. Kumar, P.; Chatli, M.K.; Mehta, N.; Singh, P.; Malav, O.P.; Verma, A.K. Meat analogues: Health promising sustainable meat substitutes. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 923–932. [CrossRef] [PubMed]
72. Rubio-Tapia, A.; Hill, I.D.; Kelly, C.P.; Calderwood, A.H.; Murray, J.A.; American College of Gastroenterology. ACG clinical guidelines: Diagnosis and management of celiac disease. *Am. J. Gastroenterol.* **2013**, *108*, 656–676. [CrossRef] [PubMed]
73. Niland, B.; Cash, B.D. Health Benefits and Adverse Effects of a Gluten-Free Diet in Non–Celiac Disease Patients. *Gastroenterol. Hepatol.* **2018**, *14*, 82–91.
74. Fernandez, M.A.; Fisberg, M.; Marette, A. Role of yogurt in the nutrition and health of children and adolescents. In *Yogurt in Health and Disease Prevention*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 491–505, ISBN 9780128052723.
75. Badem, A.; Uçar, G. Production of caseins and their usages. *Int. J. Food Sci. Nutr.* **2017**, *2*, 4–9.
76. O'Kennedy, B.T. Caseins. In *Handbook of Food Proteins*; Elsevier: Amsterdam, The Netherlands, 2011; pp. 13–29.
77. Szpendowski, J.; Siemianowski, K. Właściwości odżywcze i funkcjonalne oraz zastosowanie kazeinianów w przetwórstwie spożywczym. *Nauki Inż. Technol. Uniw. Ekon. Wrocławiu* **2013**, *3*, 122–138.
78. Singh, H. Milk Protein Products: Functional Properties of Milk Proteins. In *Encyclopedia of Dairy Sciences: Second Edition*; Elsevier Inc.: Amsterdam, The Netherlands, 2011; pp. 887–893, ISBN 9780123744029.
79. Cirillo, G.; Spizzirri, U.G.; Iemma, F. Functional Polymers in Food Science. In *Functional Polymers in Food Science: From Technology to Biology*; Cirillo, G., Spizzirri, U.G., Iemma, F., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015; Volume 2, pp. 1–335, ISBN 9781119108580.

80. Flom, J.D.; Sicherer, S.H. Epidemiology of Cow's Milk Allergy. *Nutrients* **2019**, *11*, 1051. [CrossRef]
81. Bahna, S.L. Cow's milk allergy versus cow milk intolerance. *Ann. Allergy Asthma Immunol.* **2002**, *89*, 56–60. [CrossRef]
82. Kilara, A.; Vaghela, M.N. Whey proteins. In *Proteins in Food Processing*, 2nd ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2018; pp. 1–674, ISBN 9780081007297.
83. Yang, J.; Liu, Y.; Mu, C.; Li, Y.; Tian, H. Influence of different nutrition supplement combinations on the training effect of athlete based on component analysis. *Investig. Clin.* **2020**, *95*, 4743–4747.
84. Sharma, R. Whey proteins in functional foods. In *Whey Proteins: From Milk to Medicine*; Academic Press: London, UK, 2018; pp. 1–746, ISBN 9780128121245.
85. De Castro, R.J.S.; Domingues, M.A.F.; Ohara, A.; Okuro, P.K.; dos Santos, J.G.; Brexó, R.P.; Sato, H.H. Whey protein as a key component in food systems: Physicochemical properties, production technologies and applications. *Food Struct.* **2017**, *14*, 17–29. [CrossRef]
86. Jørgensen, C.E.; Abrahamsen, R.K.; Rukke, E.O.; Hoffmann, T.K.; Johansen, A.G.; Skeie, S.B. Processing of high-protein yoghurt—A review. *Int. Dairy J.* **2019**, *88*, 42–59. [CrossRef]
87. Iqbal, S.; Ayyub, A.; Iqbal, H.; Chen, X.D. Protein microspheres as structuring agents in lipids: Potential for reduction of total and saturated fat in food products. *J. Sci. Food Agric.* **2020**, *101*, 820–830. [CrossRef] [PubMed]
88. Nys, Y.; Sauveur, B. Valeur nutritionnelle des œufs. *Prod. Anim.* **2004**, *17*, 385–393. [CrossRef]
89. Drewnowski, A. The Nutrient Rich Foods Index helps to identify healthy, affordable foods. *Am. J. Clin. Nutr.* **2010**, *91*, 1095–1101. [CrossRef]
90. Abeyrathne, E.D.N.S.; Lee, H.Y.; Ahn, D.U. Egg white proteins and their potential use in food processing or as nutraceutical and pharmaceutical agents—A review. *Poult. Sci.* **2013**, *92*, 3292–3299. [CrossRef]
91. Réhault-Godbert, S.; Guyot, N.; Nys, Y. The Golden Egg: Nutritional Value, Bioactivities, and Emerging Benefits for Human Health. *Nutrients* **2019**, *11*, 684. [CrossRef]
92. Gharbi, N.; Labbafi, M. Effect of processing on aggregation mechanism of egg white proteins. *Food Chem.* **2018**, *252*, 126–133. [CrossRef]
93. Wu, J.; Acero-Lopez, A. Ovotransferrin: Structure, bioactivities, and preparation. *Food Res. Int.* **2012**, *46*, 480–487. [CrossRef]
94. Chiang, W.D. Protein hydrolysate batch production with angiotensin I-converting enzyme inhibitory activity from egg whites. *J. Food Drug Anal.* **2006**, *14*, 385–390.
95. Bhat, Z.F.; Kumar, S.; Bhat, H.F. Bioactive peptides from egg: A review. *Nutr. Food Sci.* **2015**, *45*, 190–212. [CrossRef]
96. Rathnapala, E.C.N.; Ahn, D.U.; Abeyrathne, S. Functional properties of ovotransferrin from chicken egg white and its derived peptides: A review. *Food Sci. Biotechnol.* **2021**, *30*, 619–630. [CrossRef]
97. Zhu, Y.; Vanga, S.K.; Wang, J.; Raghavan, V. Impact of food processing on the structural and allergenic properties of egg white. *Trends Food Sci. Technol.* **2018**, *78*, 188–196. [CrossRef]
98. Duconseille, A.; Wien, F.; Audonnet, F.; Traore, A.; Refregiers, M.; Astruc, T.; Santé-Lhoutellier, V. The effect of origin of the gelatine and ageing on the secondary structure and water dissolution. *Food Hydrocoll.* **2017**, *66*, 378–388. [CrossRef]
99. Nuñez, S.M.; Guzmán, F.; Valencia, P.; Almonacid, S.; Cárdenas, C. Collagen as a source of bioactive peptides: A bioinformatics approach. *Electron. J. Biotechnol.* **2020**, *48*, 101–108. [CrossRef]
100. Zhang, D.; Wu, X.; Chen, J.; Lin, K. The development of collagen based composite scaffolds for bone regeneration. *Bioact. Mater.* **2018**, *3*, 129–138. [CrossRef]
101. Benjakul, S.; Kittiphattanabawon, P. Gelatin. In *Encyclopedia of Food Chemistry*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 2194–2220, ISBN 9780128140451.
102. Lin, L.; Regenstein, J.M.; Lv, S.; Lu, J.; Jiang, S. An overview of gelatin derived from aquatic animals: Properties and modification. *Trends Food Sci. Technol.* **2017**, *68*, 102–112. [CrossRef]
103. Bhat, Z.F.; Kumar, S.; Bhat, H.F. Antihypertensive peptides of animal origin: A review. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 566–578. [CrossRef] [PubMed]
104. Briggs, M.; Petersen, K.; Kris-Etherton, P. Saturated Fatty Acids and Cardiovascular Disease: Replacements for Saturated Fat to Reduce Cardiovascular Risk. *Healthcare* **2017**, *5*, 29. [CrossRef] [PubMed]
105. Udenigwe, C.C.; Aluko, R.E. Food protein-derived bioactive peptides: Production, processing, and potential health benefits. *J. Food Sci.* **2012**, *77*, 11–24. [CrossRef]
106. Guruprasad, L. Protein Structure. *Resonance* **2019**, *24*, 327–338. [CrossRef]
107. Chakraborty, H.J.; Gangopadhyay, A.; Ganguli, S.; Datta, A. Protein structure prediction. In *Applying Big Data Analytics in Bioinformatics and Medicine*; IGI Global: Hershey, PA, USA, 2017; pp. 1–465, ISBN 9781522526087.
108. Lafarga, T.; Hayes, M. Bioactive protein hydrolysates in the functional food ingredient industry: Overcoming current challenges. *Food Rev. Int.* **2017**, *33*, 217–246. [CrossRef]
109. Ishak, N.H.; Sarbon, N.M. A Review of Protein Hydrolysates and Bioactive Peptides Deriving from Wastes Generated by Fish Processing. *Food Bioprocess. Technol.* **2018**, *11*, 2–16. [CrossRef]
110. Taghizadeh, M.S.; Niazi, A.; Moghadam, A.; Afsharifar, A.R. The potential application of the protein hydrolysates of three medicinal plants: Cytotoxicity and functional properties. *J. Food Sci.* **2020**, *85*, 3160–3167. [CrossRef]
111. Liceaga, A.M.; Hall, F. Nutritional, functional and bioactive protein hydrolysates. In *Encyclopedia of Food Chemistry*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 456–465, ISBN 9780128140451.

112. USDA. *United States Department of Agriculture National Agricultural Statistics Service*; USDA: Washington, DC, USA, 2018.
113. Al-Doury, M.K.W.; Hettiarachchy, N.S.; Horax, R. Rice-Endosperm and Rice-Bran Proteins: A Review. *J. Am. Oil Chem. Soc.* **2018**, *95*, 943–956. [CrossRef]
114. Khir, R.; Pan, Z. Rice. In *Integrated Processing Technologies for Food and Agricultural By-Products*; Academic Press: London, UK, 2019; pp. 1–452, ISBN 9780128141397.
115. Ferreira, S.M.R.; De Mello, A.P.; De Caldas Rosa Dos Anjos, M.; Krüger, C.C.H.; Azoubel, P.M.; De Oliveira Alves, M.A. Utilization of sorghum, rice, corn flours with potato starch for the preparation of gluten-free pasta. *Food Chem.* **2016**, *191*, 147–151. [CrossRef]
116. Han, S.W.; Chee, K.M.; Cho, S.J. Nutritional quality of rice bran protein in comparison to animal and vegetable protein. *Food Chem.* **2015**, *172*, 766–769. [CrossRef]
117. Amagliani, L.; O'Regan, J.; Kelly, A.L.; O'Mahony, J.A. The composition, extraction, functionality and applications of rice proteins: A review. *Trends Food Sci. Technol.* **2017**, *64*, 1–12. [CrossRef]
118. Małecki, J.; Tomasevic, I.; Djekic, I.; Sołowiej, B.G. The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People. *Foods* **2020**, *9*, 1467. [CrossRef] [PubMed]
119. Giménez, M.A.; Drago, S.R.; Bassett, M.N.; Lobo, M.O.; Sammán, N.C. Nutritional improvement of corn pasta-like product with broad bean (Vicia faba) and quinoa (Chenopodium quinoa). *Food Chem.* **2016**, *199*, 150–156. [CrossRef] [PubMed]
120. López, O.V.; Castillo, L.A.; García, M.A.; Villar, M.A.; Barbosa, S.E. Food packaging bags based on thermoplastic corn starch reinforced with talc nanoparticles. *Food Hydrocoll.* **2015**, *43*, 18–24. [CrossRef]
121. Loy, D.D.; Lundy, E.L. Nutritional properties and feeding value of corn and its coproducts. In *Corn: Chemistry and Technology*, 3rd ed.; Woodhead Publishing: Sawston, UK; AACC International Press: Washington, DC, USA, 2018; pp. 1–690, ISBN 9780128119716.
122. Shukla, R.; Cheryan, M. Zein: The industrial protein from corn. *Ind. Crops Prod.* **2001**, *13*, 171–192. [CrossRef]
123. Li, H.M.; Wen, L.K.; Li, S.J.; Zhang, D.L.; Lin, B.S. In vitro and in vivo effects and safety assessment of corn peptides on alcohol dehydrogenase activities. *Chem. Res. Chin. Univ.* **2011**, *11*, 1813–1835.
124. Bazile, D.; Jacobsen, S.-E.; Verniau, A. The Global Expansion of Quinoa: Trends and Limits. *Front. Plant. Sci.* **2016**, *7*, 1–6. [CrossRef]
125. Craine, E.B.; Murphy, K.M. Corrigendum: Seed Composition and Amino Acid Profiles for Quinoa Grown in Washington State. *Front. Nutr.* **2020**, *7*, 22–43. [CrossRef]
126. Sobral, J.; Amaral, P.; Menegalli, F. Comparison of starch pasting and retrogradation properties of quinoa (Chenopodium quinoa), rice, potato, cassava, wheat and corn starches. In Proceedings of the 2nd Mercosur Congress on Process Systems Engineering, Costa Verde, Brasil, January 2005; pp. 1–7.
127. Lonnie, M.; Laurie, I.; Myers, M.; Horgan, G.; Russell, W.R.; Johnstone, A.M. Exploring health-promoting attributes of plant proteins as a functional ingredient for the food sector: A systematic review of human interventional studies. *Nutrients* **2020**, *12*, 2291. [CrossRef] [PubMed]
128. Luna-Vital, D.A.; Mojica, L.; González de Mejía, E.; Mendoza, S.; Loarca-Piña, G. Biological potential of protein hydrolysates and peptides from common bean (*Phaseolus vulgaris* L.): A review. *Food Res. Int.* **2015**, *76*, 39–50. [CrossRef]
129. Mattila, P.; Mäkinen, S.; Eurola, M.; Jalava, T.; Pihlava, J.M.; Hellström, J.; Pihlanto, A. Nutritional Value of Commercial Protein-Rich Plant Products. *Plant. Foods Hum. Nutr.* **2018**, *73*, 108–115. [CrossRef]
130. Samtiya, M.; Aluko, R.E.; Dhewa, T. Plant food anti-nutritional factors and their reduction strategies: An overview. *Food Prod. Process. Nutr.* **2020**, *2*, 1–14. [CrossRef]
131. Scheelbeek, P.F.D.; Bird, F.A.; Tuomisto, H.L.; Green, R.; Harris, F.B.; Joy, E.J.M.; Chalabi, Z.; Allen, E.; Haines, A.; Dangour, A.D. Effect of environmental changes on vegetable and legume yields and nutritional quality. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 6804–6809. [CrossRef] [PubMed]
132. Figueira, N.; Curtain, F.; Beck, E.; Grafenauer, S. Consumer Understanding and Culinary Use of Legumes in Australia. *Nutrients* **2019**, *11*, 1575. [CrossRef]
133. Van de Noort, M. Lupin: An Important Protein and Nutrient Source. In *Sustainable Protein Sources*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 1–456, ISBN 9780128027769.
134. Villarino, C.B.J.; Jayasena, V.; Coorey, R.; Chakrabarti-Bell, S.; Johnson, S.K. Nutritional, Health, and Technological Functionality of Lupin Flour Addition to Bread and Other Baked Products: Benefits and Challenges. *Crit. Rev. Food Sci. Nutr.* **2016**, *56*, 835–857. [CrossRef]
135. Gorissen, S.H.M.; Crombag, J.J.R.; Senden, J.M.G.; Waterval, W.A.H.; Bierau, J.; Verdijk, L.B.; van Loon, L.J.C. Protein content and amino acid composition of commercially available plant-based protein isolates. *Amino Acids* **2018**, *50*, 1685–1695. [CrossRef]
136. Czubinski, J.; Feder, S. Lupin seeds storage protein composition and their interactions with native flavonoids. *J. Sci. Food Agric.* **2019**, *99*, 4011–4018. [CrossRef] [PubMed]
137. González-Pérez, S. Sunflower Proteins. In *Sunflower: Chemistry, Production, Processing, and Utilization*; Academic Press: London, UK; AOCS Press: Urbana, IL, USA, 2015; pp. 1–728, ISBN 9781630670627.
138. FAOSTAT. Available online: http://www.fao.org/faostat/en/#data (accessed on 25 July 2021).
139. González-Pérez, S.; Vereijken, J.M. Sunflower proteins: Overview of their physicochemical, structural and functional properties. *J. Sci. Food Agric.* **2007**, *87*, 2173–2191. [CrossRef]

140. Wahlstrom, R.C. Sunflower seeds. In *Non-Traditional Feeds for Use in Swine Production (1992)*; Butterworths: Stoneham, MA, USA, 2017; pp. 1–528, ISBN 9781351359795.
141. WHO. *Protein and Amino Acid Requirements in Human Nutrition. Report of a Joint WHO/FAO/UNU Expert Consultation*; WHO: Geneva, Switzerland, 2007.
142. Collins, C.M.; Vaskou, P.; Kountouris, Y. Insect Food Products in the Western World: Assessing the Potential of a New "Green" Market. *Ann. Entomol. Soc. Am.* **2019**, *112*, 518–528. [CrossRef] [PubMed]
143. Chakravarthy, A.K.; Jayasimha, G.T.; Rachana, R.R.; Rohini, G. Insects as human food. In *Economic and Ecological Significance of Arthropods in Diversified Ecosystems: Sustaining Regulatory Mechanisms*; Springer: Singapore, 2016; pp. 133–146, ISBN 9789811015243.
144. Rumpold, B.A.; Schlüter, O. Insect-based protein sources and their potential for human consumption: Nutritional composition and processing. *Anim. Front.* **2015**, *5*, 20–24. [CrossRef]
145. Sun-Waterhouse, D.; Waterhouse, G.I.N.; You, L.; Zhang, J.; Liu, Y.; Ma, L.; Gao, J.; Dong, Y. Transforming insect biomass into consumer wellness foods: A review. *Food Res. Int.* **2016**, *89*, 129–151. [CrossRef] [PubMed]
146. Turck, D.; Castenmiller, J.; De Henauw, S.; Hirsch-Ernst, K.I.; Kearney, J.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; Pelaez, C.; et al. Safety of dried yellow mealworm (Tenebrio molitor larva) as a novel food pursuant to Regulation (EU) 2015/2283. *EFSA J.* **2021**, *19*, 6343–6372. [CrossRef]
147. Huang, C.; Feng, W.; Xiong, J.; Wang, T.; Wang, W.; Wang, C.; Yang, F. Impact of drying method on the nutritional value of the edible insect protein from black soldier fly (*Hermetia illucens* L.) larvae: Amino acid composition, nutritional value evaluation, in vitro digestibility, and thermal properties. *Eur. Food Res. Technol.* **2019**, *245*, 11–21. [CrossRef]
148. Payne, C.L.R.; Scarborough, P.; Rayner, M.; Nonaka, K. A systematic review of nutrient composition data available for twelve commercially available edible insects, and comparison with reference values. *Trends Food Sci. Technol.* **2016**, *47*, 69–77. [CrossRef]
149. Lamsal, B.; Wang, H.; Pinsirodom, P.; Dossey, A.T. Applications of Insect-Derived Protein Ingredients in Food and Feed Industry. *JAOCS J. Am. Oil Chem. Soc.* **2019**, *96*, 1–17. [CrossRef]
150. De Castro, R.J.S.; Ohara, A.; dos Santos Aguilar, J.G.; Domingues, M.A.F. Nutritional, functional and biological properties of insect proteins: Processes for obtaining, consumption and future challenges. *Trends Food Sci. Technol.* **2018**, *76*, 82–89. [CrossRef]
151. Taboada, M.C.; Millán, R.; Miguez, M.I. Nutritional value of the marine algae wakame (Undaria pinnatifida) and nori (Porphyra purpurea) as food supplements. *J. Appl. Phycol.* **2012**, *25*, 1271–1276. [CrossRef]
152. Chronakis, I.S.; Madsen, M. Algal proteins. In *Handbook of Food Proteins*; Woodhead Publishing: Sawston, UK, 2011; pp. 353–394.
153. Kadam, S.U.; Tiwari, B.K.; O'Donnell, C.P. Application of novel extraction technologies for bioactives from marine algae. *J. Agric. Food Chem.* **2013**, *61*, 4667–4675. [CrossRef]
154. Wells, M.L.; Potin, P.; Craigie, J.S.; Raven, J.A.; Merchant, S.S.; Helliwell, K.E.; Smith, A.G.; Camire, M.E.; Brawley, S.H. Algae as nutritional and functional food sources: Revisiting our understanding. *J. Appl. Phycol.* **2017**, *29*, 949–982. [CrossRef]
155. Vigani, M.; Parisi, C.; Rodríguez-Cerezo, E.; Barbosa, M.J.; Sijtsma, L.; Ploeg, M.; Enzing, C. Food and feed products from micro-algae: Market opportunities and challenges for the EU. *Trends Food Sci. Technol.* **2015**, *42*, 81–92. [CrossRef]
156. MacArtain, P.; Gill, C.I.R.; Brooks, M.; Campbell, R.; Rowland, I.R. Nutritional Value of Edible Seaweeds. *Nutr. Rev.* **2008**, *65*, 535–543. [CrossRef]
157. Bleakley, S.; Hayes, M. Algal Proteins: Extraction, Application, and Challenges Concerning Production. *Foods* **2017**, *6*, 33. [CrossRef] [PubMed]
158. Berrazaga, I.; Micard, V.; Gueugneau, M.; Walrand, S. The role of the anabolic properties of plant-versus animal-based protein sources in supporting muscle mass maintenance: A critical review. *Nutrients* **2019**, *11*, 1825. [CrossRef] [PubMed]

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The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People

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Abstract: The purpose of this study was to investigate the effect of protein sources (algae, pumpkin, wheat, sunflower, rice, soy, hemp, pea, and whey) on selected physicochemical, nutritional, and structural parameters of high-protein bars. Texture properties, such as hardness, fracturability, cohesiveness, and adhesiveness, have changed depending on the type of protein used. A significant increase, in particular the hardness parameter relating to the control sample (whey protein concentrate—WPC80), was noted for bars containing algae, sunflower, and wheat proteins, with high values of the adhesiveness parameter concurrently. The use of proteins from algae, pea, and wheat resulted in a significant reduction in the water activity of the finished product compared to WPC80. Bars made with the use of wheat, hemp and pumpkin proteins had noticeably higher viscosities than other samples. Color of the tested bars measured by means of Computer Vision System (CVS) was from light cream (soy, pea) to dark green (hemp, pumpkin). Bars prepared of wheat and algae proteins had the highest nutritional value, while the lowest one was recorded in products containing sunflower and hemp proteins. There was a clear differentiation of amino acids (g/100 g) and microstructure in bars depending on the type of protein used. However, a slight similarity can be found between whey and soy proteins (amino acids) and between whey and sunflower proteins (microstructure). Obtained results suggest that selection of the right type of protein for a given application may have a significant impact on the physicochemical features and microstructure of high-protein bars and their nutritional values.

Keywords: animal and plant proteins; computer vision system; nutritional value; texture; water activity; viscosity; microstructure; heavy metals; amino acids

1. Introduction

High-protein products, including bars, have recently become extremely popular. In particular, since products enriched in protein or in which protein is the main ingredient, can be used in products intended for a wide group of consumers [1].

This type of product can be used in the segment of quick snacks (designed to temporarily satisfy hunger), in sports nutrition (muscle tissue growth) or products intended for nutrition of the elderly

and sick people who are at risk of developing sarcopenia [2]. As a result of such a large interest in high-protein products on the market, manufacturers meet the consumers' requirements and constantly develop recipes for innovative products that can be part of current trends in healthy and functional nutrition [3]. For this purpose, manufacturers searching for suitable alternatives to commonly used ingredients, such as high fructose and glucose syrups, fats or allergenic proteins, into their alternative components, e.g., polyols, fructo-oligosaccharides, or different protein sources (plant and animal proteins), while maximizing maintaining the technological parameters of the production process. Products resulting from such activities can be of particular interest to people using different types of diets [4,5].

High-protein bars most commonly found on the store shelves contain a small range of proteins of both plant (primarily soy protein concentrates and isolates) and animal origin (especially whey protein concentrates and isolates). It was found that the addition of whey protein hydrolysates used in the application of high-protein bars has a positive effect on maintaining the soft structure of these products, but may affect the slightly bitter aftertaste [6]. Whey derivatives, such as concentrates or isolates, are abundant sources of proteins, in particular alpha-lactalbumin and beta-lactoglobulin. In the food industry, proteins of this type are widely used because of their high nutritional value, desirable sensory properties (milk flavor), and excellent functional properties [7]. For some time, however, there has been a sharp increase in interest in alternative protein sources (especially plant proteins) that could compete with the commonly used WPC protein in terms of physicochemical, textural or nutritional features [8].

Recently, plant proteins have been increasingly used as an economical and versatile alternative replacing animal source in human nutrition, as well as functional ingredients for product formulation. Animal protein presents growing costs and limited supply, which has been highly associated with climate change, freshwater depletion, biodiversity loss, and hazards for human health related to cardiovascular diseases etc. [9]. In addition, the use of plant proteins in food applications (including high-protein bars) may also increase the interest in these products among vegans, vegetarians, and people with an active lifestyle [10].

Examples of proteins that are not currently used on a large scale in Europe are e.g., sunflower, wheat, algae, hemp, and rice proteins. Sunflower seed is one of five major oil sources in the world. The defatted sunflower meals have relatively high content of protein, and have great economic value as a food additive. Due to low amounts of anti-nutritive compounds and no toxic substances found in these raw materials, they can be counted as a promising source for food proteins [11]. Sunflower protein may potentially be a functional protein due to relatively good solubility. It is often a by-product of oil extraction, which is usually denatured during processing and has reduced solubility and functionality. If protein fractions are isolated without being denatured, sunflower proteins may become soluble over a range of ionic strength and pH [10].

The wheat protein isolates are currently of special interest to processors and consumers due to low fat content and as a substitute for egg and dairy proteins. The major functional properties of wheat proteins are: hydration, foaming, improve sheeting properties of dough, light, and floppy texture as well as clean flavor [12]. Algae proteins have been valued around the world since the dawn of time for their nutritional value. Currently, there is an increasing interest in proteins of this origin also due to their functional and health-promoting properties (anti-inflammatory or enriching agents) [13]. Hemp proteins are characterized by a number of pro-health and pharmacological properties e.g., they affect the angiotensin I-converting enzyme (ACE) inhibition, renin inhibition, acetylcholinesterase (AChE) inhibition, metal-binding capacity, antioxidant activity, hypocholesterolemic effect, and serum glucose regulation and have significant amounts of arginine and glutamine [8].

Rice protein is gaining a lot of interest in the food industry due to its unique properties. Moreover, hydrolysis of protein with proteases could produce many potential peptide sequences providing numerous functional and antioxidative properties. It could also enhance the antioxidative properties of native protein by attacking the peptide bonds in the interior of polypeptide chains producing a range of polypeptides that differ in molecular weight or amino acid sequences [14].

Pumpkin proteins are an opportunity to use the large amounts of waste generated during the pumpkin seed oil pressing process. The oil cake obtained as a result of the process has a significant amount of amino acids. Moreover, the nutritional value of the protein preparations obtained from pumpkin is very high, and can be used to improve the nutritional value of food products [15,16].

Soy protein isolates (SPIs) are widely used in the food industry. Owing to the amphipathic (hydrophilic and hydrophobic) nature of soy proteins, SPI possess a favorable capacity to being adsorbed onto the oil-water or air-water interface and maintaining the structure of the corresponding system as stabilizers, i.e., SPI have good foaming and emulsifying abilities. Due to these properties and high nutritional value, low price, and availability, soy proteins are widely used [17].

Pea protein is one such protein that has garnered a great deal of interest based on its low allergenicity, high nutritional value, availability, and low cost. Similar to other plant proteins. However, challenges in utilizing pea protein as a food ingredient exist in terms of limitations in functionality, flavor, and color issues. Pea proteins contain high levels of lysine, but tend to be limiting in methionine and tryptophan. Accordingly, pea proteins are often consumed along with cereal grains, as they have a complementary essential amino acid profile in that cereal proteins are generally deficient in lysine but contain higher levels of sulfur amino acids (methionine, cysteine) [18].

Due to the characteristics of these proteins declared by the producers (nutritional value, content of saturated fatty acids, amino acid composition, fragmentation, etc.), they may be particularly interesting in research on WPC substitutes.

Texture is one of the most important parameters that determines whether a product will be positively assessed by consumers and whether the customer will decide to buy a given product many times [19]. The degree of hardness in protein bars is directly correlated with the concentration of proteins used in the recipe. Too little protein may cause the formation of a liquid and ductile bar mass. On the other hand, overdosing the protein in the application will result in a loose and crumbling structure [20]. However, depending on the type of protein used, these parameters may differ from one other.

The purpose of this article is to discuss the broadly understood physicochemical, textural, microstructural, nutritional, and sensory properties of proteins that may be alternatives to WPC proteins and their possible declarations in accordance with applicable European Union (EU) legislation. According to our current available knowledge, there is no research on ultrasonic viscosity and determining the color differences by Computer Vision System (CVS) for application of high-protein bars. Also, the use of alternative protein sources e.g., algae, pumpkin, hemp, sunflower or wheat in production of high-protein bars is limited. Therefore, the objective of this study was to evaluate the effect of different protein sources (algae, pumpkin, wheat, sunflower, rice, soy, hemp, pea, whey) on selected physicochemical, nutritional, and structural parameters of high-protein bars.

2. Materials and Methods

2.1. Materials

Whey protein concentrate (WPC—80% proteins, 7.4% fat, 4.1% carbohydrates, granule size: <200 µm) was supplied by Polser Sp. z o. o. (Toruń, Poland), soy protein isolate (SPI—87% proteins, 3.1% fat, less than 1% carbohydrates, granule size: <200 µm) was purchased from Solae, pea protein isolate (PAP—82% proteins, 4% fat, 0.8% carbohydrates, granule size: <200 µm) was a product of Cosucra (Warcoing, Belgium), rice protein concentrate (RPC—80% proteins, 1% fat, 6% carbohydrates, granule size: <300 µm) was supplied by Barentz (Warsaw, Poland), wheat protein concentrate (WHP—77% proteins, 4% fat, 4% carbohydrates, granule size: <250 µm) was received from Cargill Polska (Warsaw, Poland), whole algal protein (ALP—60% proteins, 11% fat, 19% carbohydrates, granule size: <600 µm) was a product of TerraVia (San Francisco, CA, USA), sunflower protein (SUP—55% proteins, 2% fat, 9% carbohydrates, granule size: <200 µm), hemp protein (HMP—50% proteins, 10% fat, 5% carbohydrates, granule size: <500 µm) and pumpkin protein (PMP—60% proteins, 13% fat,

3% carbohydrates, granule size: <500 µm) were purchased from All Organic Trading (Wiggensbach, Germany), glucose syrup (Dextrose Equivalent "DE"40) was a product of Amylon (Havlíčkův Brod, Czech Republic), vegetable oil (rapeseed oil) was a product of ZT "Kruszwica" S.A. (Kruszwica, Poland), maltodextrin (Dextrose Equivalent "DE" 15) was purchased from Amylon (Havlíčkův Brod, Czech Republic), powdered barley malt extract was a product of Mountons Ingredients (European Brewery Convention "EBC" color: 5 to 12), soy lecithin (Identity Preserved "IP" 50) was supplied by Brenntag (Kędzierzyn-Koźle, Poland), natural vanilla aroma in powder was received from GBD Aromaty (Warsaw, Poland), chocolate was a product of Barry Callebaut (Łódź, Poland).

2.2. Preparation of High-Protein Bars

Protein concentrates (38.18%, *w*/*w*) with maltodextrin (5.45%, *w*/*w*) and aroma (0.91%, *w*/*w*) were placed in a bowl and mixed using the B10A industrial mixer (Technologies 4ALL Sp. z o. o. Sp. k.; Kępno, Poland) for 1 min at 190 rpm. Barley malt extract (3.64%, *w*/*w*) was dissolved in water (5.45%, *w*/*w*) in a separate laboratory vessel. In another vessel, soy lecithin (0.91%, *w*/*w*) and rapeseed oil (13.64%, *w*/*w*) were combined. Glucose syrup (31.82%, *w*/*w*) was heated to 80 °C and then poured into dry ingredients placed in the mixer bowl. The remaining ingredients prepared earlier were added simultaneously after pouring the syrup. The mass prepared in this way was mixed for 5 min at 365 rpm using an oar end. Finished processed high-protein bars mass were laid onto the conveyor belt using the CONBAR 600 (SOLLICH GmbH & Co. KG, Bad Salzuflen, Germany) and pulled out by forming rollers to a height of 15 mm. The height-adjusted bar mass was then cooled to a temperature of 10 °C for 15 min using the CONBAR 600 cooling tunnel. The chilled bar mass was subjected to longitudinal cutting using the CONBAR 600 longitudinal slitter. The longitudinally cut mass was finally cut transversely into individual bars (95 × 30 mm) using the CONBAR 600 transverse guillotine. The bars prepared in this way, which were to be coated with chocolate, were transferred to the coating machine, and they were covered with chocolate (22%, *w*/*w*) using the DK3520 (A.E. NIELSEN Maskinfabrik ApS., Farum, Denmark). Chocolate had a temper index (TI) oscillating in the range of 5.0–5.5. The parameter was measured using the Temper meter RET-250TMK (ELMI Automatic Systems, Warsaw, Poland). Chocolate coated bars were cooled to a temperature of 10 °C for 15 min using the DK3520 A.E. NIELSEN cooling tunnel. The final high-protein bars were packed in high barrier foil using a manual impulse sealer PFS 200 (NOVUMPACK, Kraków, Poland). The samples were stored at room temperature for 3 weeks in a plastic container. After the storage period, the samples were tested. The bar samples were unpacked from the foil 5 min before measurements. Cylindrical blocks of equal size (height: 15 mm, diameter: 12 mm) were punched out to analyze the texture of bars. To determine water activity and viscosity, the sample was prepared in the same way by weighing 6 g of sample for testing. Every high-protein bar sample was prepared in twenty repetitions. A total of 180 samples were tested considering all tests. The composition of tested high-protein bars without and with chocolate coating are presented in Table 1.

Table 1. Composition of high-protein bars.

Composition of High-Protein Bars without Chocolate Coating	
Ingredient	**Percentage Content in Final Product (% *w*/*w*)**
Protein ingredient (WPC, SPI, PAP, RPC, WHP, ALP, SUP, HMP or PMP)	38.18
Glucose syrup	31.82
Rapeseed oil	13.64
Maltodextrin	5.45
Water	5.45
Barley malt extract	3.64
Soy lecithin	0.91
Vanilla flavor (aroma)	0.91
Composition of High-Protein Bars with Chocolate Coating	
Ingredient	**Percentage Content in Final Product (% *w*/*w*)**
Protein ingredient (WPC, SPI, PAP, RPC, WHP, ALP, SUP, HMP or PMP)	30.2
Glucose syrup	25.0
Rapeseed oil	10.8
Maltodextrin	4.3
Water	4.3
Barley malt extract	2.9
Soy lecithin	0.7
Vanilla flavor (aroma)	0.7
Chocolate	21.1

2.3. Texture Profile Analysis (TPA)

Texture measurements were carried out on TA-XT2i Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK) coupled with the Software Texture Expert. The test velocity was 1 mm/s. The high-protein bars were twice compressed by a 36 mm diameter probe (SMS P/36R) to achieve 70% deformation (interval between probe movements: 5 s). High-protein bar samples were evaluated for hardness, fracturability, adhesiveness, and cohesiveness. Analyses were carried out in five replications for each sample. The hardness value was determined as the peak force occurring during the first compression. Fracturability point was occurred where the plot has its first significant peak (where the force falls off) during the probe's first compression of the product. Adhesiveness was calculated using the area over the negative stress–strain curve after the first compression, which represents the work per unit volume. Cohesiveness was defined as the ratio of the area under the second compression curve to the area under the first compression.

2.4. Cutting Test

Cutting strength of high-protein bars was measured using Texture Analyzer (TA-XT2i). The blade set with knife (HDP/BSK) comprising a Warner Bratzler blade (a reversible blade with knife edge) with a slotted blade insert and a blade holder was used for the experiment. In operation, the blade was firmly held employing blade holder, which was screwed directly to the texture analyzer. The slotted blade insert was placed directly onto the heavy-duty platform and acted as a guide for the blade whilst providing support for the product. High-protein bars were placed on the metal plate. Then the blade was lowered at a speed of 2 mm/s. The cutting curve was obtained by recording the maximum force the blade needs to cut the sample completely. Five repetitions were applied for each formulation. The results were based on the maximum peak (maximum force) resulting from the shear stress.

2.5. Water Activity

Water activity (a_w) was measured using the AWMD-10 water activity meter (NAGY, Gäufelden, Germany) with the accuracy of ±0.001 of a_w unit. Before measurement, the apparatus was calibrated with the dedicated humidity standard (95% HR). Measurements were performed at the temperature of 25 °C, in five repetitions. For each sample, two outliers were classified as defective and were excluded from further analysis.

2.6. Computer Vision System (CVS) and Determining Color Differences

Computer Vision System (CVS) was applied according to Tomasevic et al. [21] with the use of Sony Alpha DSLR-A200 digital camera (10.2 Megapixel CCD sensor, SONY, Tokio, Japan). The color was expressed in terms of the International Commission on Illumination (CIELAB) color space with the coordinates being L* (0–100, estimation of lightness), a* (red-green) and b* (yellow-blue) [22]. The noted differences could be described as "marked changes" according to the NBS (National Bureau of Standard) reference scale, which implies that such changes are perceptible to the human eye.

The total color difference was calculated using the formula:

$$\Delta E = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2 + (L_1 - L_2)^2}$$

Moreover, the ΔE* values were converted into National Bureau of Standards (NBS) units by the equation [23]:

$$\text{NBS units} = \Delta E \times 0.92$$

2.7. Ultrasonic Viscosity

The dynamic viscosity of high-protein bars was measured using an ultrasonic viscometer Unipan type 505 (UNIPAN, Warsaw, Poland). Measurements of the viscosity were performed at 25 °C. Prior to each measurement, the ultrasound signal level was checked. The measuring probe was immersed completely in the high-protein bar. The results were read in mPas·g/cm^3. All measurements were performed in three repetitions.

Viscosity tests using ultrasounds rely on the use of a magnetostrictive probe, which produces free vibration [24]. An alternating electric current generates an alternating magnetic field that causes the phenomenon of magnetostriction, i.e., the deformation of ferromagnetic materials. Induced ultrasound waves are damped by the tested material. Ultrasound viscometers display the result as the product of viscosity and density [25]. Ultrasonic viscometer viscosity measurements are performed at high frequency, and for this reason, it is not easy to compare the obtained results with those obtained using other viscometers. In addition, ultrasonic viscometers are used for continuous measurements of viscosity under conditions where measurements can be difficult and it is not possible to use devices such as rotational viscometers [26].

2.8. Nutritional Value

Nutritional value was calculated based on raw material specifications obtained from suppliers of each of the ingredients, which was introduced into the program. Then the recipe was entered into the X-mart (X-mart Group Sp. z o. o., Lublin, Poland) software and the nutritional value of the finished product was calculated per 100 g.

2.9. Sensory Evaluation

A panel of 15 trained consumers was recruited from EUROHANSA Sp. z o. o. The criteria for selection were that the panelists should be between 18 and 60 years old and regular consumers of high-protein bars and not allergic to any raw material used. Panelists were instructed to evaluate the sensorial attributes; color, aroma, consistency and taste. A 5-point hedonic scale (1 = extremely dislike,

5 = extremely like) with significance factors (0.2—color, 0.2—aroma, 0.25—consistency and 0.35—taste) was used [27,28].

2.10. Heavy Metals Analysis

The obtained samples were grounded and about 0.5 g of the sample were weighed from the homogeneous mass on an analytical balance with an accuracy of 0.0001 g. After the tubes were closed, they were transferred to the mineralizer rotor. The mineralization was carried out in a CEM Mars Xpress microwave oven at the temperature of 210 °C and pressure of about 7 atm. The obtained clear mineralizates were quantitatively transferred to 50 cm^3 volumetric flasks and diluted with demineralized water (conductivity 0.055 μS/cm) to the mark. The obtained solutions were analyzed on an inductively coupled plasma mass spectrometer (ICP Mass Spectrometer Varian MS-820, Santa Clara, CA, USA). The gas used to generate the plasma was argon from Messer with a purity of 99.999%. No reaction chamber (CRI) was used in the analysis. The following camera settings were used: Plasma Flow—16 dm^3/min., Flow Nebulizer—0.98 dm^3/min., RF Power—1.38 kW, Sampling Depth—6.5 mm. The following isotopes of the analyzed elements were used: ^{114}Cd, ^{206}Pb, ^{207}Pb, ^{208}Pb.

The determination was made using the standard curve method. Ultra Scientific standards with a purity of 99.999% were used for the analysis. The results obtained are expressed in mg/kg fresh weight. Test quality control during the analysis was applied by measuring blank, duplicate and certified reference material "NIST-1577c Bovine Liver".

2.11. Amino Acids Determination

The sample (approx. 70 mg of pure protein) was hydrolyzed with 6 N HCl at 110 °C for 20 h. After cooling, the solution with the sample was filtered through a G-5 funnel. 4 mL of the hydrolysate was evaporated in a vacuum evaporator. The dry residue from the vacuum flask was dissolved in 5 mL of citrate buffer pH 2.2. The prepared sample was dispensed onto the amino acid analyzer column [29].

Separation of sulfur amino acids was performed as follows: cysteine was oxidized to cysteic acid, and methionine to methionine sulfone using performic acid. The mixture was then flooded with 1 mL of 40% HBr and concentrated in a vacuum evaporator. It was then quenched with 6 N HCl and hydrolyzed at 110 °C for 20 h. Further procedure was the same as for protein amino acids [30].

To determine tryptophan, the sample was subjected to alkaline hydrolysis. The sample weight containing approx. 75 mg of protein was hydrolyzed in $Ba(OH)_2$ solution at 110 °C for 20 h. The sample was then acidified with 6 N HCl and a Na_2SO_4 solution was added. The contents were transferred to centrifuge flasks and centrifuged for 15 min at 3000× *g*. The supernatant, after filtering through a syringe filter, was dosed into the amino acid analyzer.

Amino acids were determined with the AAA 400 amino acid analyzer from Ingos (Prague, Czech Republic). Amino acids were separated through ion exchange chromatography. The column with dimensions of 0.37 × 45 cm was filled with an ion exchanger in the form of a resin. LG ANB ostium was used for the hydrolysates. It is a strong cation exchanger with an average grain size of approx. 12 μm in the form of Na (column temperatures 60 °C and 74 °C). The apparatus detects the amino acids by ninhydrin derivative (this is the detection reagent). The identification of the amino acids was performed by a photometric detector at a wavelength of 570 nm for all amino acids, while for proline—440 nm. Four buffers were used for separation: 1—pH 2.6, 2—pH 3.0, 3—pH 4.25, 4—pH 7.9. After the amino acid separation, the column was regenerated using 0.2 N NaOH.

2.12. Scanning Electron Microscopy (SEM)

The samples were placed in a 4% aqueous glutaraldehyde solution at room temperature for 2 h and then transferred to a refrigerator at ca. 4 °C for 6 h. After this time, the samples were placed in Sörensen's phosphate buffer pH 7.0 and left overnight. After removing from the buffer and washing twice in distilled water, the samples were dehydrated in an acetone series. Concentrations of acetone solutions (p.a.), to which the samples were successively transferred, were: 15, 30, 50, 70, 90, 100%.

The samples were kept for 30 min in each of the solutions. At the end of the dehydration process, the samples were placed in anhydrous acetone dried on silica gel for 30 min. The last stage was carried out twice. For final removal of residual water, the material was subjected to critical point drying with carbon dioxide in an Emitech K-850 dryer (Ashford, UK). Microscope tables were prepared with a carbon substrate placed on them and dried samples of bars were attached to it. The prepared gold was sputtered with an Emitech K-550X sputter (Ashford, UK). After the preparation was completed, the obtained material was placed in a Tescan Vega LMU (Brno, Czech Republic) scanning electron microscope and examined under high vacuum.

2.13. Statistical Analysis

Statistical analysis was carried out with a help of the STATISTICA 13.3 PL software (Stat Soft Polska Sp. z o. o., Kraków, Poland). A one-way ANOVA analysis was performed, and significant differences between samples were determined applying the Tukey *post hoc* test at $p < 0.05$.

3. Results and Discussion

3.1. Texture Profile Analysis (TPA), Cutting Test and Scanning Electron Microscopy (SEM)

The influence of different proteins on hardness, fracturability, adhesiveness, and cohesiveness of the obtained processed high-protein bars with or without chocolate coating is presented in Table 2a,b. Significant differences ($p < 0.05$) were observed. The bar made of sea algae proteins (ALP) had the highest hardness (276.43 N with chocolate and 288.50 N without chocolate coating) in both cases, while the lowest hardness characterized bars made from pea protein (PAP) in the sample without chocolate (13.62 N) and made from rice protein (RPC) in the sample with chocolate coating (20.95 N).

Table 2. Effect of different protein application on high-protein bars texture attributes. (**a**) Data are presented as means ± SD (standard deviation). $^{a–h}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's honest significant difference "HSD" test). (**b**) Data are presented as means ± SD (standard deviation). $^{a–i}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's HSD test).

(a)

Type of Protein Used in Bars with Chocolate Coating	Texture Attributes			
	Hardness (N)	Fracturability (N)	Adhesiveness (J)	Cohesiveness
WPC	54.66 ^{e} ± 0.303	0.06 ^{a} ± 0.005	382.87 ^{g} ± 4.977	0.14 ^{f} ± 0.001
RPC	20.95 ^{a} ± 0.164	0.06 ^{a} ± 0.004	57.54 ^{c} ± 2.588	0.07 ^{c} ± 0.001
SPI	25.25 ^{c} ± 0.358	20.85 ^{b} ± 0.152	66.85 ^{c} ± 1.773	0.04 ^{a} ± 0.004
SUP	136.61 ^{g} ± 0.406	115.56 ^{f} ± 0.255	225.61 ^{f} ± 4.861	0.10 ^{de} ± 0.001
WHP	88.33 ^{f} ± 0.092	55.38^{e} ± 0.288	123.42 ^{d} ± 3.724	0.11 ^{e} ± 0.004
HEP	27.74 ^{d} ± 0.152	0.03 ^{a} ± 0.005	27.15 ^{b} ± 2.528	0.13 ^{f} ± 0.003
PAP	27.44 ^{d} ± 0.302	25.86 ^{d} ± 0.461	145.78 ^{e} ± 4.853	0.06 ^{b} ± 0.002
PMP	23.52 ^{b} ± 0.338	23.27 ^{c} ± 0.215	7.34 ^{a} ± 0.392	0.09 ^{d} ± 0.004
ALP	276.43 ^{h} ± 0.286	0.13 ^{a} ± 0.012	129.67 ^{d} ± 0.577	0.19 ^{g} ± 0.008

(b)

Type of Protein Used in Bars without Chocolate Coating	Texture Attributes			
	Hardness (N)	Fracturability (N)	Adhesiveness (J)	Cohesiveness
WPC	34.53 ^{f} ± 0.277	0.30 ^{a} ± 0.024	56.23 ^{d} ± 4.336	0.12 ^{d} ± 0.001
RPC	18.64 ^{c} ± 0.327	0.11 ^{a} ± 0.018	34.16 ^{c} ± 2.166	0.05 ^{b} ± 0.001
SPI	16.38 ^{b} ± 0.201	16.39 ^{b} ± 0.306	5.88 ^{a} ± 0.681	0.03 ^{a} ± 0.002
SUP	149.19 ^{h} ± 0.198	122.52 ^{e} ± 0.439	16.23 ^{b} ± 2.171	0.15 ^{e} ± 0.001
WHP	81.31 ^{g} ± 0.172	0.08 ^{a} ± 0.004	130.15 ^{e} ± 2.157	0.22 ^{g} ± 0.010
HEP	21.50 ^{e} ± 0.170	35.59 ^{c} ± 0.450	3.37 ^{a} ± 0.479	0.09 ^{c} ± 0.006
PAP	13.62 ^{a} ± 0.246	36.81 ^{d} ± 0.217	1.69 ^{a} ± 0.246	0.06 ^{b} ± 0.004
PMP	19.67 ^{d} ± 0.167	0.03 ^{a} ± 0.004	322.85 ^{f} ± 2.695	0.21 ^{g} ± 0.006
ALP	288.50 ^{i} ± 0.326	0.07 ^{a} ± 0.004	27.79 ^{c} ± 2.947	0.17 ^{f} ± 0.002

Sensory hardness can be defined as the force necessary to compress a high-protein bar with the molars. Fracturability is the tendency of a material to fracture, crumble, crack, shatter or fail upon the application of a relatively small amount of force or impact. Adhesiveness is the work/force necessary to overcome the attractive forces between the surface of a product and the surface of a material (the probe), with which the product comes in contact. Cohesiveness is the tendency of a product to cohere or stick together [31]. Generally, hardness of high-protein bars is quite high and increases with the addition of protein [32]. The developed high-protein bars are characterized by large variety of parameters. Considering the research of Banach et al. [33], a certain regularity can be noted for bars made of whey proteins. Relatively low value of the hardness parameter translates into high values of the adhesiveness and cohesiveness, and simultaneously low levels of fracturability. A completely different situation can be seen for algae protein. Despite the high hardness of the bar made of this type of protein, high values of the adhesiveness and cohesiveness parameters as well as very low fracturability values were observed in the chocolate-coated bar. The results obtained from the research on a bar made of sunflower proteins (SUP) also deserve attention due to relatively high level of all TPA parameters, in particular in the chocolate-coated sample. The intermolecular attraction, by which the elements of a body or mass of material are held together, determine its cohesiveness [34]. Banach et al. [35] found a connection between the hardness of bars and the size of the protein particles used in the recipe for making those bars. Based on the analysis of results in the Table 2a,b and pictures of the microstructure of bars (Figure 1), it can be assumed that proteins with large particle sizes used in the production of high-protein bars caused a significant increase in the hardness of the final product. According to this lead, fine-grained proteins have much lower tendency to form hard structures during the storage process and allow for the creation of a delicate and soft product structure, which is confirmed by Cho [36]. It was observed that the chocolate-coated bars showed, in most cases, higher hardness than the uncoated samples, but also had increased other TPA parameters. This is most likely related to the greater restriction of air access to these products, which slows down the drying processes of the product (as evidenced by higher adhesiveness results and water activity parameters presented in Figure 2a,b).

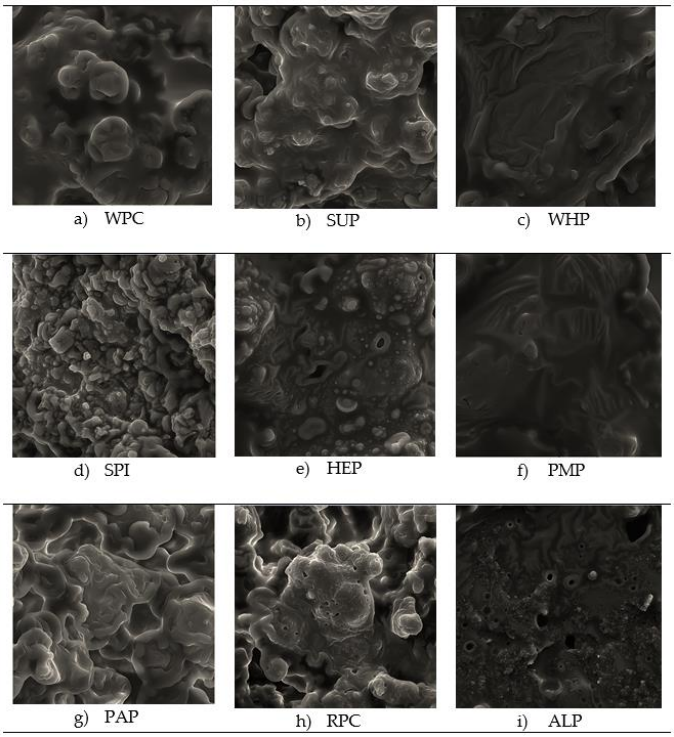


Figure 1. (**a**–**i**) Microstructure of high-protein bars from the scanning electron microscope (SEM HV: 30 kV, View field: 271 µm, SEM MAG: 800×).

Cutting test indicates the firmness/hardness of a product. If one considers that if the top front teeth were pulled from a curve-shape into a straight line, they would represent a 'knife edge'. Using a knife blade gives a close representation of the biting or cutting action [31].

With reference to Table 3, the bar made of algae proteins (ALP), both without and with chocolate coating, showed the highest cutting resistance (166.82 N without chocolate and 235.45 N with chocolate). Whereas, the most susceptible to this effect turned out to be high-protein bars made of proteins: wheat (WHP: 8.43 N without chocolate and 10.54 N with chocolate), pumpkin (PMP: 7.69 N without chocolate and 22.7 N with chocolate), hemp (HEP: 10.58 N without chocolate and 15.59 N with chocolate) and sunflower (SUP: 14.38 N without chocolate and 22.35 N with chocolate coating). The obtained results correlate with the hardness analysis and confirm the relationship between the hardness of bars and the force needed to cut them. In general, it can be observed that the chocolate-coated bars had higher resistance to the cutting force, except from WPC and PAP. The reason for this phenomenon may result from slight fluctuations in parameters in the degree of chocolate tempering, which slightly change during the chocolate tempering process. Chocolate with a temper index (TI) degree of 5.0–5.5 is characterized by high hardness causing a characteristic crackle when breaking, which is a feature desired by consumers in this type of products. This is also confirmed by the sensory analysis performed. The deviations may be related to the thickness of the chocolate layer in different places of the bars because in production conditions the products are coated with a stream of chocolate, too high layer of chocolate is blown off through a blast of compressed air, which creates a wave on the product characteristic of chocolate-coated products available on the store shelves. A properly tempered chocolate exhibits high gloss, appropriate melting temperature, and fat-bloom stability with desired characteristic crunchiness and hardness during eating depending on the amount of chocolate on the final product [37]. In addition, the flow behavior of tempered chocolate has implications for the processing of chocolate after tempering. Factors such as conching temperature, particle size distribution, fat content, type of emulsifiers, and tempering conditions determine efficiency of mixing, pumping, and transportation of final products during processing [38].

Table 3. Effect of different protein sources on high-protein bars cutting resistance.

Type of Protein Used in Bars with Chocolate Coating	Cutting Resistance Force (N)	Type of Protein Used in Bars without Chocolate Coating	Cutting Resistance Force (N)
WPC	79.31 ^{f} ± 0.298	WPC	128.39 ^{h} ± 0.393
RPC	25.75 ^{d} ± 0.198	RPC	25.36 ^{e} ± 0.084
SPI	109.69 ^{g} ± 0.112	SPI	98.21 ^{g} ± 0.162
SUP	22.35 ^{c} ± 0.298	SUP	14.38 ^{d} ± 0.149
WHP	10.54 ^{a} ± 0.073	WHP	8.43 ^{b} ± 0.020
HEP	15.59 ^{b} ± 0.271	HEP	10.58 ^{c} ± 0.126
PAP	75.34 ^{e} ± 0.222	PAP	81.45 ^{f} ± 0.194
PMP	22.70 ^{c} ± 0.143	PMP	7.69 ^{a} ± 0.148
ALP	235.45 ^{h} ± 0.366	ALP	166.82 ^{i} ± 0.138

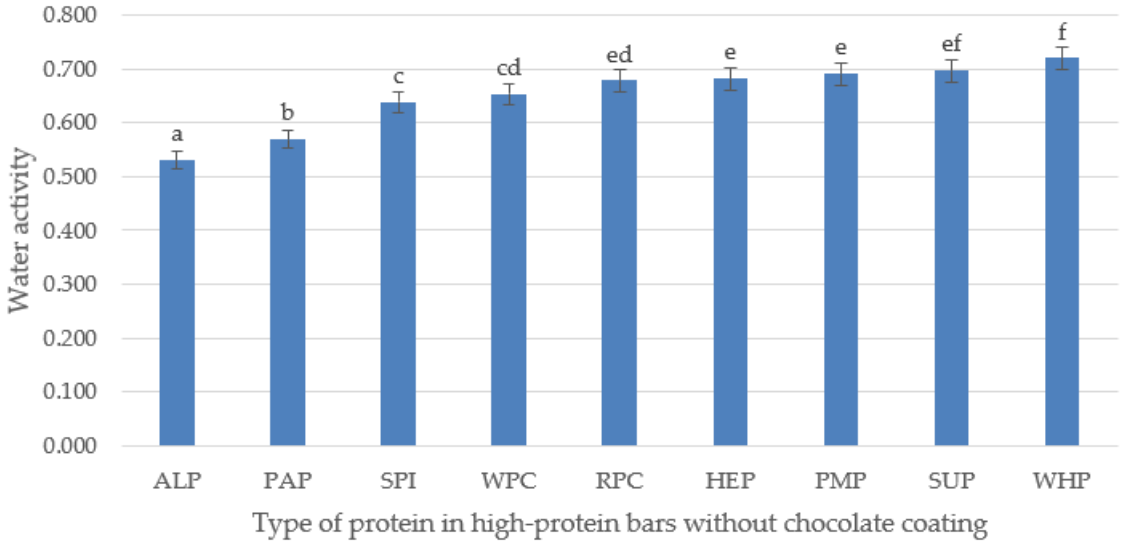
Data are presented as means ± SD (standard deviation). $^{a–i}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's HSD test).

Based on the electron microscope photos presented in Table 3 and the studies by Labuza and Hyman [39], it can be assumed that large discrepancy in the results of TPA tests may be due to factors related to the structural features, density of protein molecules and their porosity. In addition, Hogan et al. [6,40] proved that the rate of moisture migration in multi-domain foods is slower in foods with smaller pore size, presumably due to more tortuous pathways for moisture diffusion. Air occluded within powder particles may be observed as the proportion of powder volume not subjected to moisture-induced change, and thus may be beneficial to structural stability. A fairly large number of similarities were found between the microstructure of SUP, PAP, WPC and RPC proteins. Pictures of these proteins have the significant number of depressions and embossing. Taking into account the parameters of the texture analysis, such a structure probably has a significant impact on decreasing the hardness and cutting force parameters. Bars with SUP revealing much higher

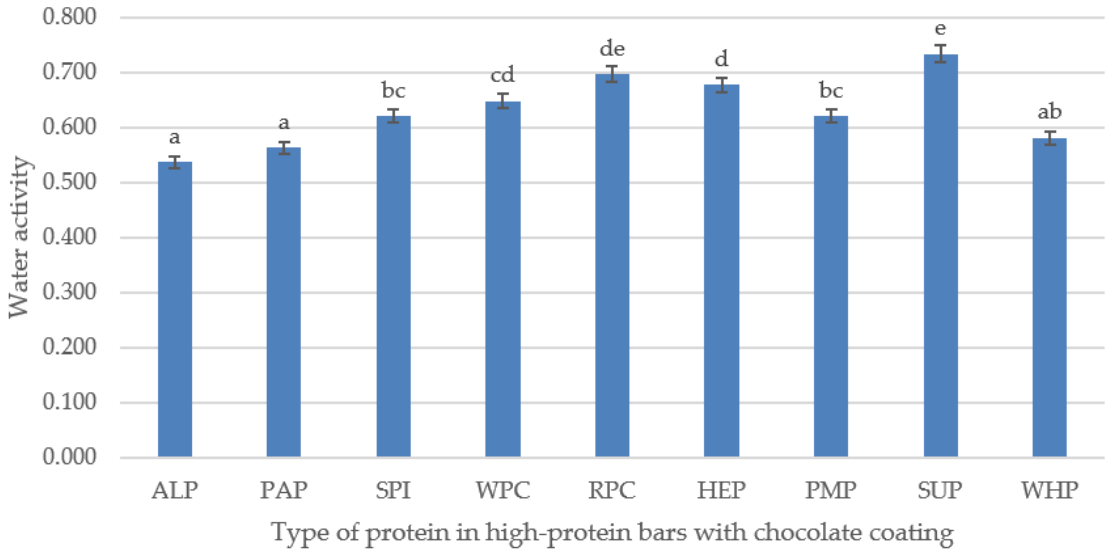
hardness, were the exception. This may be related to the formation of large clusters (agglomerates) of proteins, resulting in the formation of a compact and hard structure, which translates directly into high parameters of hardness, fracturability, and adhesiveness. It was also observed that all the above bars were characterized by quite high susceptibility to the action of shear force. It is worth mentioning that bars made of WHP and PMP proteins, having a wavy structure, without a large number of cavities and air pores, were also characterized by relatively low hardness parameters and high susceptibility to cutting. All bars made of the proteins mentioned above showed similar, technologically acceptable, water activity ($a_w < 0.735$). The bar made of ALP proteins had a very diverse structure. Numerous air pores and unevenly distributed agglomerates of protein particles in the form of bushy protrusions were observed on its surface. Interestingly, the protein protrusions were also interrupted by wavy, relatively smooth protein structures. Referring to the work of Bleakley and Hayes [41], the formation of characteristic agglomerates in the case of algae protein may be related to the presence of lectins in this type of protein. Lectins are glycoproteins known for their aggregation and high specificity binding with carbohydrates without initiating a modification through associated enzymatic activity. Completely different microstructure of ALP bars is probably the reason for the highest hardness. The use of proteins of various botanical origin in the study has a significant impact on the swelling method, reorganization of molecular structures or aggregation of proteins in the product. However, the control of micro- and macrostructures is still very difficult due to the poor knowledge of this issue [42].

3.2. Water Activity

Measurement of water activity of high-protein bars are presented on Figure 2a,b. The water activity of high-protein bars changes during the storage process [43]. Therefore, the bars were stored for 3 weeks in a sealed plastic container (metallized barrier film) at 20 °C. The optimal storage time was adopted due to the results of studies by Banach et al. [35], which showed that a_w increase after this period was not significant. Water activity of the tested samples was shown in Figure 2a,b. The highest a_w value characterized bar with chocolate coating made of sunflower protein (SUP)—0.735 and the lowest (ALP)—0.530 algae protein bar without chocolate coating. Bars made of proteins: sea algae (ALP), pea (PAP) and soybean (SPI) had a_w lower than 0.65, which guarantees the stability of samples during storage (in room temperature) and inhibition of microbial growth [44]. Other bars, made of hemp (HMP), rice (RPC) and sunflower (SUP), had water activity above 0.65. Therefore, it can be suggested that they should be stored in conditions of lower temperature. Increased water activity may indicate movement of water molecules from the intermediate phase, where they act as a plasticizer, to the bulk phase [32]. Proteins included in bars that exceeded 0.65 water activity values, had a fairly high degree of fragmentation, and originated from various plant species, which could also have a significant impact on this parameter.



(**a**)



(**b**)

Figure 2. (**a**) Effect of different protein application on water activity of high-protein bars without chocolate coating; (**b**) With chocolate coating. Letters (a–f) indicate significant differences at $p < 0.05$ (Tukey's HSD test).

According to the current knowledge, changes in the structure or organization of proteins in a product may be associated with the formation of disulfide bonds when there are no water molecules associated with the local protein domain. It may also be one of the mechanisms explaining the hardening of high-protein products over time, in particular, if whey proteins have been added to the product [45,46]. High water activity parameters for WHP without chocolate coating may be related to the high water absorption of gluten. On the other hand, the differences in the case of the sample with chocolate coating may result from the restriction of air access to the interior of the product due to the coating with a layer of chocolate. High water activity value of bars made of SUP protein may be related to the high capacity of this type of protein to absorb water and fat, as evidenced by the research of Ren et al. [47]. According to the obtained results, it can be suspected that the addition of other types of proteins, such as ALP, PAP, WHP, or SPI to food products, may have a positive effect on reducing the water activity and modifying the textural parameters of the final product.

3.3. Color Differences Measured with Computer Vision System (CVS)

Typically, the main aspect that reduces the quality of high-protein bars is their hardening over time, but color can also be an important quality indicator for consumers of this type of product. The colors of bars made of various types of proteins after three weeks of storage are presented in Table 4a. The most frequently used methods of color assessment in the analysis of this parameter in food products are colorimetric methods. In turn, the colors generated using CVS closely resemble the real color of the samples being assessed. Moreover, the color is more intense (the colors are more saturated) than for standard colorimetric methods [48]. In this study, the CVS method was used due to the studies by Tomasevic et al. [49], which proved that the CVS method gives much better results in assessing the color of food products.

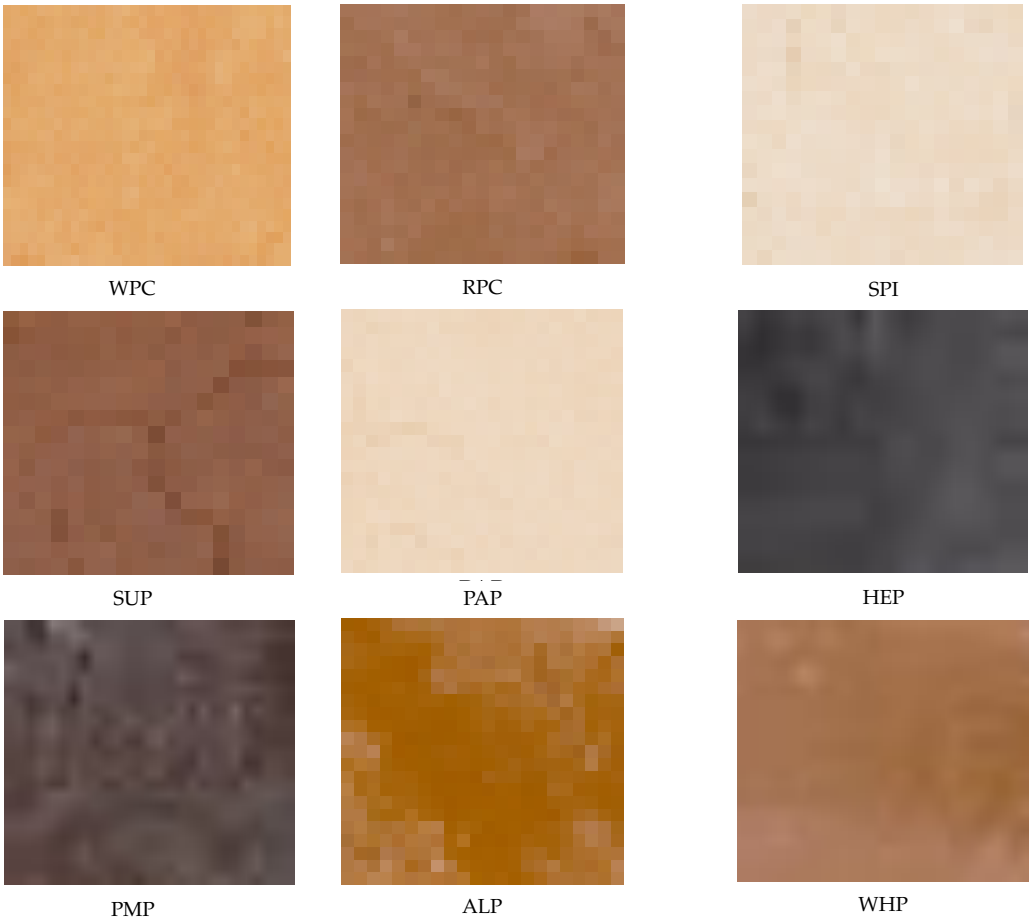
According to Inami et al. [23], all the color differences expressed by values larger than 6 are considerable. Discrepancies between the >6 prove the high impact of the protein used on the color difference of high-protein bars. Proteins from various sources were characterized by different colors compared to the blank sample made of WPC. The SPI protein was characterized by the highest brightness, which may indicate a slower ability to bind fat than other tested proteins. The fat on the surface of bars probably causes the increased ability to reflect light. The remaining differences in parameters a and b are probably directly related to the origin of the component (plant and animal proteins). Considering the Hasan [50] study, values of the L* parameters were similar for bars made of whey proteins after about 6 weeks of storage. Minor differences in the a* and b* parameters may be related to the analysis of parameters after a longer storage period. On the other hand, comparing the research results with the work of McMahon et al. [51], it can be assumed that bars made with high-fructose and glucose syrups are much more susceptible to darkening processes than in the case of other types of syrups. In this study, only glucose syrup was used in all trials. Therefore, it is probably required to conduct further tests and investigate whether the type of syrup will cause large changes in the L* a* b* parameters for the developed high-protein bars. The color of bars with chocolate coating was not examined, but it can be assumed that they would have brighter colors due to better protection against light and air access, and thus slowing down the Maillard reaction.

3.4. Ultrasonic Viscosity

The obtained ultrasonic viscosity is presented in Figure 3a,b. The ultrasonic viscometer gives the results of measurements in units of dynamic viscosity multiplied by density. The highest viscosity values were recorded for bars made of WHP and HEP proteins. However, the lowest—for ALP, WPC, PAP, and SUP. Low values of the viscosity parameter, in particular for ALP, correlate with high results of the hardness parameters and cutting force. It is also worth paying attention to the microstructure of these proteins, in which numerous clusters of wide pores (probably fat-air), a tightly compact and irregular structure can be seen (Figure 1).

Table 4. (**a**,**b**) Effect of different protein application on color of high-protein bars without chocolate coating measured with Computer Vision System (CVS).

(**a**)



(**b**)

Type of Protein Used in Bars without Chocolate Coating	Attributes			
	L*	a*	b*	NBS Units
WPC	63.86 ^{f} ± 1.069	17.29 ^{d} ± 0.488	44.43 ^{f} ± 0.976	-
RPC	43.71 ^{c} ± 0.488	10.00 ^{c} ± 0.000	21.14 ^{b} ± 0.690	29.12
SPI	79.43 ^{h} ± 0.787	5.29 ^{a} ± 0.488	19.43 ^{a} ± 0.976	29.26
SUP	34.14 ^{a} ± 0.378	11.00 ^{c} ± 0.000	22.29 ^{b} ± 0.756	34.58
WHP	40.57 ^{b} ± 0.976	10.00 ^{c} ± 0.000	31.71 ^{c} ± 1.113	25.32
HEP	50.57 ^{e} ± 0.976	47.43 ^{f} ± 1.272	50.29 ^{g} ± 1.704	30.78
PAP	78.00 ^{g} ± 0.000	8.00 ^{b} ± 0.000	23.00 ^{b} ± 0.000	25.12
PMP	49.43 ^{e} ± 1.134	40.71 ^{e} ± 1.113	34.14 ^{d} ± 2.116	27.02
ALP	47.71 ^{d} ± 0.488	10.86 ^{c} ± 0.378	39.71 ^{e} ± 0.488	16.57

Data are presented as means ± SD (standard deviation). $^{a–h}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's HSD test). "-" NBS Units of WPC protein-reference sample, not subject to calculation.

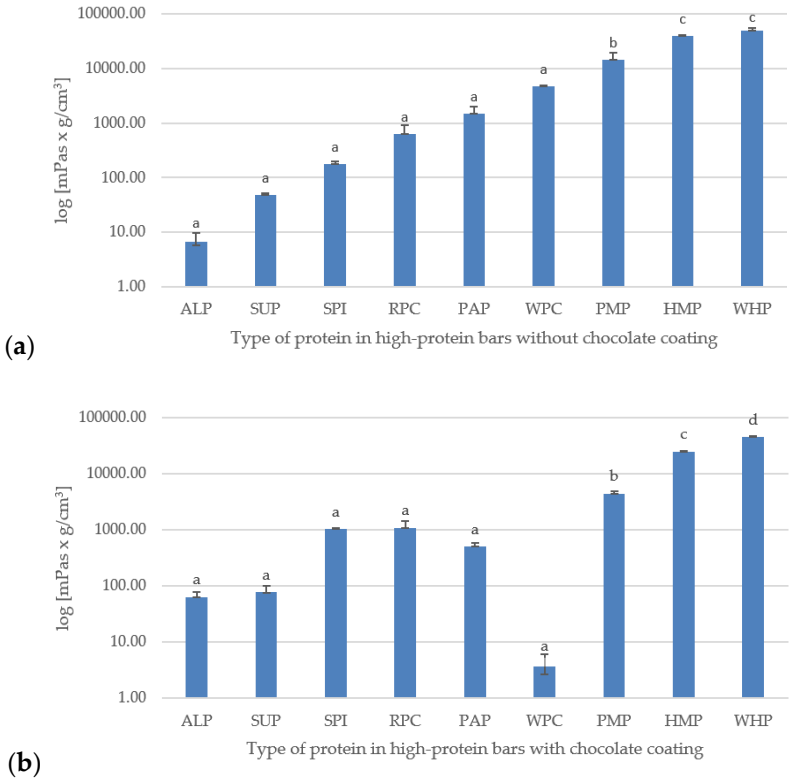


Figure 3. (**a**) Ultrasonic viscosity measurement results (mPas g/cm^3) of tested high-protein bars without chocolate coating; (**b**) With chocolate coating. Letters (a–d) indicate significant differences at $p < 0.05$ (Tukey's HSD test).

On the other hand, high-protein bars with the highest lightness values had much lower values of parameters related to hardness and cutting force. Their microstructure is free from numerous pores and the surface is much more even compared to other tested samples. Considering the obtained results and comparing them with the research by Tomczyńska-Mleko and Ozimek [52], it can be assumed that the obtained results could be influenced by factors such as degree of aeration in the bar mass and the consistency and protein concentration the product was made of. Ultrasonic viscosity tests are a rare/novel method for the analysis of food products, therefore, according to current knowledge, it is difficult to find publications to compare the obtained results.

3.5. Heavy Metals Analysis

The obtained results of testing the content of heavy metals in the developed high-protein bars are presented in Figure 4. They do not exceed the current permissible concentrations for this type of products according to Commission Regulation (EC) No 1881/2006 of 19 December 2006 [53].

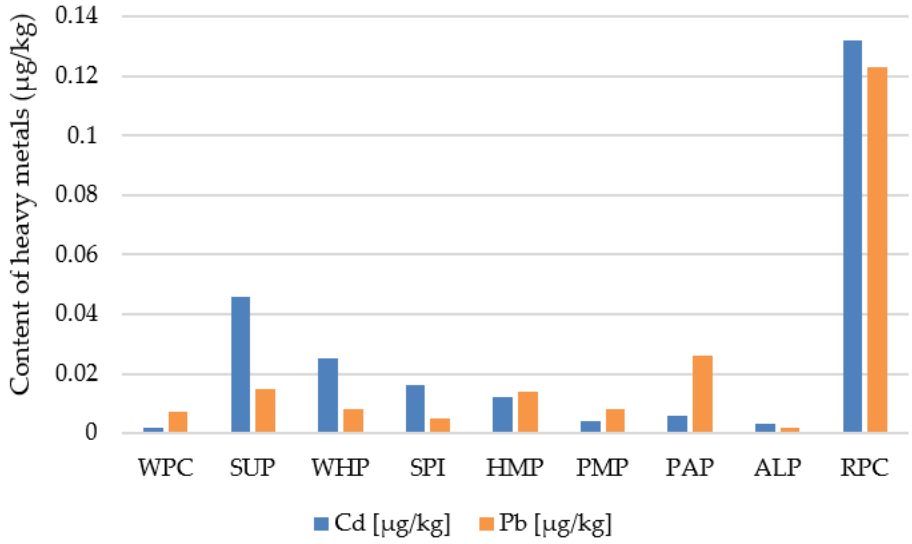


Figure 4. Content of heavy metals (cadmium and lead) in the high-protein bars.

However, a much higher level of cadmium and lead is very visible for the RPC protein. Regarding the research of Huang et al. and Kaneta et al. [54,55], it can be assumed that the increased level of these elements for bars made of RPC may result from the ability of rice, one of the most commonly cultivated plants on earth, to absorb significant amounts of heavy metals from its cultivation sites. Therefore, products made of this type of grain may be characterized by an increased content of not only cadmium and lead, but also arsenic and other heavy metals.

3.6. Amino Acids and Nutritional Value

Often, for people consuming the high-protein products (e.g., athletes, sick people or convalescents), nutritional and pro-health values are important. The obtained results of the content of amino acids in the tested bars presented in Figure 5 show significant differences between the content of individual amino acids in different types of proteins. The largest deviation can be seen in the proline content for bars made of WHP protein.

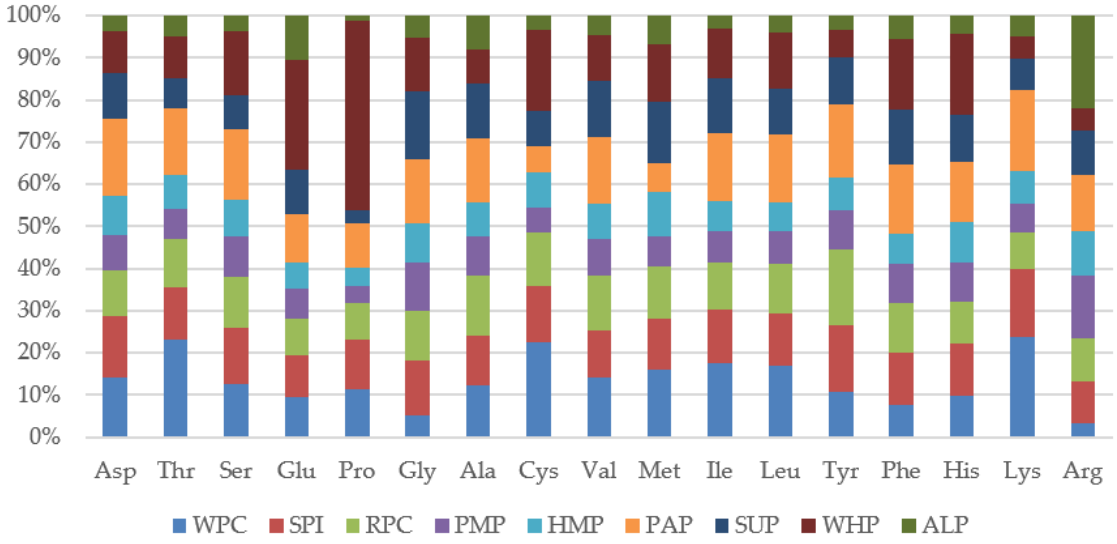


Figure 5. Percentage of individual amino acids in the high-protein bars.

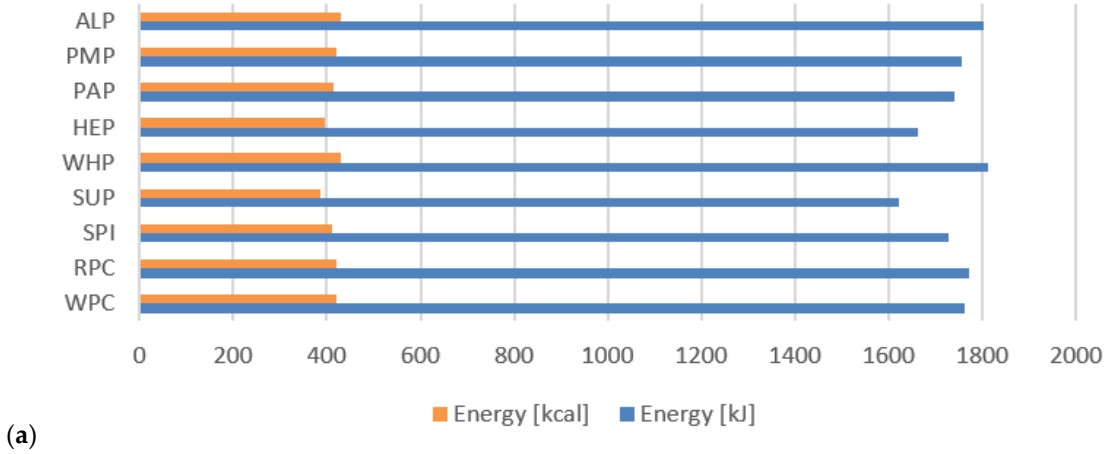
Based on the work of Kowieska et al. [56], it can be assumed that such a high content of endogenous amino acid, i.e., proline, may be caused by a naturally high content of proline in wheat grain. Proline is an important amino acid for physically active people and athletes, as it participates in the formation of secondary structures in collagen. These structures are stabilized by enzymatic hydroxylation (proline hydroxylase) or a substituent having electron withdrawing ability, e.g., fluorine, which significantly increases the stability of the collagen. Deficiencies of proline, vitamin C (being a cofactor of proline hydroxylase), and disorders of enzyme production, can lead to the scurvy [57].

Exogenous amino acids are essential and human body cannot synthesize them from scratch at a rate commensurate with their needs. Therefore, it is necessary to provide them to the body in a properly balanced diet. Out of a total 21 amino acids, nine are considered essential, including phenylalanine, valine, threonine, tryptophan, methionine, leucine, isoleucine, lysine, and histidine. Proteins found in animal sources, such as meat, poultry, fish, eggs, milk, cheese, and yogurt, provide all nine indispensable amino acids and hence they are referred to as "complete proteins." Proteins found in plants, legumes, grains, nuts, seeds, and vegetables tend to be deficient in one or more of the indispensable amino acids and are called "incomplete proteins" [58].

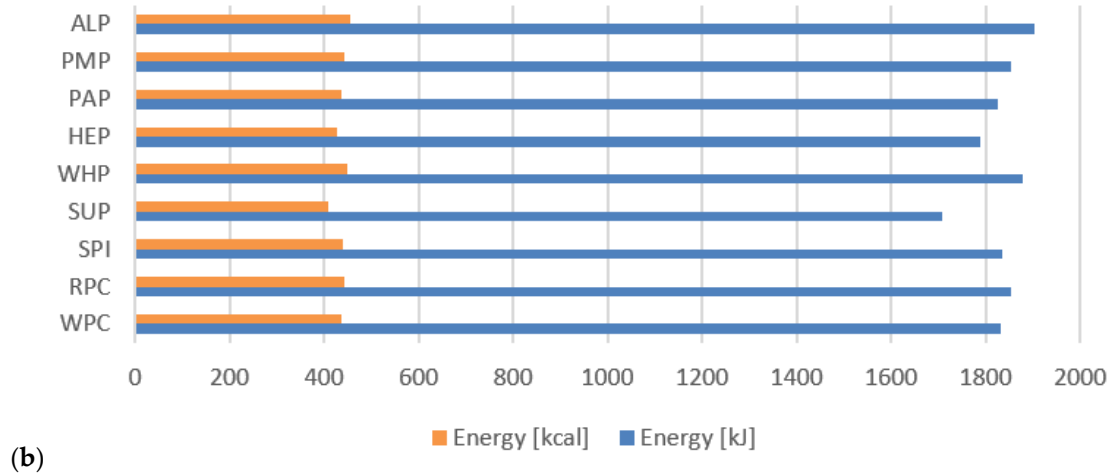
Despite the passage of time and thermal processing during production, the obtained high-protein bars are characterized by a high content of the entire spectrum of amino acids.

Considering the obtained results, it can be assumed that, despite the high content of essential amino acids in the WPC reference sample, alternative sources of plant-derived proteins may be an attractive proposition for people who do not want or cannot consume proteins of animal origin. It is worth paying attention to the high content of arginine in the ALP. As evidenced by the research of Stróżyk et al. [59], arginine is an essential amino acid in the case of increased physical exertion. It is a precursor of nitric oxide, which relaxes the smooth muscles of blood vessel walls, thus improving the blood oxygenation and replenishment of skeletal muscles. It was observed that bars made of SPI, RPC, and PAP proteins showed significant alignment of the entire spectrum of amino acids. Among which, essential amino acids, which have been determined in significant amounts, as for proteins of plant origin, deserve special attention. The high content of essential amino acids in soybean and rice protein isolates was also confirmed by Kalman [60]. Therefore, it can be assumed that these proteins may become more and more popular, especially among vegans and vegetarians and allow the essential amino acids in such diets to be satisfied.

Results obtained from the calculated nutritional value presented in Figure 6a,b and Figure 7a,b indicate slight differences in the protein and fat content as well as nutritional values in individual protein preparations used in the production of high-protein bars. However, these differences are not significant ($p > 0.05$). It is also worth paying attention to the fiber content for bars made of HEP and SUP, the content of which is significantly higher than that of other samples. In addition, this amount of fiber allows the nutrition claim "high fiber content" to be used on the packaging of these products in accordance with Regulation (EC) No 1924/2006 Of The European Parliament And Of The Council of 20 December 2006 [61] on nutrition and health claims made on foods. The consumption of fiber is an important aspect in the diet of every human being due to many positive functions of fiber. Local reactions are related to their presence in the gastrointestinal tract and systemic reactions with an effect on metabolism. Viscosity, the ability to ferment, binding water, binding bile acids, reacting with metal ions, and increased stool weight are just a few of better understood effects of dietary fiber consumption Li and Komarek [62]. Based on Figure 6a,b, it can be concluded that the developed high-protein bars had a low content of saturated fatty acids. This is an important feature from the point of view of athletes and physically active people because saturated and trans fats may also make the lining of blood vessels (the endothelium) less flexible. In addition, trans fats may depress the "good" blood cholesterol (HDL cholesterol) when eaten in large quantities [63].



(**a**)



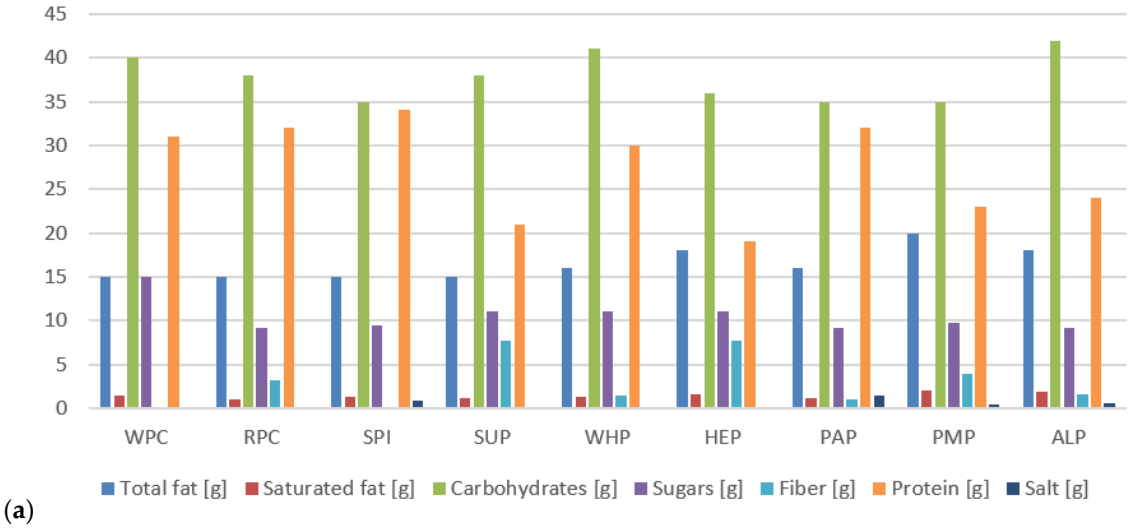
(**b**)

Figure 6. (**a**) Energy value of high-protein bars without chocolate coating; (**b**) With chocolate coating.

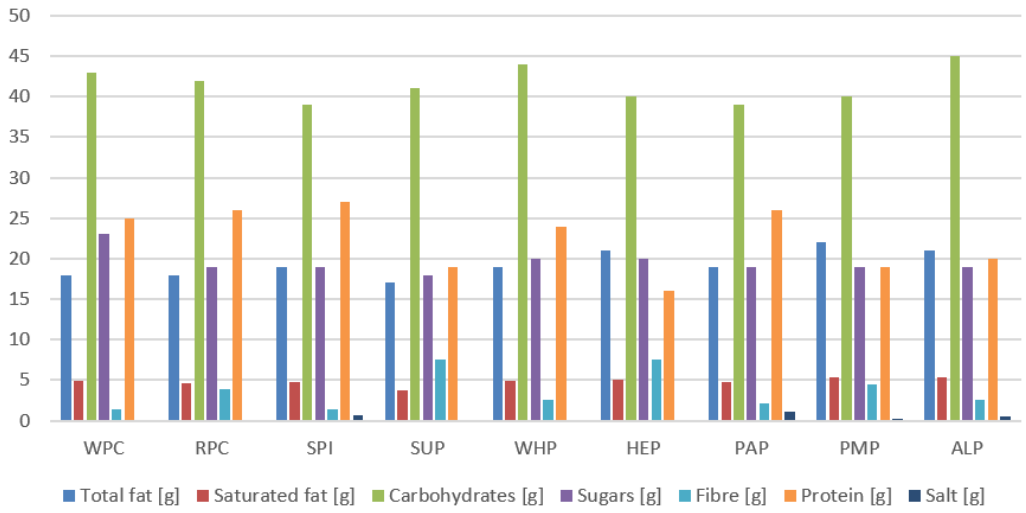
3.7. Sensory Evaluation

Results of the sensory evaluation of the tested high-protein bars are presented in Figure 8a,b. The highest scores during the analysis were obtained for bars made of WPC and PAP proteins. The evaluators appreciated the external appearance, color and taste sensations the most in the highest rated bars. High ratings for these types of proteins are associated with a pleasant consistency, taste and color, according to the judges. The worst rated bar (ALP) had too high hardness, an unpleasant aftertaste and a green-yellow color, which gave it the lowest scores. Negative assessments of the taste of the ALP bar may also be caused by too much dosing of this type of protein for a given application. Based on research by Hall et al. [64], in which the addition of algae protein in bread was 4%, it can be suspected that low taste ratings of bars made of algae proteins were probably caused by too high percentage in the final product (30%, *w/w*). In contrast, the research of Prabhasankar et al. [65] prove that the addition of algae protein in the amount >10%, *w/w* in pasta causes acceptable sensory features for those taking part in the sensory evaluation. Considering the above results, it can be concluded that the chocolate coating of high-protein products significantly increases their palatability. Ratings for individual chocolate bars were clearly higher than their non-chocolate counterparts. The remaining high-protein bars were rated at an average level with a tendency to be more positive. Referring to the research by Usha et al. [66], in which the effect of adding the pumpkin flour to baby food after weaning was examined, the ratings of products, in which addition was 20–30%, *w/w* pumpkin flour, were on the average level (on a nine-point scale) with a tendency to higher one, in particular if dosing

at the level of 10%, *w*/*w*. It is worth mentioning that the worst rated parameter by the team was the taste of dishes, which can be correlated with the results obtained from the study of high-protein bars.

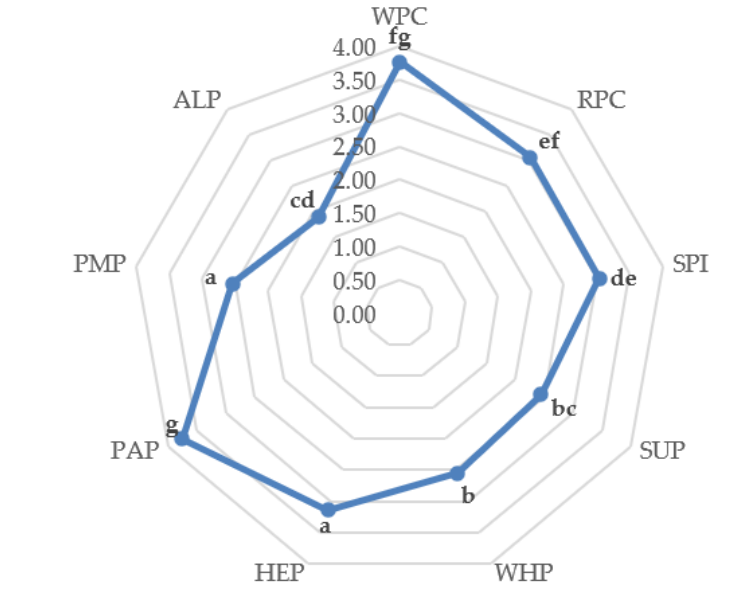


(**a**)

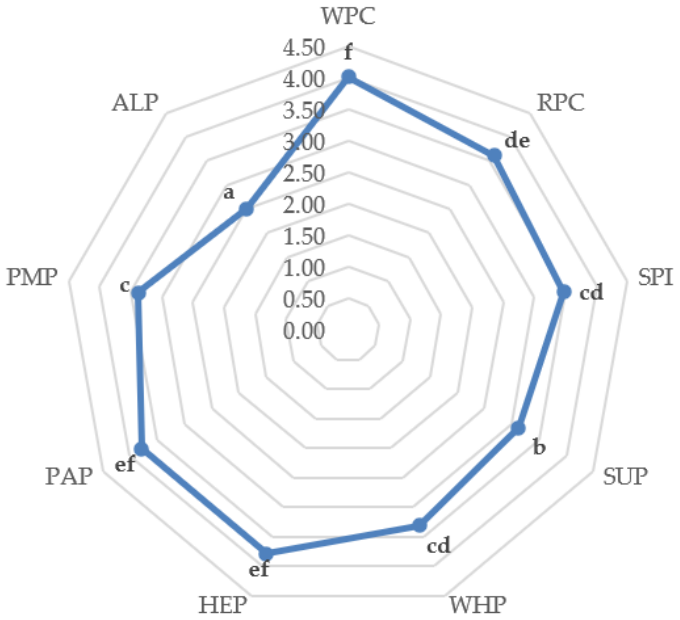


(**b**)

Figure 7. (**a**) Nutritional value of high-protein bars without chocolate coating; (**b**) With chocolate coating.



(**a**)



(**b**)

Figure 8. (**a**) Sensory evaluation of high-protein bars without chocolate coating; (**b**) With chocolate coating. $^{a–g}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's HSD test).

4. Conclusions

Based on the experiment, it can be concluded that changes in textural parameters, nutritional values or physicochemical parameters significantly depend on the type of protein used. Differences in the parameters of texture profile analysis (TPA) and cutting forces show significant differences, of which bars made of RPC, HEP, PAP, and PMP were characterized by the lowest results during the TPA test and ultrasonic viscosity. Differences in the microstructural structure of the tested bars significantly translated into the physical, chemical and textural features presented by proteins. It can be suspected that the microstructure of proteins has a significant effect on the water activity of high-protein bars. In particular, ALP proteins showed the lowest results of this parameter ($a_w < 0.55$), which ensures

the microbiological stability of the final product, even during long storage periods. The obtained results of the amino acid content give the possibility that the SPI, RPC, and PAP proteins can compete with the WPC protein in terms of essential amino acid content. Bars made of RPC proteins had an increased content of heavy metals but these values did not exceed the acceptable EU standards. In terms of the nutritional value studied, all types of protein deserve attention due to the low content of saturated fat. Bars made of SUP and HEP proteins, apart from high protein content, also allowed for the declaration of high fiber content (fiber content above 6 g/100 g). Based on sensory analysis and the color assessment using the CVS method of bars without chocolate coating, it can be concluded that the color plays an important role for the consumer. Sensory analysis showed that the coating of high-protein bars with chocolate increases scores of the tested products, masking specific smells, color to a large extent, the aftertaste of some types of proteins, thus contributing to an increase in the overall sensory assessment. Therefore, it can be clearly defined that high-protein bars should be covered with chocolate. The conducted research shows that proteins of plant origin can be successfully used in the food industry as an alternative to WPC proteins, however it is not possible to clearly indicate which type of protein is the best option. Nevertheless, the high content of exogenous amino acids or the technological utility resulting from the texture parameters of bars made of RPC, SPI and PAP proteins speak for these sources. More research is needed on storage trials, microbiological tests, and examining the effect of changing other components in the recipe that may affect the parameters important for the food industry.

Author Contributions: Conceptualization, B.G.S. and J.M.; methodology, B.G.S., J.M., I.T., I.D.; software, B.G.S., J.M., I.T., I.D.; validation, B.G.S., J.M., I.T., I.D.; formal analysis, J.M.; investigation, J.M.; resources, B.G.S., J.M.; data curation, J.M.; writing—original draft preparation, J.M.; writing—review and editing, B.G.S., I.T., I.D.; visualization, J.M.; supervision, B.G.S., I.T., I.D.; final approval of the version to be published, B.G.S., J.M., I.T., I.D.; project administration, B.G.S.; funding acquisition, B.G.S., J.M. All authors have read and agreed to the published version of the manuscript.

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References

1. Goodbody, A. Raise the bar. *Min. Mag.* **2013**, 73–78. [CrossRef]
2. Clary, D.; Van de Bussche, T.; Janis, M.; Gossip, M.; Sloan, A.E. The top 10 functional food trends. The next generation. *Food Technol.* **2002**, *56*, 32–57. [CrossRef]
3. Riaz, M.N. *Soy Applications in Food*; CRC Press: Boca Raton, FL, USA, 2005.
4. Walia, A.; Gupta, A.K.; Sharma, V. Role of Bioactive Compounds in Human Health. *Acta Sci. Med. Sci.* **2019**, *3*, 25–33.
5. Potes, N.; Kerry, J.P.; Roos, Y.H. Protein Modifications in High Protein-Oil and Protein-Oil-Sugar Systems at Low Water Activity. *Food Biophys.* **2014**, *9*, 49–60. [CrossRef]
6. Hogan, S.A.; Chaurin, V.; O'Kennedy, B.T.; Kelly, P.M. Influence of dairy proteins on textural changes in high-protein bars. *Int. Dairy J.* **2012**, *26*, 58–65. [CrossRef]
7. Weeks, E.R. Soft jammed materials. *Stat. Phys. Complex Fluids* **2007**, *2*, 87.
8. Wang, Q.; Xiong, Y.L. Processing, Nutrition, and Functionality of Hempseed Protein: A Review. *Compr. Rev. Food Sci. Food Saf.* **2019**, *18*, 936–952. [CrossRef]
9. Sá, A.G.A.; Moreno, Y.M.F.; Carciofi, B.A.M. Plant proteins as high-quality nutritional source for human diet. *Trends Food Sci. Technol.* **2020**, *97*, 170–184. [CrossRef]
10. Ermiş, E.; Karasu, E.N. Püskürtmeli Kurutucu Ile Yağı Alinmiş Ayçiçeği Protein Ekstrakti Tozu Üretimi: Fonksiyonel Özellikleri Ve Toz Karakterizasyonu. *Gida/J. Food* **2020**, *45*, 39–49. [CrossRef]

11. Pihlanto, A.; Mattila, P.; Mäkinen, S.; Pajari, A.M. Bioactivities of alternative protein sources and their potential health benefits. *Food Funct.* **2017**, *8*, 3443–3458. [CrossRef]
12. Hassan, H.M.M.; Afify, A.S.; Basyiony, A.E.; Ahmed, G.T. Nutritional and functional properties of defatted wheat protein isolates. *Aust. J. Basic Appl. Sci.* **2010**, *4*, 348–358.
13. Wells, M.L.; Potin, P.; Craigie, J.S.; Raven, J.A.; Merchant, S.S.; Helliwell, K.E.; Smith, A.G.; Camire, M.E.; Brawley, S.H. Algae as nutritional and functional food sources: Revisiting our understanding. *J. Appl. Phycol.* **2017**, *29*, 949–982. [CrossRef] [PubMed]
14. Phongthai, S.; Homthawornchoo, W.; Rawdkuen, S. Preparation, properties and application of rice bran protein: A review. *Int. Food Res. J.* **2017**, *24*, 25–34.
15. Vinayashree, S.; Vasu, P. Biochemical, nutritional and functional properties of protein isolate and fractions from pumpkin (Cucurbita moschata var. Kashi Harit) seeds. *Food Chem.* **2020**, *340*, 128177. [CrossRef] [PubMed]
16. Rezig, L.; Riaublanc, A.; Chouaibi, M.; Guéguen, J.; Hamdi, S. Functional Properties of Protein Fractions Obtained from Pumpkin (Cucurbita Maxima) Seed. *Int. J. Food Prop.* **2016**, *19*, 172–186. [CrossRef]
17. Xu, Y.T.; Liu, L.L. Structural and Functional Properties of Soy Protein Isolates Modified by Soy Soluble Polysaccharides. *J. Agric. Food Chem.* **2016**, *64*, 7275–7284. [CrossRef]
18. Lam, A.C.Y.; Can Karaca, A.; Tyler, R.T.; Nickerson, M.T. Pea protein isolates: Structure, extraction, and functionality. *Food Rev. Int.* **2018**, *34*, 126–147. [CrossRef]
19. Hogenkamp, P.S.; Stafleu, A.; Mars, M.; Brunstrom, J.M.; de Graaf, C. Texture, not flavor, determines expected satiation of dairy products. *Appetite* **2011**, *57*, 635–641. [CrossRef]
20. De la Fuente, M.A.; Singh, H.; Hemar, Y. Recent advances in the characterisation of heat-induced aggregates and intermediates of whey proteins. *Trends Food Sci. Technol.* **2002**, *13*, 262–274. [CrossRef]
21. Tomasevic, I.; Tomovic, V.; Milovanovic, B.; Lorenzo, J.; Đorđević, V.; Karabasil, N.; Djekic, I. Comparison of a computer vision system vs. traditional colorimeter for color evaluation of meat products with various physical properties. *Meat Sci.* **2019**, *148*, 5–12. [CrossRef]
22. Milovanovic, B.; Djekic, I.; Djordjevic, V.; Tomovic, V.; Barba, F.; Tomasevic, I.; Lorenzo, J.M. Pros and cons of using a computer vision system for color evaluation of meat and meat products. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *333*, 012008. [CrossRef]
23. Inami, T.; Tanimoto, Y.; Minami, N.; Yamaguchi, M.; Kasai, K. Color stability of laboratory glass-fiber-reinforced plastics for esthetic orthodontic wires. *Korean J. Orthod.* **2015**. [CrossRef]
24. Balter, A.; Szubiakowski, J. Fluorescence probes of viscosity: A comparative study of the fluorescence anisotropy decay of perylene and 3,9-dibromoperylene in glycerol. *J. Fluoresc.* **1993**, *3*, 247–249. [CrossRef]
25. Galant, S. Formation of collagen-like structure of gel after radiation modification of gelatin. *Colloid Polym. Sci.* **1983**, *261*, 445–451. [CrossRef]
26. Sheen, S.H.; Chien, H.-T.; Raptis, A.C. An in-Line Ultrasonic Viscometer. In *Review of Progress in Quantitative Nondestructive Evaluation*; Springer Science & Business Media: Berlin, Germany, 1995.
27. Stone, H. *Sensory Evaluation Practices*; Academic Press: Cambridge, MA, USA, 2012; ISBN 9780123820860.
28. Kowalski, S.; Lukasiewicz, M.; Juszczak, L.; Sikora, M. Charakterystyka teksturalna i sensoryczna mas cukierniczych otrzymanych na bazie miodu naturalnego i wybranych hydrokoloidów polisacharydowych. *Żywność Nauk. Technol. Jakość* **2011**, *18*, 3.
29. Le Roux, L.; Ménard, O.; Chacon, R.; Dupont, D.; Jeantet, R.; Deglaire, A.; Nau, F. Are faba bean and pea proteins potential whey protein substitutes in infant formulas? An in vitro dynamic digestion approach. *Foods* **2020**, *9*, 362. [CrossRef]
30. Badzian, B. Poziom aminokwasów egzogennych w ścianie jelita cienkiego, wątrobie i osoczu krwi kurcząt po zastosowaniu witamin rozpuszczalnych w wodzie. *Acta Sci. Pol. Med. Vet.* **2007**, *6*, 3–14.
31. Novaković, S.; Tomašević, I. A comparison between Warner-Bratzler shear force measurement and texture profile analysis of meat and meat products: A review. In Proceedings of the 59th International Meat Industry Conference MEATCON2017, Zlatibor, Serbia, 1–4 October 2017; Volume 85. [CrossRef]
32. Li, Y.; Szlachetka, K.; Chen, P.; Lin, X.; Ruan, R. Ingredient characterization and hardening of high-protein food bars: An NMR state diagram approach. *Cereal Chem.* **2008**, *85*, 780–786. [CrossRef]
33. Banach, J.C.; Clark, S.; Lamsal, B.P. Particle size of milk protein concentrate powder affects the texture of high-protein nutrition bars during storage. *J. Food Sci.* **2017**, *82*, 913–921. [CrossRef]

34. Trinh, T.; Glasgow, S. On the texture profile analysis test. In Proceedings of the Chemeca 2012: Quality of life through chemical engineering, Wellington, New Zealand, 23–26 September 2012; Available online: https://www.researchgate.net/publication/316093466_On_the_texture_profile_analysis_test (accessed on 9 October 2020).
35. Banach, J.C.; Clark, S.; Lamsal, B.P. Instrumental and Sensory Texture Attributes of High-Protein Nutrition Bars Formulated with Extruded Milk Protein Concentrate. *J. Food Sci.* **2016**, *81*, S1254–S1262. [CrossRef]
36. Cho, M.J. Soy Protein Functionality and Food Bar Texture. In *Chemistry, Texture, and Flavor of Soy*; American Chemical Society: Washington, DC, USA, 2010; ISBN 9780841225619.
37. Debaste, F.; Kegelaers, Y.; Liégeois, S.; Amor, H.B.; Halloin, V. Contribution to the modelling of chocolate tempering process. *J. Food Eng.* **2008**, *88*, 568–575. [CrossRef]
38. Quiñones-Muñoz, T.; Gallegos-Infante, J.A.; Rocha-Guzmán, N.E.; Ochoa-Martinez, L.A.; Morales-Castro, J.; González-Laredo, R.F.; Medina-Torres, L. Mixing and tempering effect on the rheological and particle size properties of dark chocolate coatings. *CYTA J. Food* **2011**, *9*, 109–113. [CrossRef]
39. Labuza, T.P.; Hyman, C.R. Moisture migration and control in multi-domain foods. *Trends Food Sci. Technol.* **1998**, *9*, 47–55. [CrossRef]
40. Hogan, S.A.; Famelart, M.H.; O'Callaghan, D.J.; Schuck, P. A novel technique for determining glass-rubber transition in dairy powders. *J. Food Eng.* **2010**, *99*, 76–82. [CrossRef]
41. Bleakley, S.; Hayes, M. Algal Proteins: Extraction, Application, and Challenges Concerning Production. *Foods* **2017**, *6*, 33. [CrossRef]
42. Purwanti, N.; van der Goot, A.J.; Boom, R.; Vereijken, J. New directions towards structure formation and stability of protein-rich foods from globular proteins. *Trends Food Sci. Technol.* **2010**, *21*, 85–94. [CrossRef]
43. Banach, J.C.; Clark, S.; Lamsal, B.P. Texture and other changes during storage in model high-protein nutrition bars formulated with modified milk protein concentrates. *LWT Food Sci. Technol.* **2014**, *56*, 77–86. [CrossRef]
44. Loveday, S.M.; Hindmarsh, J.P.; Creamer, L.K.; Singh, H. Physicochemical changes in a model protein bar during storage. *Food Res. Int.* **2009**, *42*, 798–806. [CrossRef]
45. Zhou, P.; Liu, X.; Labuza, T.P. Moisture-induced aggregation of whey proteins in a protein/buffer model system. *J. Agric. Food Chem.* **2008**, *56*, 2048–2054. [CrossRef]
46. Zhou, P.; Liu, X.; Labuza, T.P. Effects of moisture-induced whey protein aggregation on protein conformation, the state of water molecules, and the microstructure and texture of high-protein-containing matrix. *J. Agric. Food Chem.* **2008**, *56*, 4534–4540. [CrossRef]
47. Ren, J.; Sun, X.H.; Lin, G.P.; Zheng, X.Q.; Liu, X.L. Isolation and Characterization of Sunflower Protein Isolates and Sunflower Globulins. In *Information Technology and Agricultural Engineering*; Springer: Berlin/Heidelberg, Germany, 2012.
48. Tomasevic, I.; Tomovic, V.; Ikonic, P.; Lorenzo Rodriguez, J.M.; Barba, F.J.; Djekic, I.; Nastasijevic, I.; Stajic, S.; Zivkovic, D. Evaluation of poultry meat colour using computer vision system and colourimeter: Is there a difference? *Br. Food J.* **2019**, *121*, 1078–1087. [CrossRef]
49. Tomasevic, I.; Tomovic, V.; Barba, F.J.; Vasilev, D.; Jokanovic, M.; Sojic, B.; Manuel Lorenzo, J.; Djekic, I. How the color of game meat should be measured. *Fleischwirtschaft* **2019**, *99*, 85–89.
50. Hassan, S.K. Quantitative and qualitative effects of proteins and natural sugars on hardening and color of high-protein nutrition bars during storage. *EurAsian J. Biosci.* **2020**, *14*, 915–932.
51. Mcmahon, D.J.; Adams, S.L.; Mcmanus, W.R. Hardening of high-protein nutrition bars and sugar/polyol-protein phase separation. *J. Food Sci.* **2009**, *74*, E312–E321. [CrossRef]
52. Tomczyńska-Mleko, M.; Ozimek, L. Ultrasound viscosity measurements allow determination of gas volume fraction in foamed gels. *J. Food Process Eng.* **2013**, *36*, 572–578. [CrossRef]
53. The Commission of the European. EU Commision Regulation (EC) No 1881/2006. Setting maximum levels for certain contaminants in foodstuffs. *Off. J. Eur. Union* **2006**, *364*, 5–24.
54. Huang, D.; Liu, L.; Zeng, G.; Xu, P.; Huang, C.; Deng, L.; Wang, R.; Wan, J. The effects of rice straw biochar on indigenous microbial community and enzymes activity in heavy metal-contaminated sediment. *Chemosphere* **2017**, *174*, 545–553. [CrossRef]
55. Kaneta, M.; Hikichi, H.; Endo, S.; Sugiyama, N. Chemical form of cadmium (and other heavy metals) in rice and wheat plants. *Environ. Health Perspect.* **1986**, *65*, 33–37. [CrossRef]
56. Kowieska, A.; Lubowicki, R.; Jaskowska, I. Chemical composition and nutritional characteristics of several cereal grain. *Acta Sci. Pol. Zootech.* **2011**, *10*, 2.

57. Szpak, P. Fish bone chemistry and ultrastructure: Implications for taphonomy and stable isotope analysis. *J. Archaeol. Sci.* **2011**, *38*, 3358–3372. [CrossRef]
58. Jennifer, J.O.; Jennifer Pitzi Hellwig, L.D.M. *Dietary Reference Intakes: The Essential Guide to Nutrient Requirements*; National Academies Press: Washington, DC, USA, 2006; ISBN 9780309100915.
59. Strozyk, A.K.; Pachocka, L. The role of nuts consumption in the primary and secondary prevention of type 2 diabetes. *Clin. Diabetol.* **2017**, *6*, 26–33. [CrossRef]
60. Kalman, D. Amino Acid Composition of an Organic Brown Rice Protein Concentrate and Isolate Compared to Soy and Whey Concentrates and Isolates. *Foods* **2014**, *3*, 394–402. [CrossRef] [PubMed]
61. The European Parliment and the Council of the European Union Regulation (EC) No 1924/2006. *Off. J. Eur. Union* **2011**. Available online: https://esinvesticijos.lt/uploads/main/documents/files/20111018_general_proposal_en.pdf (accessed on 9 October 2020).
62. Li, Y.O.; Komarek, A.R. Dietary fibre basics: Health, nutrition, analysis, and applications. *Food Qual. Saf.* **2017**, *1*, 47–59. [CrossRef]
63. Gershuni, V.M. Saturated Fat: Part of a Healthy Diet. *Curr. Nutr. Rep.* **2018**, *7*, 85–96. [CrossRef]
64. Hall, A.C.; Fairclough, A.C.; Mahadevan, K.; Paxman, J.R. Ascophyllum nodosum enriched bread reduces subsequent energy intake with no effect on post-prandial glucose and cholesterol in healthy, overweight males. A pilot study. *Appetite* **2012**, *58*, 379–386. [CrossRef]
65. Prabhasankar, P.; Ganesan, P.; Bhaskar, N.; Hirose, A.; Stephen, N.; Gowda, L.R.; Hosokawa, M.; Miyashita, K. Edible Japanese seaweed, wakame (Undaria pinnatifida) as an ingredient in pasta: Chemical, functional and structural evaluation. *Food Chem.* **2009**, *115*, 501–508. [CrossRef]
66. Usha, R.; Lakshmi, M.; Ranjani, M. Nutritional, sensory and physical analysis of pumpkin flour incorporated into weaning mix. *Malays. J. Nutr.* **2010**, *16*, 379–387.

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Research Article

The Influence of the Syrup Type on Rheology, Color Differences, Water Activity, and Nutritional and Sensory Aspects of High-Protein Bars for Sportsmen

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Most often, high-protein bars consist of a protein preparation in the form of a loose powder, stuck together with a syrup mixture, ensuring a stable mass. According to the legal regulations in force, at least 20% of the energy value must come from protein for the product to be called high-protein. The objective of this study was to evaluate the impact of different syrup sources (oligofructose, maltitol, tapioca fiber, and chickpea-maize fiber) on rheology, water activity, color, and nutritional and sensorial properties of high-protein bars. Texture has changed depending on the type of syrup used. A significant increase of the hardness parameter referring to the control sample was noted for bars containing chickpea-maize liquid fiber in chocolate (311.65 N), with low adhesiveness simultaneously (54.71 N). Samples without chocolate made with the use of oligofructose syrup had apparently higher dynamic viscosities than other bars (226.67 mPas · g/cm^3). The water activity of all tested bars indicated the high stability of samples over time (<0.80), except for samples without chocolate made of PM syrup. The color of the tested bars was from light cream to Earth yellow. Bars obtained with tapioca liquid fiber had the lowest nutritional value. Results presented in this study suggest that selecting the correct type of syrup may significantly influence the functional properties of high-protein bars.

1. Introduction

High-protein bars have been a growing industry over the last few years [1]. Because of this growth, manufacturers are preparing new formulations to meet consumer needs, first of all, with a reduced tendency to harden during storage. However, on the EU market, the vast majority of high-protein products are still made with high-sugar, glucose-fructose, and glucose syrups due to the excellent technological properties of these syrups. The addition or substitution of different ingredients like protein, syrup, fat, sweetener, and inclusions can potentially increase the chance of manufacturing issues [2].

The food industry has developed many new high-protein bar recipes to keep current with consumer preferences and expectations. Unfortunately, due to the low cost of standard raw materials (high-fructose syrups and sugar syrups), most producers do not decide to modify these elements in their recipes, especially when it comes to syrups. High-protein bar formulations consist of three common ingredients: protein powder, syrup, and some form of fat [3]. First, these ingredients conditioned the creation of the correct features of a high-protein product from production (features determining technological suitability allowing for high production efficiency) until the product hits the store shelf and the final consumer. Therefore, it seems appropriate to search for suitable alternatives to commonly used ingredients such as high-fructose and glucose syrups, fats, or allergenic proteins, into their alternative components, e.g., polyols, fructooligosaccharides, or different protein sources (plant and animal

proteins), while maximizing maintaining the technological parameters of the production process [4].

Food research is constantly searching for new ways to replace sugar. It is due to the negative connotations of sugar consumption on health, which has driven consumer demand for healthier products and is reflected on a national level by taxation, especially sugary beverages. Sugar alcohols, a class of polyols, are present at varying levels in many fruits and vegetables and can be added to foods such as low calorific sweeteners. The most commonly used polyols in food include sorbitol, mannitol, xylitol, erythritol, maltitol, lactitol, and isomalt. Products resulting from such activities can be of particular interest to people using different diets [5]. It is worth noting that obesity has increased dramatically in recent decades, a phenomenon widely associated with the so-called "western diet": energy-dense, highly palatable foods with high fat and sugar content. Dietary fiber consists of nondigestible forms of carbohydrate, usually polysaccharides, which originate from plant-based foods. Over recent decades, our diet within Westernized societies has changed radically from our hominid ancestors, with implications for our coevolved gut microbiota. It includes increased ingestion of ultraprocessed foods that are typically impoverished of dietary fiber and associated reduction in the intake of fiber-replete plant-based foods. Over recent decades, there has been a transformation in our understanding of the health benefits of dietary fiber [6]. Based on observation of most commercial high-protein bar labels, there is a low variety of each basic ingredient used; for simplicity, this study used a model system composed of glucose syrup (GS), whey protein concentrate (WPC), and liquid vegetable fat, that is, rapeseed oil. In general, the level of each ingredient likely impacts the mechanical behaviors, textures, and nutritional value of high-protein bars [7].

According to our current available knowledge, there is no research on ultrasonic viscosity and determining the color differences by Computer Vision System (CVS), and no such studies are using industrial devices, which ensure high repeatability of the parameters of the final products for the application of high-protein bars. Furthermore, the use of alternative syrup sources, e.g., chickpea-maize fiber, oligofructose, and tapioca in the production of high-protein bars, is limited. The research was aimed at determining whether the replacement of the type of syrup (oligofructose, maltitol, tapioca fiber, chickpea, and corn fiber) will have an impact on the texture, rheology, water activity, differences in color, and nutritional and sensory properties of high-protein bars and their possible declarations in accordance with applicable European Union (EU) legislation.

2. Materials and Methods

2.1. Materials. The following raw materials were used to prepare high-protein bars: glucose syrup (GS—Dextrose Equivalent "DE" 40, Amylon, Havlíčkův Brod, Czech Republic), maltitol syrup (ML — 50–55% maltitol, Roquette, Lestrem, France), oligofructose syrup from chicory inulin (OF—oligofructose content ≥73%, Sensus, Roosendaal, Netherlands), tapioca liquid fiber (TF—dry substances ≥75%, K2B, Searles Meadow, Cambridge, United Kingdom), chickpea-maize liquid fiber (PM—dry substances ≥74%, HiFood, Parma, Italy), whey protein concentrate (WPC80, 80% proteins, Polser Sp. z o. o., Toruń, Poland), maltodextrin (Dextrose Equivalent "DE" 15, Amylon, Havlíčkův Brod, Czech Republic), vegetable oil (rapeseed oil) (ZT "Kruszwica" S.A., Kruszwica, Poland), soy lecithin (Identity Preserved "IP" 50, Brenntag, Kędzierzyn-Koźle, Poland), powdered barley malt extract (Mountons Ingredients, European Brewery Convention "EBC" color: 5 to 12), chocolate (Barry Callebaut, Łódź, Poland), and natural vanilla aroma in powder (GBD Aromaty, Warsaw, Poland).

2.2. Preparation of High-Protein Bars. The first step was to mix protein concentrate (38.18%, w/w) with aroma (0.91%, w/w) and maltodextrin (5.45%, w/w) using the B10A industrial mixer (Technologies 4ALL Sp. z o. o. Sp. k.; Kępno, Poland) at 190 rpm for 1 min. In a separate laboratory vessel, barley malt extract (3.64%, w/w) was dissolved in water (5.45%, w/w). Soy lecithin (0.91%, w/w) and rapeseed oil (13.64%, w/w) were mixed in the second vessel. Syrups (31.82%, w/w) were heated to 80°C and then combined with dry ingredients. The remaining ingredients prepared earlier were added to the mixer bowl simultaneously after pouring the syrup. The prepared mass was mixed for 5 min at 365 rpm using an oar end. In the end, processed high-protein bar mass was laid onto the conveyor belt using the CONBAR 600 (SOLLICH GmbH & Co. KG, Bad Salzuflen, Germany) and pulled out by forming rollers to a height of 15 mm and then cooled to 10°C for 15 min using the cooling tunnel. The chilled bar mass was subjected to longitudinal cutting using the longitudinal slitter. Finally, the longitudinally cut mass was cut transversely using the CONBAR 600 transverse guillotine into individual bars (95 × 30 mm). The bars to be coated with chocolate were covered with chocolate (22%, w/w) using the DK3520 (A.E. NIELSEN Maskinfabrik ApS., Farum, Denmark). Chocolate had a temper index (TI) oscillating in the range of 5.0–5.5, measured using the Temper meter RET-250TMK (ELMI Automatic Systems, Warsaw, Poland). Next, chocolate-coated bars were cooled using the DK3520 A.E. NIELSEN cooling tunnel to a temperature of 10°C for 15 min. The prepared bars were packed in high-barrier foil using a manual impulse sealer PFS 200 (NOVUMPACK, Kraków, Poland). After the storage period (room temperature, plastic container), the samples were tested. The high-protein bar samples were unpacked from the foil 5 min before measurements. Cylindrical blocks in height of 15 mm and diameter of 12 mm were punched out to analyze the texture of tested bars. The sample was prepared alike by weighing 6 g of sample for testing to determine viscosity and water activity. Each high-protein bar sample was prepared in twenty repetitions.

The recipe was developed on the basis of products available on the market, our experience and knowledge of current market trends, and a previous publication [4]. Before that, an optimization of different ingredients was performed.

2.3. Texture Profile Analysis (TPA). Hardness, adhesiveness, fracturability, and cohesiveness were evaluated using the TA-XT2i Texture Analyzer (Stable Micro Systems,

Godalming, Surrey, UK). All measurements were performed, following the protocol defined by Małecki et al. [4]. The samples were pressed twice by a probe with a diameter of 36 mm (SMS P/36R) until deformation of 70% was obtained (load cell 50 kg, the speed rate of the probe was 1 mm/s, interval between probe movements: 5 s). Analyses were carried out in five replications for each sample.

2.4. Cutting Test. According to the method of Małecki et al. [4], the cutting strength of high-protein bars was measured using TA-XT2i Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK). The blade set with a knife (HDP/BSK) comprising a Warner Bratzler blade (a reversible blade with knife edge) with a slotted blade insert and a blade holder was used for the experiment. The samples were placed on a metal plate. The used blade was lowered at a speed of 2 mm/s. Five repetitions were applied for each formulation.

2.5. Viscoelastic Properties. The Kinexus lab + rheometer (Malvern Panalytical, Cambridge, UK) with serrated plates (PU40 SR3012 SS and PLS40 S2339 SS, at the plate-plate configuration) was used to evaluate storage (G′), loss (G″) moduli, and phase angle (δ) of high-protein bars. Measurements were made at 21°C and frequency of 0.1 Hz and computer-registered in the Kinexus Malvern program—rSpace.

2.6. Back Extrusion. The TA-XT2i Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK) was used with a back extrusion test to measure the consistency of syrups used to obtain bars. A back extrusion ring was used with a container diameter of 50 mm and a head diameter of 45 mm. Head travel speed was 1 mm/s. Measurements were performed in three replications.

2.7. Water Activity. According to Szafrańska et al. [8], measurements were performed at the temperature of 25°C, in five repetitions using the AWMD-10 water activity meter (NAGY, Gäufelden, Germany). Water activity (a_w) was measured with an accuracy of ±0.001 of the a_w unit.

2.8. Computer Vision System (CVS) and Determining Color Differences. Color differences were determined using Computer Vision System (CVS), according to Tomasevic et al. [9]. Colorimetric measurements (three repetitions) of obtained products was expressed in terms of the International Commission on Illumination (CIE L^* a^* b^*) color space with the coordinates being a^* (red-green), b^* (yellow-blue), and L^* (0–100, estimation of lightness) [10]. According to the NBS (National Bureau of Standard) reference scale, the notable differences could be described as "marked changes", implying that such changes are perceptible to the human eye. A bar made of GS syrup was adopted as a control sample.

The total color difference was calculated using the following formula:

$$\Delta E = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2 + (L_1 - L_2)^2}. \quad (1)$$

The ΔE^* values were converted into National Bureau of Standards (NBS) units by equation (11):

$$\text{NBS units} = \Delta E \times 0.92. \quad (2)$$

2.9. Ultrasonic Viscosity. The ultrasonic viscometer Unipan type 505 (UNIPAN, Warsaw, Poland) was applied to evaluate the dynamic viscosity of bars according to the method of Małecki et al. [4]. Viscosity tests using ultrasonic signals involve the use of a probe that generates free vibrations. The alternating electric current induces an alternating magnetic field, which deforms ferromagnetic materials (magnetostriction). The generated waves are damped by the tested material. Measurements of the viscosity were performed at 25°C. The results were read in mPas · g/cm^3. All measurements were performed in three repetitions.

2.10. Nutritional Value. Nutritional value was calculated using the X-mart (X-mart Group Sp. z o. o., Lublin, Poland) software based on raw material specifications obtained from suppliers of each ingredient. Data was introduced into the program, and the nutritional value of the finished product was calculated per 100 g.

2.11. Sensory Evaluation. Fifteen trained consumers took part in sensory evaluation. They were recruited from EUROHANSA Sp. z o. o. (Puławy, Poland). The criteria used in panelists selection are as follows: age between 18 and 60 years old, regular consumers of high-protein bars, and not allergic to any raw material used. Panelists were instructed to evaluate the sensory attributes: aroma, color, taste, and consistency. A 5-point scale was used to describe each product (from 1 = extremely dislike to 5 = extremely like) based on the Quantitative Descriptive Analysis (QDA) method with significance factors (0.2—aroma, 0.2—color, 0.35—taste, and 0.25—consistency) [12, 13].

2.12. Statistical Analysis. Statistical analysis was carried out using STATISTICA 13.3 PL software (Dell Software Inc., Round Rock, USA). A one-way ANOVA analysis was applied. Significant differences between high-protein bars were determined by the Tukey *post hoc* test at $P < 0.05$.

3. Results and Discussion

3.1. Texture Profile Analysis (TPA) and Cutting Test. The impact of various syrups on the hardness, fracturability, cohesiveness, adhesiveness, and cutting resistance of the acquired prepared high-protein bars with or without chocolate covering is introduced in Tables 1 and 2. Huge contrasts ($P < 0.05$) were noticed. The bars made of glucose syrup (GS) and chickpea-maze syrup (PM) had the most elevated hardness (91.43 N—GS and 81.97 N—PM for bars without chocolate and 311.65 N—PM and 106.26 N—GS for

Table 1: Impact of different syrup applications on high-protein bars texture attributes and cutting resistance.

Type of syrup used in bars without chocolate covering	Texture attributes				Cutting resistance force (N)
	Hardness (N)	Fracturability (N)	Adhesiveness (J)	Cohesiveness	
OF	$26.75^{a} \pm 0.893$	$0.13^{b} \pm 0.017$	$13.47^{c} \pm 1.320$	$0.34^{bc} \pm 0.009$	$133.25^{a} \pm 3.622$
TF	$53.06^{b} \pm 1.981$	$0.21^{d} \pm 0.011$	$16.13^{d} \pm 2.000$	$0.34^{bc} \pm 0.015$	$163.25^{c} \pm 3.999$
ML	$62.44^{c} \pm 0.692$	$0.20^{cd} \pm 0.007$	$28.22^{e} \pm 1.518$	$0.36^{c} \pm 0.020$	$167.56^{c} \pm 1.337$
PM	$81.97^{d} \pm 1.261$	$0.19^{c} \pm 0.009$	$3.01^{a} \pm 0.446$	$0.17^{a} \pm 0.005$	$135.49^{a} \pm 2.808$
GS	$91.43^{e} \pm 0.250$	$0.04^{a} \pm 0.002$	$8.68^{b} \pm 0.299$	$0.32^{b} \pm 0.017$	$156.16^{b} \pm 2.947$

Data are presented as means ± SD (standard deviation). $^{a-e}$ Means in the same column with different superscripts are significantly different ($P < 0.05$, Tukey's honestly significant difference "HSD" test). OF: oligofructose, TF: tapioca liquid fiber, ML: maltitol, and PM: chickpea-maize liquid fiber.

Table 2: Impact of different syrup applications on high-protein bars texture attributes and cutting resistance.

Type of syrup used in bars with chocolate covering	Texture attributes				Cutting resistance force (N)
	Hardness (N)	Fracturability (N)	Adhesiveness (J)	Cohesiveness	
OF	$38.79^{a} \pm 0.432$	$0.10^{cb} \pm 0.013$	$145.32^{b} \pm 15.302$	$0.27^{b} \pm 0.010$	$70.10^{a} \pm 0.803$
TF	$81.61^{b} \pm 1.167$	$0.12^{c} \pm 0.011$	$214.53^{c} \pm 14.285$	$0.23^{a} \pm 0.015$	$124.95^{b} \pm 0.566$
ML	$73.36^{b} \pm 0.672$	$0.09^{b} \pm 0.007$	$236.99^{c} \pm 24.602$	$0.30^{b} \pm 0.009$	$132.01^{c} \pm 2.145$
PM	$311.65^{d} \pm 10.401$	$0.12^{c} \pm 0.012$	$54.71^{a} \pm 3.596$	$0.28^{b} \pm 0.013$	$124.12^{b} \pm 0.928$
GS	$106.26^{c} \pm 2.149$	$0.04^{a} \pm 0.009$	$571.75^{d} \pm 23.101$	$0.34^{c} \pm 0.033$	$148.68^{d} \pm 4.688$

Data are presented as means ± SD (standard deviation). $^{a-d}$ Means in the same column with different superscripts are significantly different ($P < 0.05$, Tukey's HSD test). OF: oligofructose, TF: tapioca liquid fiber, ML: maltitol, and PM: chickpea-maize liquid fiber.

bars with chocolate covering). In correlation, the most reduced hardness described bars were produced using oligofructose (OF) in both the examples without chocolate (26.75 N) and with the chocolate covering (38.79 N).

A possible way to explain the tendency to harden high-protein bars may also be the phenomenon of dissolving some proteins during the mixing of ingredients and then precipitation of proteins for the next few days from the production of the final products. It can cause the extraction of water from the product and dissolved protein, which is related to the competition for hydration water between dissolved and undissolved proteins [14]. By and large, the hardness of high-protein bars is generally high and increases with the expansion of protein [15]. A wide variety of parameters characterized the developed high-protein bars. Considering the examination of Małecki et al. [4] and Mcmahon et al. [16], some routineness can be seen for bars made of whey proteins, glucose syrup, or high-fructose corn syrups. A high worth of the hardness goes with bars made of this kind of protein and syrups. A relatively low value of the hardness parameter translates into low adhesiveness values in bars without chocolate and higher levels of this parameter in chocolate-coated bars. The different situations can be seen for PM syrup. Despite the high hardness of the bar made of this type of syrup, it correlates with low adhesiveness values in both samples (with and without chocolate). The results obtained from the research on a bar made of PM syrup also deserve attention due to the relatively low level of all TPA parameters, particularly in the sample without chocolate covering. The obtained results also confirm the research carried out earlier by McMahon et al. [16] in which the use of polyhydric alcohols such as sorbitol or maltitol reduces the hardness of high-protein bars during the storage process compared to products made on glucose syrups and high-fructose corn syrups.

Regarding Tables 1 and 2, the bars made of ML and TF without chocolate (167.56 N—ML; 163.25 N—PM) and GS with the chocolate covering (148.68 N) showed the most considerable cutting opposition. Then, again, the most minor cutting opposition characterized a high-protein bar made with OF syrup without chocolate (70.10 N). The acquired outcomes correspond with the cohesiveness examination and affirm the connection between the cohesiveness of bars and the power expected to cut them. As a general rule, it very well may be seen that the chocolate-covered bars had higher protection from the cutting power. Cutting resistance differences for bars bade of GS, ML, TF, and PM are significant but not very large. This occurrence may result from the degree of chocolate tempering, which slightly changes during the chocolate tempering process. Chocolate with a temper index (TI) level of 5.0–5.5 is described as high hardness, causing a snap when breaking, which is an element wanted by buyers in this kind of item. It is likewise affirmed by the sensory examination performed. The deviations

might be identified with the adhesiveness of the chocolate layer in some places of the bars because under conditions, the products are covered with a surge of chocolate, and too high layer of chocolate is brushed off through an impact of packed air, which makes a wave on the item normal for chocolate-covered items accessible on the store racks. An appropriately tempered chocolate displays reflexive, proper dissolving temperature and fat-blossom security with wanted trademark crunchiness and hardness during eating, relying upon the measure of chocolate on the result [17].

3.2. Back Extrusion and Viscoelastic Properties. Concerning Table 3, OF (1.515 N), TF (10.536 N), and ML (36.520 N) syrups showed the most reduced protection from the activity of the pivot power. The main trouble in embeddings and broadening the pivot, which was related to the need to apply an immense power, can be seen due to PM (309.583 N) and GS (295.730 N). Presumably, the fundamental justification of the distinctions in these boundaries is the consistency of the syrups utilized and the individual parts that are segments of these syrups. For Newtonian liquids (counting water, which is the fundamental segment of all syrups utilized), the consistency does not rely upon the shear rate; however, it relies upon the substance's properties shaping the liquid and its thermodynamic boundaries like temperature and pressing factor. On the other hand, the various carbohydrates present in the syrups (including polyhydric alcohols) mean that these syrups do not behave like Newtonian liquids, which means that they are characterized by different parameters of backward extrusion analysis [18, 19].

With regard to Table 3, G′ values increase significantly in the case of PM syrup, which testifies the strengthening of the gel structure of high-protein bars made of it ($P < 0.05$). The storage (G′) modulus values were consistently lower than the loss (G″) modulus in all tested samples. It means that measured syrups exhibited viscous properties during the whole measurement. A correlation of storage (G′) and loss (G″) with hardness values of high-protein bars was noticed, indicating that the structure of obtained product becomes harder and more compact along with the use of PM syrup to application. When the loss tangent $\delta < 45^{\circ}$, the product exhibits elastic (gel) properties; otherwise (i.e., $\delta > 45^{\circ}$), the product shows viscous properties. In every tested syrup, the value of δ was higher than 45°, so they can be considered viscous-like products. The PM syrup presented the highest value of measure features, which means that this syrup has greater elastic properties than other tested samples. The highest values of shear stress were also found for this syrup. It is consistent with the conclusions of other researchers who have studied agave syrup used for muffin making [20], high-fructose corn syrup used for high-protein bars production [2], and syrup systems with various viscoelastic properties [21], who showed that the use of different sources of carbohydrates and polyols and their mutual ratio and degree of hydration affect the storage (G′) and loss (G″) moduli values. An increase in the water content in syrups probably causes a decrease in their viscosity parameters, thus contributing to increased parameters related to castability properties. It may play an important role, especially in the case of baked products, due to the need to extend the long thermal processes to achieve the textural parameters of the finished products comparable to the commonly used syrups (sugar, glucose, glucose-fructose syrups) [20]. According to other researchers, there is a direct link between the amount of protein and storage values (G′) and loss (G″) in high-protein products. It is because with a low sugar content in whey protein concentrates and isolates, when the proteins are denatured, their gelation temperature is shifted [22]. Based on the research performed by Koh et al. [23], it is possible that the development nature of the storage values (G′) and its thermal stability change as a result of the addition of different levels of cosolvent (40–70%) in the formulation of the products. In addition, there is a sharp drop in the storage modulus between 40 and 70% of the sugar concentration of the polysaccharide used for production. This is the same for all the syrups used in our study, except PM, possibly as a result of the high soluble fiber content.

3.3. Water Activity. The estimation of water activity of high-protein bars is shown in Figure 1. During the storage stage, the water activity of high-protein bars changes [24]. The explanation of this process may be the research carried out earlier by other researchers. It is assumed that high-protein bars have water in two states: bound water and free water. The interaction between free water and the protein surface is usually weak, while bound water shows a strong association with protein and saccharide molecules [25]. Various states of humidity are exchanged between the zones surrounding the surface of protein molecules. During the storage period, the humidity increases by approx. 4%. The hydrophobicity of different types of proteins when combined with individual syrups can vary considerably. The interaction between bound water and protein is enhanced, which is one of the reasons why high-protein bars harden [26, 27]. Hence, the bars were put away for three weeks in a fixed plastic box (each bar was additionally wrapped in a high-barrier metalized foil) at 20°C. The stockpiling time was obtained based on Banach et al.'s [28] research, which showed that the aw increase was not significant after this period.

The highest a_w esteem described a bar without chocolate covering made with chickpea-maize syrup (PM) of 0.802 and the least (GS) of 0.715 high-protein bar made with glucose syrup and chocolate covering. Acknowledged speculations guarantee that most offal microbes will develop down to about 0.95 aw, which is the reason microorganisms are the dominant vegetation of most high-moisture food sources. Other bacteria, many of public health concern, may reach values of 0.90 or even 0.85 a_w. Except for moderate and high halophilic ones (e.g., those that settle brackish waters and salt-rich food sources), microbes do not contend well in "high osmotic" (low a_w) conditions. Accordingly, food items with a water activity underneath 0.85 are moderately microbiological safe [29]. All prepared bars had a water activity beneath 0.85. Nonetheless, considering the outcomes got on account of a bar made of PM syrup, it tends to be expected that it will show the most elevated helplessness to the improvement of microorganisms specifically forms (mycotoxigenic *penicillia*),

Table 3: Values of back extrusion force, G′, G″ modulus, and δ (°) of tested syrups used in high-protein bars.

Type of syrup	Force (N)	G′ (Pa)	G″ (Pa)	δ (°)
OF	$1.515^{a} \pm 0.058$	$0.104^{a} \pm 0.102$	$2.484^{a} \pm 0.133$	$90.919^{b} \pm 3.207$
TF	$10.536^{b} \pm 0.420$	$0.801^{a} \pm 0.141$	$16.915^{b} \pm 1.825$	$90.028^{ab} \pm 5.330$
ML	$36.520^{c} \pm 1.219$	$0.124^{a} \pm 0.115$	$2.325^{a} \pm 0.182$	$88.472^{a} \pm 4.094$
PM	$309.583^{e} \pm 3.247$	$48.340^{b} \pm 10.697$	$158.417^{d} \pm 23.573$	$98.582^{c} \pm 18.856$
GS	$295.730^{d} \pm 2.993$	$0.798^{a} \pm 0.641$	$32.292^{c} \pm 1.043$	$89.390^{ab} \pm 1.475$

Data are presented as means ± SD (standard deviation). $^{a-e}$ Means in the same column with different superscripts are significantly different ($P < 0.05$, Tukey's HSD test). OF: oligofructose, TF: tapioca liquid fiber, ML: maltitol, and PM: chickpea-maize liquid fiber.

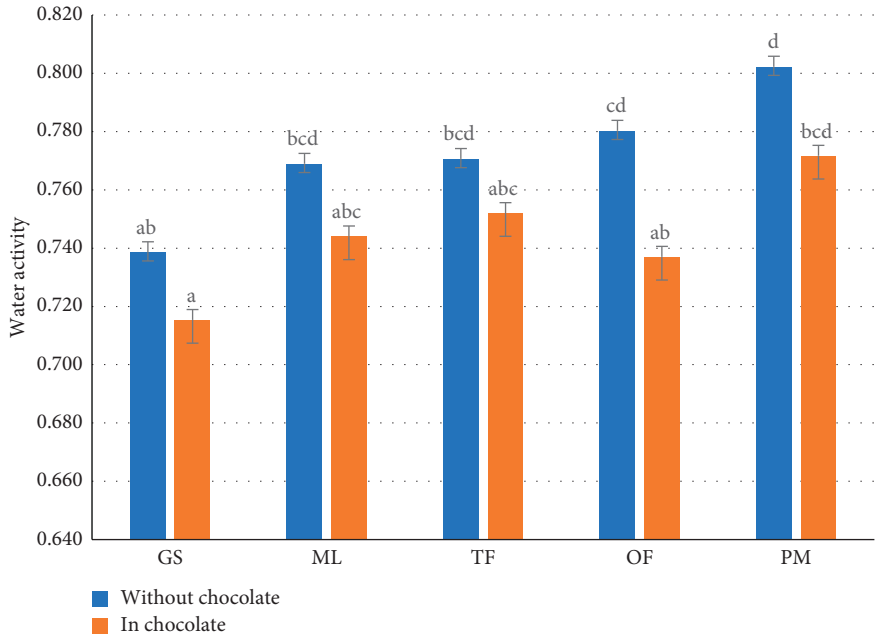


Figure 1: Impact of different syrup applications on water activity of high-protein bars without chocolate covering and with chocolate covering. Letters (a-d) indicate significant differences at $P < 0.05$ (Tukey's HSD test). OF oligofructose, TF—tapioca liquid fiber, ML—maltitol, PM—chickpea-maize liquid fiber.

Staphylococcus aureus, Saccharomyces (most *bailii* spp., *Debaryomyces*) [30]. Such high water activity boundaries on account of this syrup might show a high substance of artificially unbound water in this sort of syrup [31]. Bound water molecules have intense water–ion and possibly hydrogen–ion and water–dipole interactions between the water and protein and sugar/polyol molecules as indicated by the current information on changes in the design or association of syrups in an item might be related to the actual properties of syrups and the protein utilized. Properties, for example, water content, Brix, consistency, and the capacity to emulsify assume a significant role [32]. The distinctions on account of the examples with chocolate covering might result from the limitation of air admittance to the item's inside because of the covering with a layer of chocolate. The high water action worth of bars made of PM syrup might be identified with the high limit of this sort of syrup to assimilate water and fat [33].

3.4. Computer Vision System (CVS) and Determining Color Differences. Usually, the fundamental perspective that lessens the nature of high-protein bars is their solidifying after some time. In any case, visual assessment can likewise be a basic quality pointer for customers of this kind of product. The color of bars made of different kinds of syrups following three weeks of storage is introduced in Tables 4 and 5. The color of a bar made of GS was adopted as the reference sample.

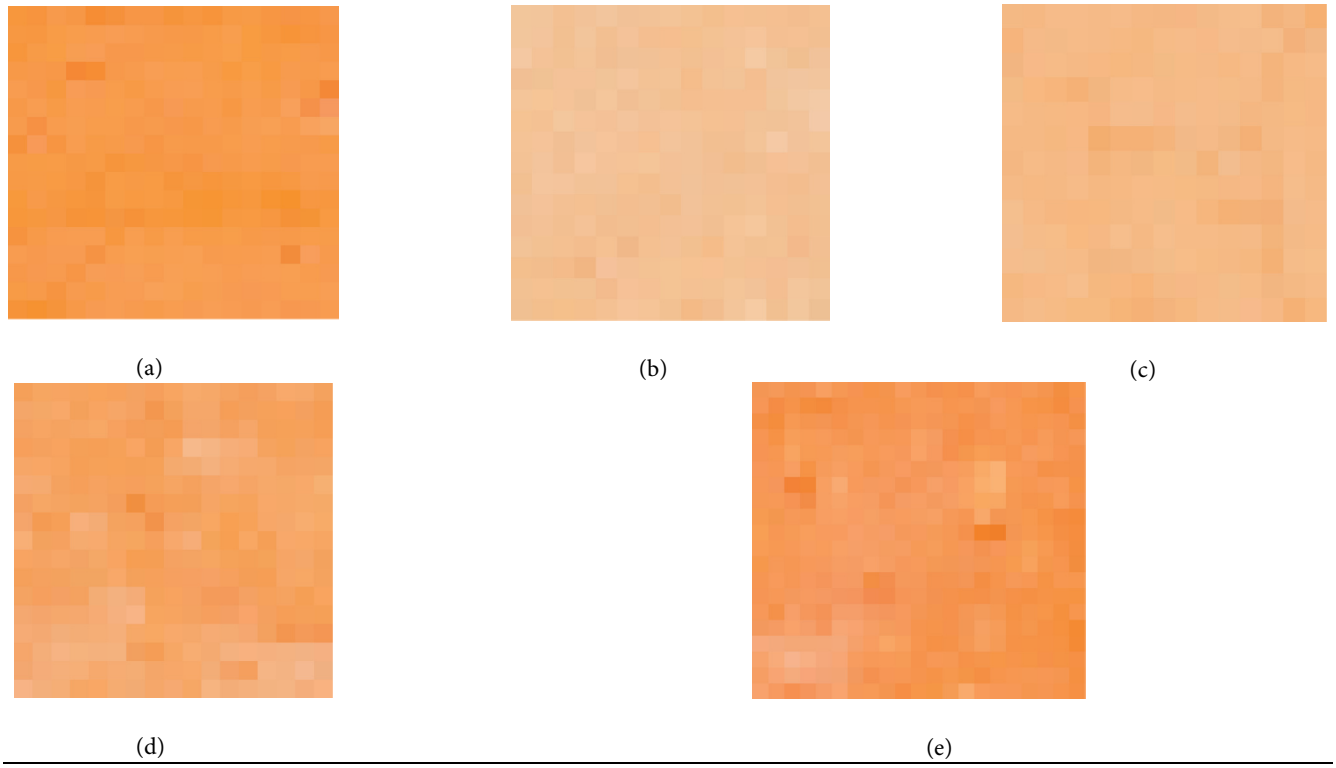
The most habitually utilized strategies for color appraisal in the investigation of food items are colorimetric techniques. In turn, the colors tested using Computer Vision System accurately resemble the actual color of the samples being evaluated. In addition, the color is more intense than for standard colorimetric methods [34]. Inami et al. [35] indicated that all the color contrasts communicated by values more significant than 6 are considerable. Discrepancies <6 prove a slight influence of the syrup used on the difference in the color of high-protein bars. In this situation, an eyewitness will notice differences in the color of the product. The shade of the bars made of PM and ML syrups most closely resembled the shade of the control sample made of GS. Considering examination of McMahon et al. [16], the adjustment of the shade of high-protein bars dependent on whey proteins after the 20th day of storage, paying little heed to the kind of syrup utilized, causes a

Table 4: Impact of different syrups on the color of high-protein bars without chocolate covering measured with computer vision system (CVS).

Type of syrup used in bars with chocolate covering	Attributes				
	L^*	a^*	b^*	ΔE	NBS units
OF	$58.86^{a} \pm 0.388$	$19.71^{a} \pm 0.488$	$49.71^{d} \pm 0.488$	22.21	20.44
TF	$60.29^{b} \pm 0.488$	$20.29^{a} \pm 0.756$	$52.14^{e} \pm 1.069$	23.46	21.58
ML	$65.57^{c} \pm 0.787$	$15.43^{d} \pm 0.535$	$44.57^{c} \pm 0.787$	13.02	11.98
PM	$70.00^{d} \pm 0.000$	$12.86^{c} \pm 0.378$	$40.43^{b} \pm 0.535$	6.77	6.23
GS	$72.14^{e} \pm 0.378$	$10.57^{b} \pm 0.535$	$34.43^{a} \pm 1.134$	—	—

Data are presented as means ± SD (standard deviation). $^{a-e}$Means in the same column with different superscripts are significantly different ($P < 0.05$, Tukey's HSD test). "-" NBS Units of GS syrup reference sample, not subject to calculation. OF: oligofructose, TF: tapioca liquid fiber, ML: maltitol, and PM: chickpea-maize liquid fiber.

Table 5: Recorded differences in the color of the tested high-protein bars based on computer vision system (CVS) photos.



perceptible change in the b* boundary, yellow tone, which becomes brown. The investigations performed additionally affirm McMahon et al.'s [16] research that bars made of whey proteins with glucose syrup over the long haul have a high propensity to darkening. The hue of bars with chocolate covering was not analyzed. Yet, it may be accepted that they would have more splendid hues because of better assurance against light and air access and subsequently hindering the Maillard reaction.

3.5. Ultrasonic Viscosity. Ultrasonic viscometer viscosity estimations were performed at high frequency, and therefore, it is difficult to contrast the acquired outcomes, and those got utilizing different other viscometers. Likewise, ultrasonic viscometers are utilized for ceaseless viscosity estimations under conditions where estimations can be troublesome, and devices like rotational viscometers cannot be adopted [36]. The ultrasonic viscosity is introduced in Figure 2.

The distinctions in the outcomes for the bars tried in this examination were not huge (besides OF syrup); notwithstanding, the most elevated consistency esteems were recorded for bars made with OF and ML syrups and the least for PM and TF. The results of the bars made of GS syrup are hesitant. In the case of bars without chocolate, this sample showed a low viscosity, while in the case of bars in the chocolate covering, it was definitely one of the highest in the measurement. This outcome is presumably impacted by chocolate, which has a higher unique viscosity than the syrup-protein mix utilized in this bar. The decrease in viscosity on account of most chocolate-covered bars (OF, ML, TF) might be identified with the more slow drying out of high-protein bars by restricting air admittance to the center of the bar. Low values of the viscosity parameter,

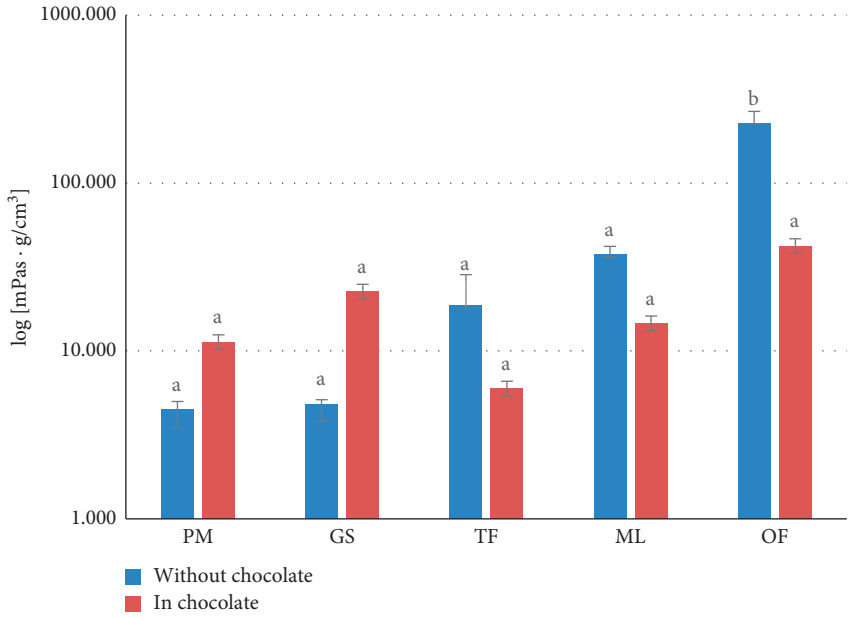


FIGURE 2: Ultrasonic viscosity measurement results (mPas g/cm^3) of tested high-protein bars without chocolate covering and with chocolate covering. Letters (a-b) indicate significant differences at $P < 0.05$ (Tukey's HSD test). OF oligofructose, TF—tapioca liquid fiber, ML—maltitol, PM—chickpea-maize liquid fiber.

particularly for PM and GS, correlate with high results of the hardness parameters in bars without chocolate covering and high parameters of G″ moduli for GS and PM syrups. On the other hand, the relatively high dynamic viscosity of the parameters of the bars made from syrups OF, ML, and TF has been linked to their relatively low hardness and the low parameters of the cutting force. Considering the obtained results and comparing them with the research by Tomczyńska-Mleko et al. [37], it can be assumed that the obtained results could be influenced by factors such as degree of aeration in the bar mass and the consistency and protein concentration the product was made of. Moreover, research conducted by Małecki et al. [4] concerned the use of various types of proteins in high-protein bars and confirmed the dependence that low values of the product viscosity parameter correlate with high hardness parameters. In addition, it is not easy to find other publications to compare the results obtained in this study because the ultrasonic viscosity tests are a rare/novel method for analyzing food items.

3.6. Nutritional Value. Nutritional data and health benefits on the packaging of all food items are obligatory and normalized by pertinent EU guidelines, chiefly by Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers [38]. For the present purchasers who pick protein-advanced items, one of the urgent things is a dietary benefit. The aftereffects of the tried bars' energy and sustenance esteem introduced in Figures 3(a), 3(b), 4(a), and 4(b) show a contrast between the bars made of different syrups.

The main deviation can be found in the higher energy worth and fiber content for bars made of GS syrup. Bars made of TF and PM syrup had the most reduced energy esteem. It was additionally connected with the most significant levels of fiber when these syrups were utilized. It is essential that the utilization of TF, OF, and PM syrups brought about high-fiber content in completed items (>6%). This measure of fiber allows the nutrition claim "high-fiber content" to be used on the packaging of these products following Regulation (EC) No 1924/2006 of The European Parliament and of The Council of 20 December 2006 [39] on nutrition and health claims made on foods. It is essential because observational examinations have shown that dietary fiber admission is related to diminished danger of cardiovascular sickness. Dietary fiber is a nonedible type of sugars because of the absence of enzymes in the human digestive system needed to process this component. The recommended daily allowances (RDAs) for total fiber intake for men and women aged 19–50 are 38 g/day and 25 g/day, respectively [6]. Analyzing the work of researchers [40], in which high-protein bars were analyzed as substitutes for meals for athletes, with a mixture of glycerol, maltodextrin, and inulin as a sticking agent, it can be assumed that the bars obtained in this study also fit this trend, and in the case of TF, OF syrups and PM products contain significant amounts of fiber and the product does not require any warning information to be placed on the packaging against a possible laxative effect. In accordance with the applicable EU law, the use of polyhydric alcohols in the amount greater than 10% requires such a declaration [41]. Based on Figures 4(a) and 4(b), it can be observed that the measured high-protein bars had a low content of saturated fats. It is a crucial feature of food, especially for actively practicing sports and being physically active. Saturated and trans fatty acids are considered to be the most harmful to health types of fatty acids. Their high consumption is conducive to the development of, among others, risk of cardiovascular disease and type 2 diabetes [42].

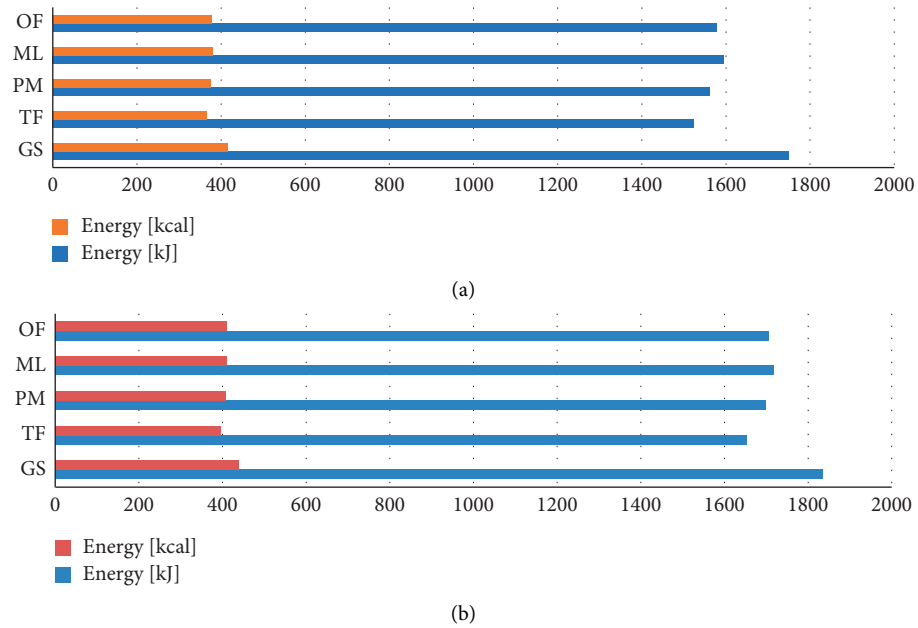


Figure 3: (a) Energy value of high-protein bars without chocolate covering; (b) with chocolate covering. OF oligofructose, TF—tapioca liquid fiber, ML—maltitol, PM—chickpea-maize liquid fiber.

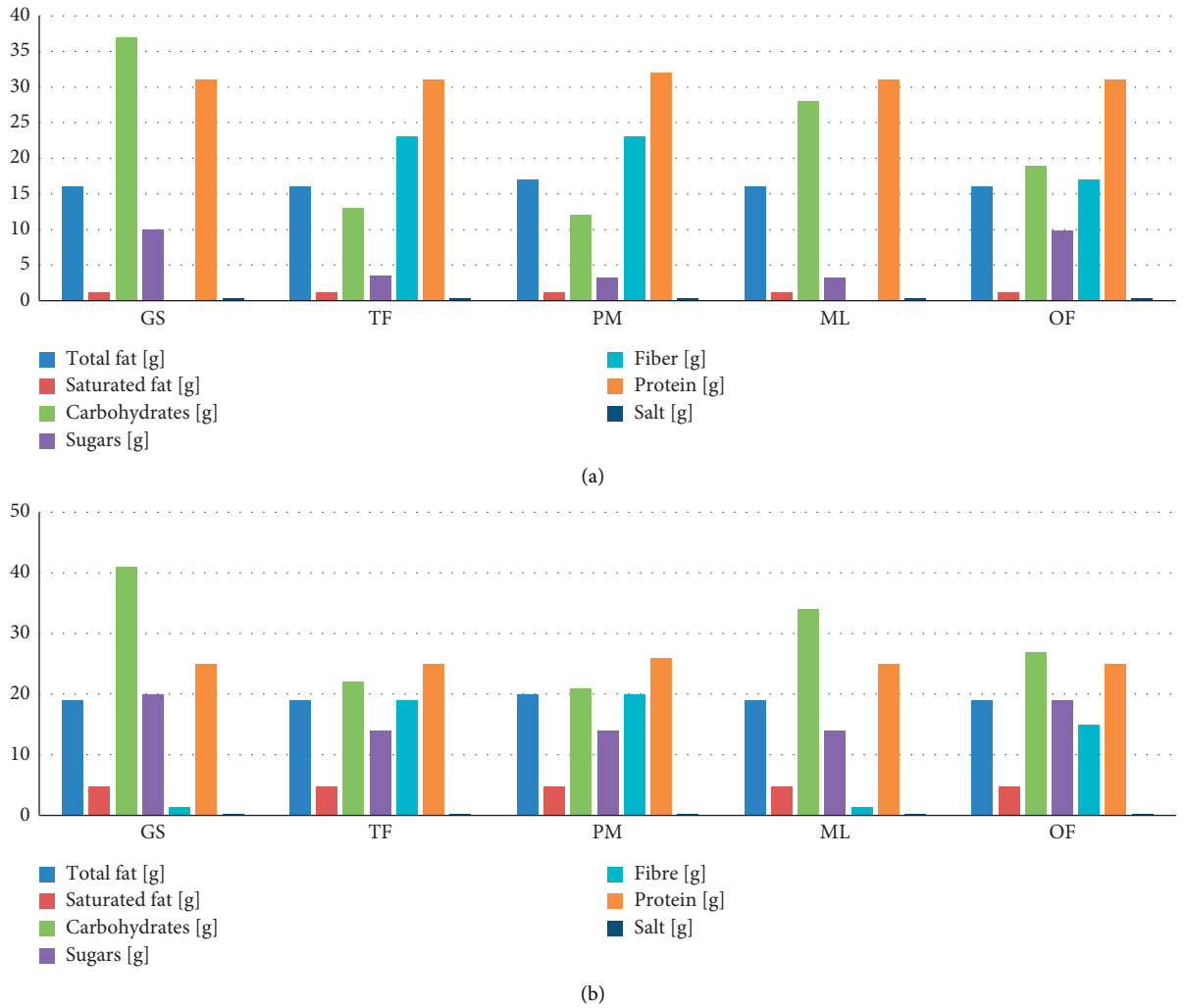


Figure 4: (a) Nutritional value of high-protein bars without chocolate covering; (b) with chocolate covering. OF oligofructose, TF—tapioca liquid fiber, ML—maltitol, PM—chickpea-maize liquid fiber.

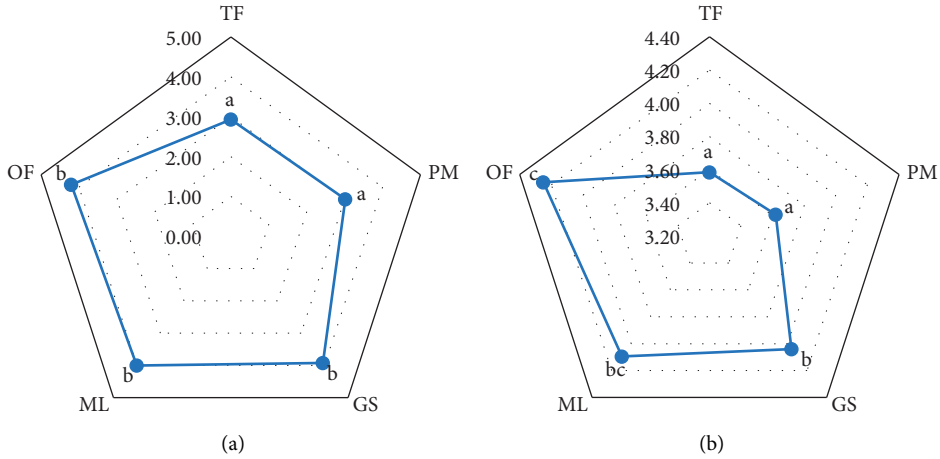


Figure 5: (a) Sensory evaluation of high-protein bars without chocolate covering; (b) with chocolate covering. Means in the same point with different superscripts ($^{a\text{-}c}$) are significantly different ($P < 0.05$, Tukey's HSD test). OF oligofructose, TF—tapioca liquid fiber, ML—maltitol, PM—chickpea-maize liquid fiber.

3.7. Sensory Evaluation. Aftereffects of the sensory evaluation of the tested high-protein bars are introduced in Figures 5(a) and 5(b). The most elevated scores were got for bars made with OF, ML, and GS syrups. The evaluators most liked the outside appearance, surface, and taste impressions of the bars. Sensory studies conducted by other researchers [40, 43] also indicate that color, textural parameters (primarily hardness and chewiness), aftertaste (mainly bitter), and not-specific smell may exert the greatest influence on the assessments of people participating in the study. Consumers prefer sweet flavors with a balanced, easy-to-chew texture [43].

The most exceedingly terrible appraised bars (TF and PM) had too high chomp hardness and an indistinct unsavory lingering flavor, which gave them the most minor evaluations. It might presumably be identified with the extremely high-fiber content of these kinds of syrups used in bars. However, tapioca, which is a good source of vitamin C, calcium, phosphorus, and probiotics, can improve digestion and boost the immune system in humans. Based on the available knowledge, this type of fiber can also be used to lower the percentage of fat in food products [44, 45]. Acquired outcomes propose that high-protein bars with chocolate covering significantly upgrade their agreeability. Obtained results suggest that high-protein chocolate covering greatly enhances their palatability. Referring to the research conducted by other researchers, which concerned research on the use of polyols in shaping the physicochemical properties of soybean isolates, the high ratings of the bar made of ML syrup may be related to the influence of polyols on the structural and surface properties. The interaction of proteins with polyols induces an increased structural order and concentration of protein molecules [5].

4. Conclusions

Based on the sophistication, it can be concluded that changes in the texture and rheology, as well as color, and nutritional and sensorial properties significantly depend on the type of syrup used in the study. The lowest results characterized bars made with OF, TF, and ML syrups during the TPA test and evaluation of viscoelastic properties (G′, G″ moduli) and provide similar parameters of water activity as when using standard glucose syrup (GS). It may indicate the use of these syrups may potentially result in lower hardness of the finished products related to the control sample. Bars made with OF syrup were characterized by the lowest parameters in TPA determinations, which also translated into high parameters of the sensory evaluation of this type of bars. All the glucose syrup equivalents used, except for ML syrup, enable the declaration of "high-fiber content" on the product packaging based on EU standards. It is worth noting that the product made of PM syrup had the highest fiber content (20%), which may be especially valid for people interested in a high-fiber diet. Based on the color assessment using the CVS method and sensory analysis of bars without chocolate covering, it can be concluded that color plays a relevant role for consumers. Sensory analysis showed that the covering of high-protein chocolate bars raises assessment of the tested products, essentially masking certain smells, colors, and tastes of some kinds of syrups, thus helping to increase the overall sensory evaluation. Therefore, it can be unequivocally suggested that high-protein bars should be covered with chocolate. Taking into account the obtained results, however, it can be assumed that such syrup as OF, TF, or ML may be an attractive alternative to GS in high-protein products. More research is needed into storage tests and to investigate the impact of changes in other ingredients in the recipe that may affect parameters necessary for products in the food industry.

Data Availability

The data used to support the findings will be available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

B.G.S. and J.M. conceptualized the study, acquired funding, and provided resources. B.G.S., I.T. were responsible for methodology; provided software; and supervised and validated the study. J.M. was responsible for formal analysis and investigation. J.M. was responsible for data curation, original draft preparation, and visualization. B.G.S. reviewed and edited the manuscript and responsible for project administration. All authors have read and agreed to the published version of the manuscript.

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References

[1] M. Henchion, M. Hayes, A. Mullen, M. Fenelon, and B. Tiwari, "Future protein supply and demand: strategies and factors influencing a sustainable equilibrium," *Foods*, vol. 6, no. 7, pp. 53–21, 2017.

[2] K. Sparkman and H. S. Joyner, "Impact of formulation on high-protein bar rheological and wear behaviors," *Journal of Texture Studies*, vol. 50, no. 6, pp. 445–455, 2019.

[3] S. R. Imtiaz, B. Kuhn-Sherlock, and M. Campbell, "EFfect of dairy protein blends on texture of high protein bars," *Journal of Texture Studies*, vol. 43, no. 4, pp. 275–286, 2012.

[4] J. Małecki, I. Tomasevic, I. Djekic, and B. G. Sołowiej, "The effect of protein source on the physicochemical, nutritional properties and microstructure of high-protein bars intended for physically active people," *Foods*, vol. 9, no. 10, p. 1467, 2020.

[5] P. Mingzhe, M. Xianjun, J. Lianzhou, Y. Dianyu, and L. Tianyi, "Effect of cosolvents (polyols) on structural and foaming properties of soy protein isolate," *Czech Journal of Food Sciences*, vol. 35, no. 1, pp. 57–66, 2017.

[6] G. A. Soliman, "Dietary fiber, atherosclerosis, and cardiovascular disease," *Nutrients*, vol. 11, no. 5, p. 1155, 2019.

[7] S. A. Hogan, I. B. O'Loughlin, and P. M. Kelly, "Soft matter characterisation of whey protein powder systems," *International Dairy Journal*, vol. 52, pp. 1–9, 2016.

[8] J. O. Szafrańska, S. Muszyński, and B. G. Sołowiej, "Effect of whey protein concentrate on physicochemical properties of acid casein processed cheese sauces obtained with coconut oil or anhydrous milk fat," *LWT-Food Science and Technology*, vol. 127, Article ID 109434, 2020.

[9] I. Tomasevic, V. Tomovic, B. Milovanovic et al., "Comparison of a computer vision system vs. traditional colorimeter for color evaluation of meat products with various physical properties," *Meat Science*, vol. 148, pp. 5–12, 2019.

[10] B. Milovanovic, I. Djekic, V. Djordjevic et al., "Pros and cons of using a computer vision system for color evaluation of meat and meat products," *IOP Conference Series: Earth and Environmental Science*, vol. 333, no. 1, Article ID 012008, 2019.

[11] S. A. Hogan, V. Chaurin, B. T. O'Kennedy, and P. M. Kelly, "Influence of dairy proteins on textural changes in high-protein bars," *International Dairy Journal*, vol. 26, no. 1, pp. 58–65, 2012.

[12] E. Ermiş and E. N. Karasu, "Püskürtmeli kurutucu İle Yağı alinmiş Ayçiçeği Protein ekstrakti tozu Üretimi: fonksiyonel Özellikleri ve toz Karakterizasyonu," *Gida/Journal of Foodservice*, vol. 45, pp. 39–49, 2020.

[13] A. Pihlanto, P. Mattila, S. Mäkinen, and A.-M. Pajari, "Bioactivities of alternative protein sources and their potential health benefits," *Food & Function*, vol. 8, no. 10, pp. 3443–3458, 2017.

[14] S. M. Loveday, J. P. Hindmarsh, L. K. Creamer, and H. Singh, "Physicochemical changes in a model protein bar during storage," *Food Research International*, vol. 42, no. 7, pp. 798–806, 2009.

[15] Y. Li, K. Szlachetka, P. Chen, X. Lin, and R. Ruan, "Ingredient characterization and hardening of high-protein food bars: an NMR state diagram approach," *Cereal Chemistry Journal*, vol. 85, no. 6, pp. 780–786, 2008.

[16] D. J. McMahon, S. L. Adams, and W. R. Mcmanus, "Hardening of high-protein nutrition bars and sugar/polyol-protein phase separation," *Journal of Food Science*, vol. 74, no. 6, pp. E312–E321, 2009.

[17] F. Debaste, Y. Kegelaers, S. Liégeois, H. B. Amor, and V. Halloin, "Contribution to the modelling of chocolate tempering process," *Journal of Food Engineering*, vol. 88, no. 4, pp. 568–575, 2008.

[18] T. Hoshino, K. Kawai, and Y. Hagura, "Proposal of short back extrusion method for enabling consecutive viscosity measurements of high-viscosity Newtonian fluid," *Nippon Shokuhin Kagaku Kogaku Kaishi*, vol. 60, no. 2, pp. 100–109, 2013.

[19] C. M. Ionescu, I. R. Birs, D. Copot, C. I. Muresan, and R. Caponetto, "Mathematical modelling with experimental validation of viscoelastic properties in non-Newtonian fluids," *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences*, vol. 378, no. 2172, pp. 20190284–20190321, 2020.

[20] C. Ozuna, E. Trueba-Vázquez, G. Moraga, E. Llorca, and I. Hernando, "Agave syrup as an alternative to sucrose in muffins: impacts on rheological, microstructural, physical, and sensorial properties," *Foods*, vol. 9, no. 7, pp. 895–915, 2020.

[21] R. Wang and R. W. Hartel, "Effects of moisture content and saccharide distribution on the stickiness of syrups," *Journal of Food Engineering*, vol. 284, pp. 110067–110081, 2020.

[22] K. Kusio, J. O. Szafrańska, W. Radzki, and B. G. Sołowiej, "Effect of whey protein concentrate on physicochemical, sensory and antioxidative properties of high-protein fat-free dairy desserts," *Applied Sciences*, vol. 10, no. 20, p. 7064, 2020.

[23] L. Koh, B. Jiang, S. Kasapis, and C. W. Foo, "Structure, sensory and nutritional aspects of soluble-fibre inclusion in processed food products," *Food Hydrocolloids*, vol. 25, no. 2, pp. 159–164, 2011.

[24] J. C. Banach, S. Clark, and B. P. Lamsal, "Texture and other changes during storage in model high-protein nutrition bars formulated with modified milk protein concentrates," *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology*, vol. 56, no. 1, pp. 77–86, 2014.

[25] D. J. McClements, "Modulation of globular protein functionality by weakly interacting cosolvents," *Critical Reviews in Food Science and Nutrition*, vol. 42, no. 5, pp. 417–471, 2002.
[26] P. Zhou, X. Liu, and T. P. Labuza, "Moisture-induced aggregation of whey proteins in a protein/buffer model system," *Journal of Agricultural and Food Chemistry*, vol. 56, no. 6, pp. 2048–2054, 2008.
[27] J. Li, Y. Wu, Y. Ma, N. Lu, J. M. Regenstein, and P. Zhou, "Effects of addition of hydrocolloids on the textural and structural properties of high-protein intermediate moisture food model systems containing sodium caseinate," *Food & Function*, vol. 8, no. 8, pp. 2897–2904, 2017.
[28] J. C. Banach, S. Clark, and B. P. Lamsal, "Instrumental and sensory texture attributes of high-protein nutrition bars formulated with extruded milk protein concentrate," *Journal of Food Science*, vol. 81, no. 5, pp. S1254–S1262, 2016.
[29] M. S. Tapia, S. M. Alzamora, and J. Chirife, "Effects of water activity (a w) on microbial stability as a hurdle in food preservation," *Water Activity in Foods*, vol. 14, pp. 323–355, 2020.
[30] A. Schiraldi, D. Fessas, and M. Signorelli, "Water activity in biological systems—a review," *Polish Journal of Food and Nutrition Sciences*, vol. 62, no. 1, pp. 5–13, 2012.
[31] "Thermal processing of food," *Safefood Whitepaper*, vol. 1, pp. 1–8, 2014.
[32] L. Ninni, M. S. Camargo, and A. J. A. Meirelles, "Water activity in polyol systems," *Journal of Chemical & Engineering Data*, vol. 45, no. 4, pp. 654–660, 2000.
[33] W. Chanasattru, E. A. Decker, and D. Julian McClements, "Impact of cosolvents (polyols) on globular protein functionality: ultrasonic velocity, density, surface tension and solubility study," *Food Hydrocolloids*, vol. 22, no. 8, pp. 1475–1484, 2008.
[34] I. Tomasevic, V. Tomovic, P. Ikonic et al., "Evaluation of poultry meat colour using computer vision system and colourimeter," *British Food Journal*, vol. 121, no. 5, pp. 1078–1087, 2019.
[35] T. Inami, Y. Tanimoto, N. Minami, M. Yamaguchi, and K. Kasai, "Color stability of laboratory glass-fiber-reinforced plastics for esthetic orthodontic wires," *The Korean Journal of Orthodontics*, vol. 45, no. 3, p. 130, 2015.
[36] A. G. A. Sá, Y. M. F. Moreno, and B. A. M. Carciofi, "Plant proteins as high-quality nutritional source for human diet," *Trends in Food Science & Technology*, vol. 97, pp. 170–184, 2020.
[37] M. Tomczyńska-Mleko and L. Ozimek, "Ultrasound viscosity measurements allow determination of gas volume fraction in foamed gels," *Journal of Food Process Engineering*, vol. 36, no. 5, pp. 572–578, 2013.
[38] A. Fransvea, G. Celano, C. N. Pagliarone et al., "Food labelling: a brief analysis of European Regulation 1169/2011," *Italian Journal of Food Safety*, vol. 3, no. 3, p. 3, 2014.
[39] J. Borrell Fontelles and J. Korkeaoja, "The european parliment and the council of the european union regulation (EC) No 1924/2006," *Official Journal of the European Union*, no. 404, pp. 1–17, 2011.
[40] P. Jovanov, M. Sakač, M. Jurdana et al., "High-protein bar as a meal replacement in elite sports nutrition: a pilot study," *Foods*, vol. 10, no. 11, pp. 2628–2712, 2021.
[41] M. Carocho, P. Morales, and I. C. F. R. Ferreira, "Sweeteners as food additives in the XXI century: a review of what is known, and what is to come," *Food and Chemical Toxicology*, vol. 107, pp. 302–317, 2017.
[42] A. Astrup, F. Magkos, D. M. Bier et al., "Saturated fats and health: a reassessment and proposal for food-based recommendations," *Journal of the American College of Cardiology*, vol. 76, no. 7, pp. 844–857, 2020.
[43] V. R. A. Pinto, T. B. d. O. Freitas, M. I. d. S. Dantas et al., "Influence of package and health-related claims on perception and sensory acceptability of snack bars," *Food Research International*, vol. 101, pp. 103–113, 2017.
[44] F. J. San José, M. Collado-Fernández, and R. López, "Sensory evaluation of biscuits enriched with artichoke fiber-rich powders (Cynara scolymus L.)," *Food Sciences and Nutrition*, vol. 6, no. 1, pp. 160–167, 2018.
[45] G. Yadav, J. David, S. Thakur et al., "Evaluation of sensory attributes in different levels of Tapioca in pro-biotic Ice cream," *The Pharma Innovation*, vol. 9, no. 1, pp. 404–407, 2020.

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Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used

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Abstract: The main objective of this study was to investigate the possibility of using a combination of vegetable proteins from soybean (SOY), rice (RPC), and pea (PEA) with liquid syrups: tapioca fiber (TF), oligofructose (OF), and maltitol (ML) in the application of high-protein bars to determine the ability of these ingredients to modify the textural, physicochemical, nutritional, surface properties, microstructure, sensory parameters, and technological suitability. Ten variants of the samples were made, including the control sample made of whey protein concentrate (WPC) in combination with glucose syrup (GS). All combinations used had a positive effect on the hardness reduction of the bars after the storage period. Microstructure and the contact angle showed a large influence on the proteins and syrups used on the features of the manufactured products, primarily on the increased hydrophobicity of the surface of samples made of RPC + ML, SOY + OF, and RPC + TF. The combination of proteins and syrups used significantly reduced the sugar content of the product. Water activity (<0.7), dynamic viscosity (<27 mPas·g/cm^3), and sensory analysis (the highest final ratings) showed that bars made of RPC + OF, SOY + OF, and SOY + ML are characterized by a high potential for use in this type of products.

Keywords: plant protein; liquid fiber; industrial application; nutritional value; optical microscopy; contact angle

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1. Introduction

Nowadays, due to the increased interest in this type of product, high-protein bars are important on the food market, primarily in the case of food for athletes and people on vegan and vegetarian diets. Most of the recipes created for scientific research are not directly translated into an industrial scale. Due to the possibility of using a professional industrial line and performing the described tests of high-protein bars on it, the results of our research will be able to be used by food industry plants as an aid in the development of base recipes. Furthermore, based on our research, producers will be able to create high-protein products with the most desirable physicochemical and sensory properties.

Previous studies of high-protein bars available in the literature mainly concerned their tendency to harden over time due to many physicochemical changes in storage, such as Maillard reactions, water activity changes, sugar crystallization, and molecular migrations, which can cause texture hardening. They were also concerned with the method of reducing this tendency by primarily reducing the content of whey proteins in the recipe for their replacement with other commonly used proteins and the use of mainly polyhydric alcohol syrups [1,2].

Nowadays, functional food, including high-protein bars intended for athletes, military food, or ordinary high-protein products available on store shelves, is becoming more and more common. Sports food is not defined in EU law. Until recently, these products could be classified both as foods for particular nutritional uses or as food intended for people exerting intense physical effort, especially athletes. However, due to the change in the regulations on specific food groups, starting 20 July 2016, these products have been defined as general consumption food [3]. Due to a shortage of free time and often feeling overworked, people are more likely to choose ready-made snacks and meal solutions to satisfy their hunger while being reasonably healthy and tasty [4]. In addition, both taste and texture, color and smell also play an important role in making the customer decide to buy a certain product again or not [5]. The increased demand for energy and nutrients requires the consumption of several times more food weight, including protein. With general recommendations that the food consumed by athletes should be of small volume and easy to digest, supplements and functional food become the optimal solution. Their use is more and more common in the world of sports and medicine and among amateurs practicing sports [6,7]. The purpose of consuming these substances (balanced amounts of carbohydrates, fiber, proteins, and fats) is to provide concentrated nutrients that prevent their deficiency in everyday food or increase the absorption of nutrients in an appropriate and harmless way in the body. Moreover, these agents are the source of many bioactive substances (prebiotics, minerals, or unsaturated fatty acids). The use of supplements and functional foods in sports is mainly aimed at accelerating regeneration and increasing body efficiency [8].

Hydrocolloids such as plant protein isolates, currently obtained mainly from soybeans, peas, and rice, which are an alternative to commonly used animal proteins (whey proteins, egg white, albumins, etc.) also exhibit gelling properties during heat treatment. They can be used as emulsion stabilizers, emulsifiers, ingredients to control the crystallization process, thickening ingredients, and foaming, binding, texturing and texture parameters (modification of product hardness and other texture parameters) [9]. Due to the neutral taste and smell, as well as very good functional properties, primarily soy protein isolates are used in the production of foods for special nutritional purposes, sports supplements, people on a diet, pro-health food, milk replacers as well as soups, sauces, mayonnaise, bakery and confectionery products [10]. They are also used as ingredients in edible coatings, mainly in the meat industry. In vegetarian and vegan products, rice and pea proteins are used as enrichment substances in the production of meatless sausages and meat analogues, and more and more often in bakery and confectionery products, which have been enjoying growing interest in the market in recent years [9,11]. Currently, vegetable liquid fibers, particularly oligofructose and a number of innovative syrups containing similar fructooligosaccharides fiber compositions derived from various plants such as corn or tapioca liquid fibers, are among the most commonly used prebiotic substances to replace glucose and glucose-fructose syrups. They exhibit resistance to the action of digestive enzymes in the digestive system. Therefore, they pass into the large intestine, where they are used by the beneficial microflora living in it, influencing its multiplication and improvement of the host's health significantly [12]. Oligofructoses affect the lipid profile and reduce the level of cholesterol in the blood serum, increase the bioavailability of minerals, prevent and support the treatment of diabetes, have anti-carcinogenic effects and reduce the level of metabolites, allow for the reduction or complete elimination of sugar, glucose syrups and fat in food products, allowing for the formation of attractive dietary products [13]. Polyols, also known as polyalcohols, sugar, or polyhydric alcohols, are a class of semi-synthetic sweeteners. Plums, pears, peaches, apples, olives, figs, strawberries, and raspberries are examples of plants and fruits that contain them naturally. Maltitol, xylitol, sorbitol, lactitol, mannitol, and isomalt are examples of polyols. Sugar alcohols have a lower sweetness than sucrose, allowing them to be employed in larger amounts in food than powerful sweeteners. The lower energy value of these ingredients (2.4 kcal/g) allows for an increase in the percentage of the syrup mass and influences the change of textural parameters, including a reduction

in hardness [14,15]. They operate as fillers, like glucose syrups and increase the product's volume and lowering its specific energy value. They are resistant to enzyme activity and difficult to ferment yet have high chemical stability. Passive diffusion allows polyalcohols to be partly absorbed in the digestive system. Because this process is gradual, it does not result in a surge in blood glucose levels or insulin production by pancreatic cells [16]. However, it should be remembered that the use of polyols in the amount of more than 10% in the finished product requires a declaration on the packaging that the product consumed in large amounts may cause a laxative effect [15].

One of the major problems with high-protein bars is their tendency to harden over time, making the product less affordable and attractive for the consumer. The proteins and syrups used may alter this regularity. This is mainly due to the differences in the origin and individual properties represented by proteins and syrups of plant origin in relation to whey proteins and glucose syrup, most used in the food industry. The mentioned affliction of high-protein bars and the continuous increase in interest in animal protein, high-fructose and glucose syrups equivalents contribute to the growth of this branch of food products. The constant increase in consumer awareness and their search for innovative products require producers to constantly invent new recipes and products [17]. Our previous research was concerned with the effect of various types of proteins on the characteristics and parameters of high-protein bars [18]. The current research focuses on the influence of the best combinations of proteins and syrups on the textural, physicochemical, and sensory parameters in high-protein bars based on selected combinations of soy, rice, pea, and whey proteins, as well as syrups such as oligofructose, liquid tapioca fiber, maltitol, and glucose syrups. The aim of this study was to determine the best possible substitutes for the whey protein concentrate and glucose syrup in the application of high-protein bars made under industrial conditions, considering such aspects as microstructure, water activity, texture analysis, surface tests (contact angle surface), sensory evaluation and a number of physicochemical trials (ultrasonic viscosity, energy, nutritional value, and turbiscan measurement).

2. Materials and Methods

2.1. Materials

The following ingredients were used in the manufactured products: isolate of soy protein (SOY—proteins ≥87 g/100 g, fat 3.1 g/100 g, ≤1 g/100 g carbohydrates, fragmentation: <200 µm, The Solae Company, Geneva, Switzerland), concentrate of whey protein (WPC—protein ≥80 g/100 g, fat 7.4 g/100 g, carbohydrates 4.1 g/100 g, fragmentation: <200 µm, Polser, Toruń, Poland), concentrate of rice protein (RPC—protein ≥80 g/100 g, fat 1 g/100 g, carbohydrates 6 g/100 g, fragmentation: <300 µm, Barentz, Warsaw, Poland), isolate of pea protein (PEA—protein ≥82 g/100 g, fat 4 g/100 g, carbohydrates 0.8 g/100 g, fragmentation: <200 µm, Cosucra, Warcoing, Belgium), glucose syrup (GS—reducing sugar "DE" 40, viscosity—71.6 Pa·s, water content—20%, Cargill, Warsaw Poland), oligofructose syrup from chicory (OF—dry matter ≥73–75.5 g/100 g, viscosity—5.0 Pa·s, water content—25% Cosucra, Warcoing, Belgium), maltitol syrup (ML-maltitol content ≥50 g/100 g, viscosity—4.6 Pa·s, water content—25% Roquette, Lestrem, France), syrup of tapioca fiber (TF—dry matter ≥75 g/100 g, viscosity—33.0 Pa·s, water content—25% Anderson Ingredients, Raalte, Holland), rapeseed oil (Zakłady Tłuszczowe Kruszwica, Kruszwica, Poland), maltodextrin ("DE" 15, Amylon, Havlíčkův Brod, Czech Republic), barley malt extract in powder ("EBC-European Brewery Convention" color: 5–12, WES, Wolsztyn, Poland), soy lecithin (Donauchem, Rokietnica, Poland), and natural vanilla flavor (GBD, Warsaw, Poland).

2.2. Preparation of High-Protein Bars

The production process was conducted in accordance with the methodology of Małecki et al. [18], as further research related to the topic of high-protein bars. Based on the research carried out so far, the most promising specific combinations of proteins and syrups for this

application have been selected. The developed high-protein bars consisted of 38.18 g/100 g protein component (RPC, SOY, WPC, or PEA), 31.82 g/100 g syrup element (OF, GS, ML, or TF), 13.64 g/100 g canola oil, 5.45 g/100 g maltodextrin, 5.45 g/100 g water, 3.64 g/100 g malt extract (from barley), 0.91 g/100 g emulsifier: soy lecithin and 0.91 g/100 g vanilla aroma. The developed products were stored under controlled conditions (relative air humidity 50%, temperature 20 °C) in a plastic container for three weeks.

2.3. Texture Profile Analysis (TPA)

The texture attributes were analyzed using the Texture Analyzer TA-XT2i (Stable Micro Systems, Godalming, UK) and Software Texture Expert, as described by Małecki et al. [18]. The measurements were carried out five times. A 36 mm diameter probe (SMS P/36R) was used to doubly press the high-protein bars to achieve 70 percent deformation. The probe motions were interrupted every 5 s, and the test velocity was adjusted at 1 mm/s.

2.4. Cutting Strength Test

The cutting test of high-protein bars was performed using a Texture Analyzer (TA-XT2i) in line with the Małecki et al. technique [18]. A Warner Bratzler blade with a slotted reversible blade insert and a blade holder with the knife edge made up the blade set with the knife (HDP/BSK). The knife descended at a rate of 2 mm/s. Five repetitions of the measurements were carried out. The cutting curve was obtained by recording the maximum force the blade needed to cut the sample completely. The results were based on the maximum peak (maximum force) resulting from the shear stress.

2.5. Water Activity

On an AWMD-10 water activity meter (NAGY Messsysteme GmbH, Gäufelden, Germany), water activity (a_w) was measured according to the Małecki et al. method [18]. The measurements were carried out five times at a temperature of 25 °C. For each sample, two outliers were classified as defective and were excluded from further analysis.

2.6. Optical Microscopy

The surface and microstructure of the measured high-protein bars were examined using a polarising optical microscope Eclipse E600Pol (Nikon, Tokyo, Japan). The bars samples with an approximate area of one square centimeter were observed directly at the magnifications of ×40, ×100, ×200 and ×400 [19].

2.7. Contact Angle Test

Changes of contact angles on the surfaces of the high-protein bars were tested by making use of a contact angle meter GBX (Rue Loire, France), appointed with the digital camera, temperature, and humidity-controlled measuring compartment (20 °C and 50% relative humidity). A droplet (6 µL) from a syringe was put gently on the bar sample surface using the automatic deposition system. The formed contact angle was rated from the droplet shape by the computer software Win Drop. Distilled water was selected for the measurements [20]. The measurements were performed three times for each sample, and average values were calculated.

2.8. Turbiscan Measurements

Because syrups are one of the main ingredients in high-protein bars and important in shaping their features, dedicated analyzes were performed for these ingredients.

The changes in the fluidity of syrups used in producing the developed high-protein bars were investigated on the Turbiscan LabExpert fitted with a cooling module—TLab Cooler (Formulation, Toulouse, France) in the 20–60 °C range for 45 min. The processed syrup samples in a glass phial were placed in a temperature-controlled chamber. Then, the collimated light beam (λ = 880 nm) generated by an electroluminescence diode passed through the processed syrup sample, and the transmission detector measured the transmit-

ted light at an angle of 0° while the backscatter detector (using a different diode) recorded the light scattered at an angle of 135°. Based on the analysis the Turbiscan Stability Index (*TSI*) values were determined from the equation (Turbiscan Easy Soft, Formulaction, Toulouse, France) [19]:

$$TSI = \sqrt{\frac{\sum_{i=1}^{n}\left(x^i - x_{BS}\right)^2}{n-1}}$$

where x^i is the mean backscatter every 1 min of measurement, x_{BS} is the mean of x^i, and n is the number of scans taken by the instrument.

2.9. Ultrasonic Viscosity

The ultrasonic viscometer Unipan 505 type was used to test the dynamic viscosity of high-protein bars (UNIPAN, Warsaw, Poland). The measurements were taken at a temperature of 25 °C. The ultrasound signal level was checked before each measurement. The measuring probe's tip was entirely immersed in the high-protein bar. The data were measured in mPas·g/cm^3 and represented as mPas·g/cm^3. All samples were tested three times [18].

2.10. Energy and Nutritional Value

The nutritional and energy values of the developed high-protein bars were calculated using the X-mart computer program (X-mart Group, Lublin, Poland) based on the raw material specifications of each ingredient obtained from the individual suppliers. The values were converted into 100 g of the finished product.

2.11. Sensory Analysis

The evaluation group consisted of 15 people from EUROHANSA Sp. z o. o. trained in the sensory analysis. The panelists were between 18 and 60 years of age, with no allergies to any of the ingredients in the tested products, and were regular consumers of high-protein products. A five-point scale (1—extremely dislike, 5—extremely like) with the significance coefficients (0.2—color, 0.2—aroma, 0.25—consistency, and 0.35—taste) was used for the study [21,22].

2.12. Statistical Processing of the Results

The STATISTICA 13.3 program (Stat Soft Polska, Kraków, Poland) was used to undertake statistical analysis of the acquired findings. The significant differences between the tested samples were assessed using a one-way ANOVA with a Tukey's post hoc test at $p < 0.05$.

3. Results and Discussion

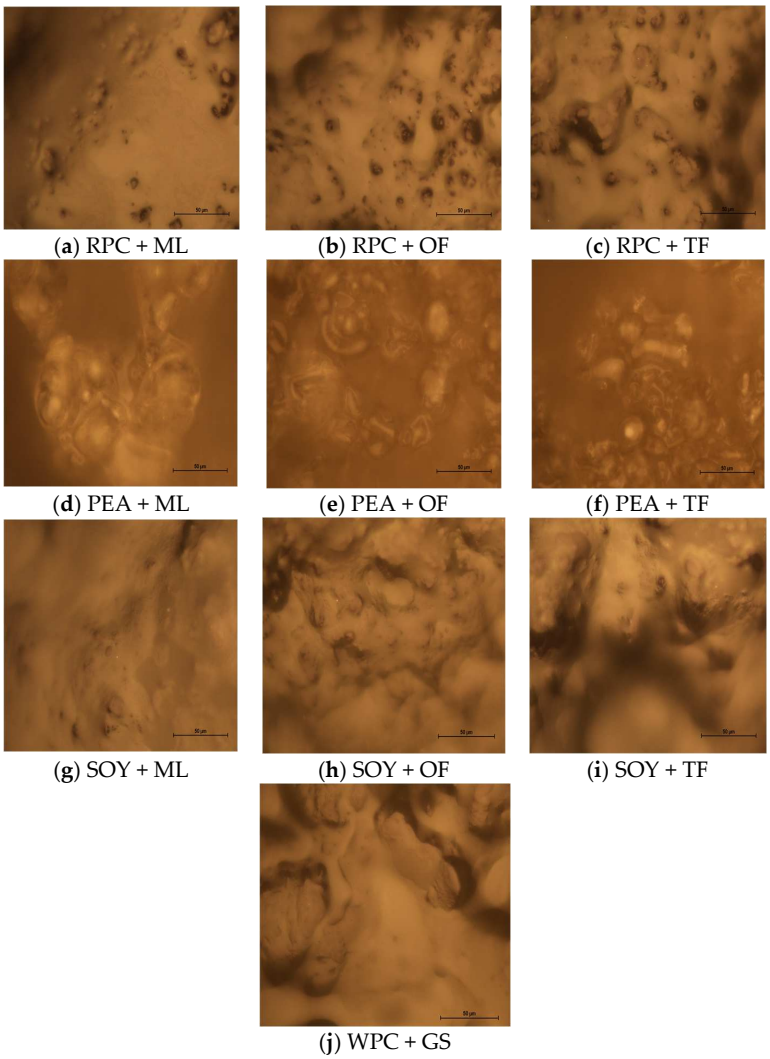
3.1. Texture Profile Analysis (TPA), Cutting Test and Optical Microscopy

The effect of the use of various protein-syrup combinations on the texture parameters and the cutting resistance force is presented in Table 1. The microscopic images of the microstructures of the tested high-protein bars are given in Figure 1a–j. Based on the analyzes, significant ($p < 0.05$) differences were observed between the performed trials. According to the research, the control bars made of commonly used sources (WPC + GS) were characterized by the greatest hardness (281.90 N). The least hardness parameters were found in the samples made of soy (18.76 N) and rice (19.92 N) proteins combined with maltitol syrup (SOY + ML and RPC + ML). It is worth noting that least hardness parameters for the individual types of tested high-protein bars are possibly related with the equally small cut resistance parameters.

Table 1. Impact of different protein and syrup combinations on the high-protein bars texture attributes and cutting resistance.

Combination of Protein and Syrup	Texture Attributes				Cutting Resistance Force [N]
	Hardness [N]	Fracturability [N]	Adhesiveness [J]	Cohesiveness	
WPC + GS	281.90 ^{h} ± 1.32	0.32 ^{ab} ± 0.13	1.66 ^{f} ± 0.11	0.28 ^{h} ± 0.01	49.27 ^{i} ± 0.15
RPC + ML	19.92 ^{a} ± 0.48	0.16 ^{a} ± 0.02	1.53 ^{e} ± 0.05	0.14 ^{e} ± 0.01	8.27 ^{a} ± 0.03
RPC + OF	27.67 ^{b} ± 0.18	0.27 ^{ab} ± 0.02	3.34 ^{g} ± 0.03	0.12 ^{de} ± 0.01	11.51 ^{b} ± 0.14
RPC + TF	35.53 ^{c} ± 0.49	0.47 ^{ab} ± 0.02	0.10 ^{a} ± 0.01	0.10 ^{cd} ± 0.01	15.73 ^{d} ± 0.16
PEA + ML	56.22 ^{d} ± 0.30	89.13 ^{c} ± 0.43	0.14 ^{a} ± 0.01	0.02 ^{a} ± 0.01	29.79 ^{f} ± 0.05
PEA + OF	106.68 ^{f} ± 0.22	141.45 ^{d} ± 0.79	0.17 ^{ab} ± 0.01	0.07 ^{bc} ± 0.01	48.55 ^{h} ± 0.23
PEA + TF	71.76 ^{e} ± 0.29	157.33 ^{e} ± 1.08	0.25 ^{b} ± 0.03	0.06 ^{b} ± 0.01	49.94 ^{j} ± 0.07
SOY + ML	18.76 ^{a} ± 0.62	0.13 ^{a} ± 0.01	1.51 ^{e} ± 0.03	0.25 ^{gh} ± 0.03	14.26 ^{c} ± 0.15
SOY + OF	136.46 ^{g} ± 2.97	1.14 ^{b} ± 0.10	1.21 ^{d} ± 0.06	0.24 ^{fg} ± 0.01	46.58 ^{g} ± 0.21
SOY + TF	34.82 ^{c} ± 0.65	0.30 ^{ab} ± 0.02	0.48 ^{c} ± 0.01	0.23 ^{f} ± 0.02	21.53 ^{e} ± 0.21

The data are presented as means ± SD (standard deviation). $^{a–j}$ Means in the same column with different superscripts are significantly different ($p < 0.05$, Tukey's honest significant difference "HSD" test). The tests were carried out in five replications ($n = 5$).



(**a**) RPC + ML (**b**) RPC + OF (**c**) RPC + TF

(**d**) PEA + ML (**e**) PEA + OF (**f**) PEA + TF

(**g**) SOY + ML (**h**) SOY + OF (**i**) SOY + TF

(**j**) WPC + GS

Figure 1. (**a**–**j**) Microstructure of the surface of the tested high-protein bars from the optical microscope (MAG: 400×). The method used to present photos of the microstructure of the surface for comparison for individual components.

The hardness assessed by the instrumental methods can be understood as the force required to compress the high-protein bar between the consumer's thumb and forefinger or as the force required to bite the bar by the molars [23,24]. Fracturability is a parameter that shows how a sample tends to disintegrate during compression [23]. Adhesiveness is the product's ability to stick to the surface. If the surface of the test sample is sticky, more force will be generated, translating into a feeling of stickiness when eating. Cohesiveness is a reflection of the degree of sample consistency during double squeezing and stretching, instrumentally imitating the chewing process in the mouth [25,26]. The cutting resistance force (shear force) is closely related to the force required to cut the sample by the consumer's incisors while eating the first bite [23]. The hardness of the high-protein bars is usually due to the great concentration of proteins which, due to such factors as the Maillard reactions, water migration, protein aggregation, or sugar crystallization, may cause hardening during the storage period of this type of product [2,18].

The tested high-protein bars exhibited a variety of texture characteristics. The use of optical microscopy was primarily aimed at showing the differences in the created surface structure depending on the type of protein used and the degree of its fragmentation. A certain regularity was noticed; the high degree of the hardness parameter also reduces the tendency of high-protein bars to stick to the surface. Thus the relatively small adhesiveness and cohesiveness parameters in favor of the usually elevated adhesiveness parameter. This is also confirmed by the Banach et al. research [27]. Based on the Hogan et al. study, hardness, was probably related to the microstructure of the molecules of a given type of protein and their ability to aggregate inside the food product [28]. Based on the research carried out by Małecki et al. [18] and Hogan et al. [28], the differences in the textural parameters and the resistance to cutting of the various types of proteins could be related to pore size and the degree of fragmentation of the protein molecules which changes the degree of moisture migration in the multi-domain products (proteins with smaller pore sizes) and slows down the hardening processes, lowers the cut resistance and an increased tendency to stick to the surface [18,28]. As follows from Figure 1a–j of the microstructure, there are substantial similarities in the size of the pores and the folding of the structure of the tested plant proteins, which probably reduces the TPA parameters and cut-resistance compared to the control sample (WPC + GS). Additionally, a significant effect of the syrups used in the application of the syrups on the reduction of parameters related to the textural analysis and the reduction of resistance to cutting was observed. The explanation for this phenomenon can be the Hassan research (2020), on the basis of which it can be assumed that the use of sugar and glucose syrups alternatives can reduce the degree of high-protein products hardness by reducing the interactions of surface-solvent bonds by reducing the covalent interactions between the proteins and syrups which include hydrogen bonds, van der Waals or ionic forces [29].

3.2. Water Activity and Ultrasonic Viscosity

The results of the obtained water activity and ultrasonic viscosity analyses made on the developed high-protein bars are presented in Figure 2a,b. During the storage process, many physicochemical and textural parameters of high-protein products change, mainly in terms of water activity and hardness [30]. For this reason, the developed products were stored under the controlled conditions (relative air humidity 50%, temperature 20 °C) for a period of three weeks. Each bar was packed in a metallized barrier foil and placed in a plastic container. The storage conditions and time were selected on the basis of the tests carried out by Banach et al. [27], which stated that parameters such as water activity change to the greatest extent within a month from the date of production of high-protein products [31].

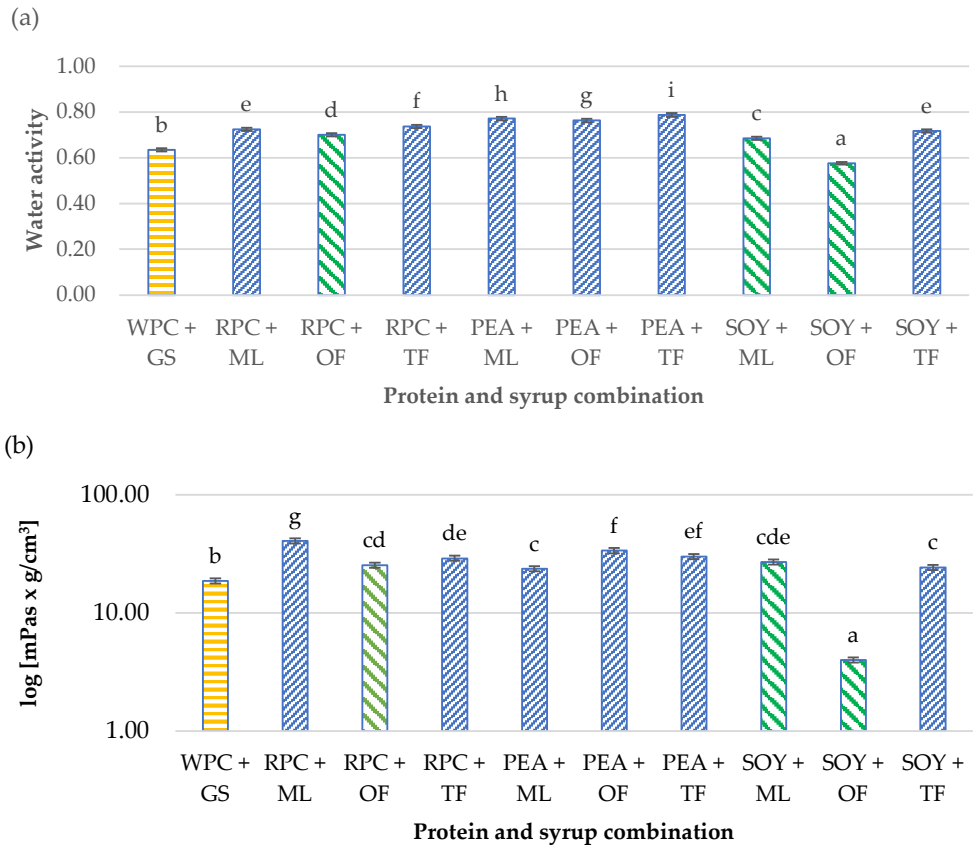


Figure 2. Influence of the combination of proteins and syrups on the (**a**) water activity (a_w) and (**b**) ultrasonic viscosity of the developed high-protein bars. The letters (a–i) indicate significant differences at $p < 0.05$ (Tukey's HSD test). The control sample color is yellow. The best prognostic samples for both determinations are marked green. The a_w tests were carried out in five repetitions ($n = 5$) and ultrasonic viscosity in three replications ($n = 3$).

The differences in the obtained results of the a_w and ultrasonic viscosity of the tested products were significant ($p < 0.05$). Water activity determines the course of biological processes, and it especially influences the development of microorganisms. The condition for the growth of microorganisms is that the aw in the environment is maintained at the optimal level for a given microorganism. For most microorganisms, the range is 0.990–0.995. It is assumed that below the water activity value of 0.7, growth and development are not possible for most bacteria and significantly impede the survival of yeast and molds [32]. A certain relationship was found between the water activity and the dynamic viscosity. The PEA + TF high protein bar was characterized by the largest water activity (0.79), and at the same time, it had one of the greatest viscosities (30 mPas·g/cm^3). On the other hand, the SOY + OF bar was characterized by the smallest water activity (0.58) and dynamic viscosity (4 mPas·g/cm^3). This dependence applied to all tested samples. Based on the previous Małecki et al. [18] studies and the research carried out by Tomczyńska-Mleko et al. [33], differences in the water activity and the ultrasonic viscosity may result from the microstructure of individual types of proteins, their concentration in the product, the tendency to agglomerate them overtime or the amount of air pores in the product formed during the process of mixing and aerating the bar mass. The scientific literature lacks the data regarding ultrasonic viscosity determination, that why it is difficult to find test results to compare with [18,33].

3.3. Energy, Nutritional Value and Sensory Evaluation

First of all, for people who pay attention to their diet and control their calories and nutrients, it is important that each snack and meal contain the highest nutritional value and the largest possible content of balanced nutrients [34]. The energy and nutritional value of the tested samples are presented in Figure 3a,b. The obtained results show that in the case of the control sample, the increased energy value was mainly caused by the increased content of carbohydrates, which resulted in the poor balance of individual components. The other trials were characterized by similar energy values and increased protein content, owing to the reduction of carbohydrate content using glucose syrup equivalents. For athletes, the diet should promote the development of exercise capacity and rapid regeneration after large physical loads. The qualitative composition of meals, their distribution, and energy value should be related to the size of energy losses and the metabolism characteristic of training loads. Provided in the right proportions, proteins, fats, and carbohydrates are the sources of ATP, a high-energy compound that breaks down into ADP during muscle work with the simultaneous release of energy. Their number and properly selected proportions must stimulate the appropriate energy dosage depending on the type of practiced sports discipline, the duration of exercise, and changes in its intensity [35]. All the tests carried out fit in this trend.

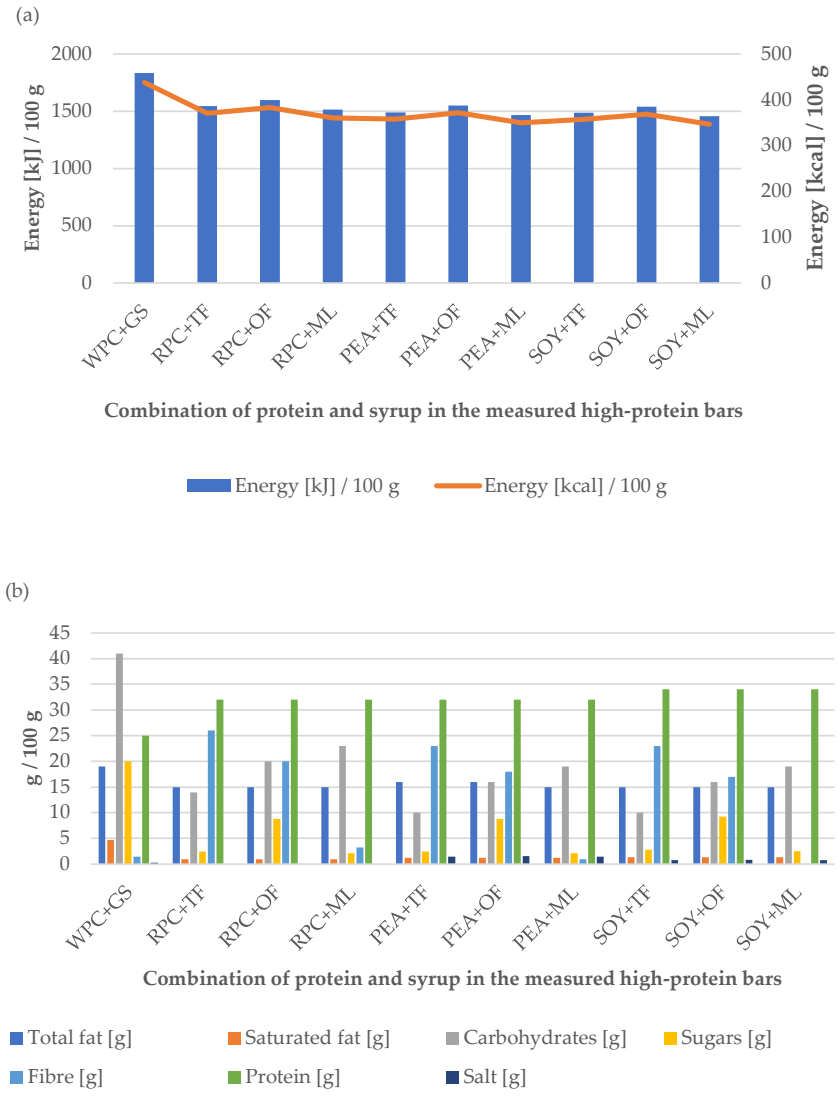


Figure 3. Influence of the combination of proteins and syrups on the (**a**) energy value and (**b**) nutritional value of the developed high-protein bars.

However, it should be noted that the product made of SOY + ML was characterized by the greatest degree of energy value reduction. This is probably due to the reduced caloric content of maltitol (2.4 kcal/g). It is worth paying special attention to the dietary fiber content in the obtained samples, especially RPC + TF (26 g/100 g), PEA + TF (23 g/100 g), and SOY + TF (23 g/100 g), which had the highest levels of fiber content. The products to which liquid fibers were added during the production process are characterized by a high fiber content in the final product and may be an additional selection criterion for potential consumers. Fiber products also allow the claim to be "high in fiber" in line with the current EU legislation [36]. In addition, dietary fiber is an important bioactive component that plays a significant role in rational nutrition, as well as in the treatment and prevention of many diseases. Its action mainly involves regulating intestinal peristalsis, preventing constipation, removing toxins and metabolic products from the body, and consequently reducing the risk of cancer, especially of the large intestine. An important property of insoluble fiber is the ability to bind carcinogenic, mutagenic, and other toxins formed during the digestion of food. The fiber that binds to the toxins is eliminated from the body in the stool. The soluble fibers can be broken down into short-chain fatty acids such as butyrate, propionate, and acetate by fermentation. The addition of fiber to the food products reduces the energy density of food and also extends the time of feeling full [37–39].

The sensory analysis showed that the high-protein bars made of soy and rice proteins enjoyed the highest ratings, with particular emphasis on the repetitions containing mainly oligofructose and tapioca fiber (RPC + OF, SOY + OF, and SOY + TF) (Figure 4). The sample made of soy protein and, with the addition of polyhydric alcohol (maltitol), was also highly rated (SOY + ML). High scores of these tests can be linked with the relatively small parameters of ultrasonic viscosity and the parameters of texture analysis of the same products, which could contribute significantly to the positive assessments of the respondents. The research results [18] show that the bars made of rice and soy proteins were highly rated during the sensory evaluation, which is also confirmed by the analyses. On the other hand, according to the Gunyaphan et al. studies (2020), the protein bars made of pea proteins were assessed very positively by consumers. The differences in these results may result from the concentration of proteins in the finished product and the degree of their fragmentation and deodorization [40].

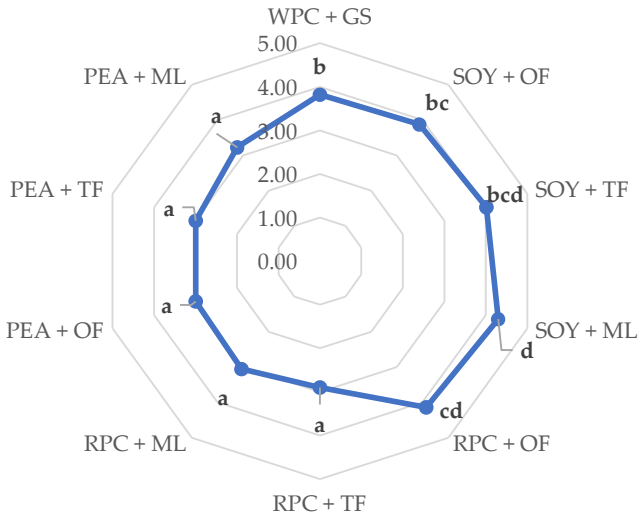


Figure 4. Influence of the combination of proteins and syrups on the sensory evaluation of the developed high-protein bars. The letters (a–d) indicate significant differences at $p < 0.05$ (Tukey's HSD test). Fifteen trained evaluators participated in the study ($n = 15$).

Considering the high-protein products available on the store shelves, they are often coated in chocolate. It should be remembered that mainly dark chocolates (with a high cocoa

mass content) have the ability to mask the aftertaste of proteins, so it can be assumed that pouring the tests in chocolate would increase the ratings of each high-protein product [41,42].

3.4. Water Droplets Kinetics—Contact Angle

Wettability is a very important physical property that characterizes the surface of materials. Its value determines the basic functions of food products and other materials, including adhesion or lubricity [43]. The purpose of the study of the surface structure was to determine the degree of hydrophobicity, hydrophilicity, and surface roughness depending on the type of protein and syrup used. The measure of the wettability of a solid surface with a small molecular weight liquid is the angle (colloquially called the contact angle) between the tangent to the droplet at the point of contact with the surface being tested and this surface. Thus, the measurement of the static contact angle can be reduced to placing a drop of a low molecular weight liquid on the surface of the tested material, measuring the angle of inclination of the tangent to the outline of the drop surface at the point of its contact with the substrate [44]. The results of the obtained contact angles are shown in Figure 5. They indicate significant differences in the obtained parameters depending on the combination of proteins and syrups.

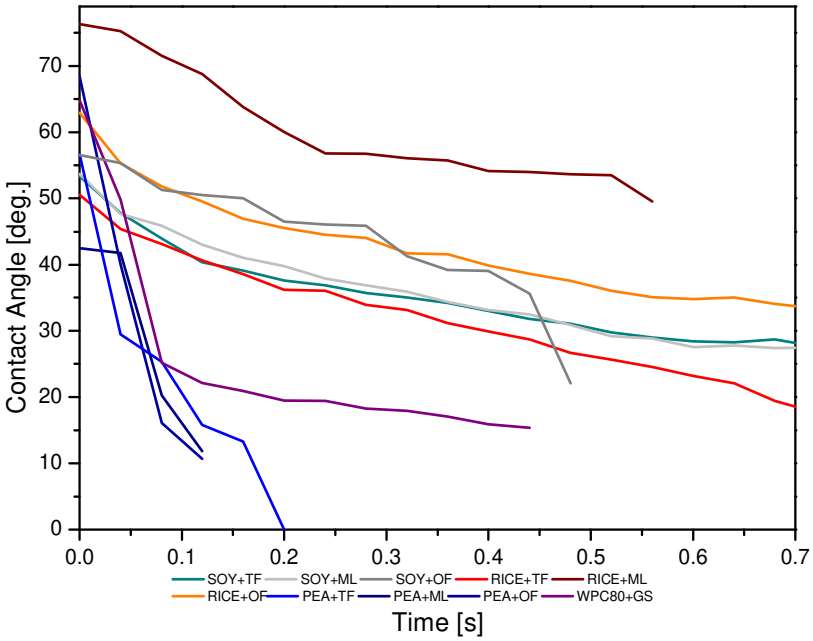


Figure 5. Comparison of individual water droplets kinetics depending on the type of protein and syrup used in the production of the developed high-protein bars.

The sample consisting of RPC + ML was characterized by the greatest surface hydrophobicity as the contact angles were the highest (close to 80°). The lowest contact angles were characterized by the product made of PEA + TF, so the surface of this product showed the most hydrophilic features. It is also worth noting that in the case of this test, this angle decreased very quickly over time. Based on the research of Perez-Huertas et al. (2020) and Huhtamaki et al. (2018), it can be assumed that the differences in the contact angles can be influenced by the roughness of the given surface of the tested products resulting from the substances that make it up [20,45]. The tested bars were characterized by the ability to spread water droplets quickly over the surface compared to the products of other researchers. Considering the analyses, this may be related to the relatively small water activity of the presented products and the large content of dry ingredients with great water absorption (proteins, barley malt, maltodextrin), which is also confirmed by the Ojogbo et al. studies, in which the products with a dry structure were tested. It is worth noting that the obtained contact angle results are usually not equal to 0, which probably indicates a

large degree of surface roughness of the tested products [44]. On the other hand, based on the Małecki et al. research, it can also be assumed that the degree of moisture absorption by a given type of proteins can be related to the different microstructure of individual raw materials, in particular proteins (the degree of their fragmentation and the ability to create conglomerates) [18].

3.5. Turbiscan Measurements

Turbiscan measurements enable fast and sensitive identification of destabilization mechanisms (such as creaming, sedimentation, etc.). A temperature-controlled measurement cell allows stability monitoring at specific storage temperatures or accelerates the destabilization process. The obtained Turbiscan Stability Index (*TSI*) results for the individual types of syrups used to produce the tested high-protein bars are presented in Figure 6. The Turbiscan Stability Index measures the global stability of a product and is used to compare the stability of different samples. Higher *TSI* values mean greater system instability. Accordingly, the *TSI* parameter is called the instability factor [46]. Worthily to this methodology, the TF syrup was characterized by the greatest stability in the full scope of the study. The most unstable sample was GS, commonly used in the food industry. Based on the Schellart research (2011), the great instability of this syrup may result from its very high ability to change viscosity depending on the temperature. At a low temperature, glucose syrups are characterized by very large viscosities, and with increasing temperature, their viscosity decreases significantly [47]. This is critical during the syrup dispensing process for various types of products. Typically, the syrup is heated to provide an easier pumping process and to reduce the load on the pumps. Taking into account the research carried out by Małecki et al., it can be assumed that such a great GS viscosity at temperatures close to 20–30 °C may be the reason for the increased hardness of high-protein products, which is undesirable [18].

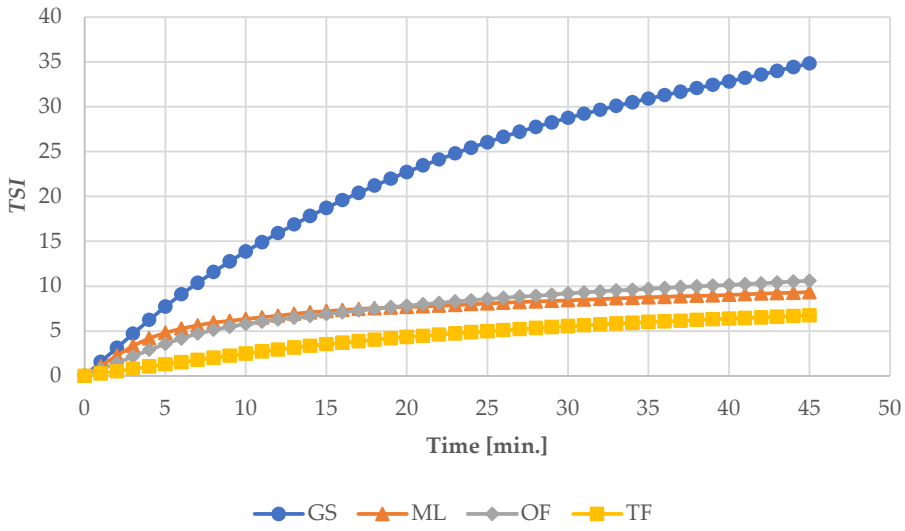


Figure 6. Changes in the *TSI* over time during the heating of individual syrups used in the production of high-protein bars being the subject of implementation.

In turn, the TF syrup was characterized by large fluidity and little viscosity in the entire measuring range. Taking into account other analyses performed, a small *TSI* for the TF syrup may be the reason for the tendency of high-protein bars towards the higher water activity results and accelerated risk of surface drying due to the moisture migration into the internal structures and increasing the water absorption rate and brittleness of the surface. Taking into account the *TSI* results obtained for the OF and ML syrups, they were characterized by balanced *TSI* ranges. According to the Nastaj et al. (2020) studies, also the type and concentration of protein may have an effect on the *TSI* parameter [19].

4. Conclusions

High-protein bars made of a combination of protein components and syrup substances selected based on the previous studies showed significant differences in the tests. It should be noted that all the presented solutions resulted in the desired lowering the degree of hardness in relation to that of the control sample, as the tendency towards hardening over time is one of the most important parameters regarding this type of product. Each of the proteins used had a different microstructure, as evidenced by the images from an optical microscope. Based on the current and previously carried out research, it can be assumed that this had an impact on the variable characteristics of each type of bar, primarily water activity and dynamic viscosity, where the best results were the bars made of soy proteins (SOY) and rice proteins (RPC) in combination with the OF and ML syrups. In terms of nutritional and energy values, all trials were on a similar level where there was a significant decrease in the contents of carbohydrates and sugars and an increase in the percentage of protein compared to the control sample, which may be an additional attractive feature for athletes and people who care about a low carbohydrate diet. Taking into account the analysis of contact angles, it can be assumed that the combinations of SOY and RPC proteins with OF and ML syrups ensure the hydrophobicity of the product surface similar to standard products made with WPC + GS. The *TSI* parameter suggests that the glucose syrup (GS) remains the least attractive syrup in terms of the production of this type of product due to a very wide spectrum of viscosity changes in different temperature ranges, which decreases the scope of its application. On the other hand, the remaining syrups showed little differentiation in *TSI*, which proves their stability and slight changes in viscosity in various temperature ranges, which may be beneficial for the application of this type of high-protein bars. It can be assumed that SOY + OF, SOY + ML, and RPC + OF may be the best alternatives to the commonly used WPC + GS, owing to the attractive assessments and parameters in practically each of the analyses being made. The combinations of the syrups with the pea proteins also deserve attention due to the significant reduction in hardness and energy value of the obtained products.

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Institutional Review Board Statement: Only adults participated in the sensory study of high-protein bars. The Local Bioethics Committee in Lublin, Poland, concluded that the above study did not require the consent of the Commission. This study did not have any predictable risks, nor did it expose participants to pain. No personal or identifying information was collected and all data were analyzed anonymously. As such, while written participant consent was not collected for this study, all participants gave verbal informed consent to participate. They were informed of the nature of the study and its objectives and advised of participants' confidentiality and anonymity. To make participants feel comfortable, they were allowed to withdraw from the study at any time and for any reason. All participants evaluated the tested products objectively and agreed to the publication of their evaluation results, which would remain anonymous.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sparkman, K.; Joyner, H.S. Impact of formulation on high-protein bar rheological and wear behaviors. *J. Texture Stud.* **2019**, *50*, 445–455. [CrossRef] [PubMed]
2. Jiang, Z.; Wang, K.; Zhao, X.; Li, J.; Yu, R.; Fu, R.; He, Y.; Zhao, P.; Oh, K.C.; Hou, J. High-protein nutrition bars: Hardening mechanisms and anti-hardening methods during storage. *Food Control* **2021**, *127*, 108127. [CrossRef]
3. Röttger-Wirtz, S.; De Boer, A. Personalised Nutrition: The EU's Fragmented Legal Landscape and the Overlooked Implications of EU Food Law. *Eur. J. Risk Regul.* **2021**, *12*, 212–235. [CrossRef]
4. Abd El-Salam, M.H.; El-Shibiny, S. Hardness of high protein nutrition bars based on milk protein concentrates: A review. *Biointerface Res. Appl. Chem.* **2020**, *10*, 4914–4921. [CrossRef]
5. Stávková, S.; Prudilová, H.; Toufarová, Z.; Nagyová, L. Factors influencing the consumer behaviour when buying food. *Agric. Econ.* **2007**, *53*, 276–284. [CrossRef]
6. Travis, T.; Burke, L.; Erman, K. Nutrition and Athletic Performance. *Med. Sci. Sports Exerc.* **2016**, *48*, 543–568. [CrossRef]
7. Gavrilova, N.; Chernopolskaya, N.; Rebezov, M.; Schetinina, E.; Suyazova, I.; Safronov, S.; Ivanova, V.; Sultanova, E. Development Of Specialized Food Products For Nutrition Of Sportsmen. *J. Crit. Rev.* **2020**, *7*, 233–236. [CrossRef]
8. Holway, F.E.; Spriet, L.L. Sport-specific nutrition: Practical strategies for team sports. *J. Sports Sci.* **2011**, *29*, 115–125. [CrossRef]
9. Zhao, H.; Shen, C.; Wu, Z.; Zhang, Z.; Xu, C. Comparison of wheat, soybean, rice, and pea protein properties for effective applications in food products. *J. Food Biochem.* **2020**, *44*, e13157. [CrossRef]
10. Nishinari, K.; Fang, Y.; Nagano, T.; Guo, S.; Wang, R. Soy as a food ingredient. In *Proteins in Food Processing*, 2nd ed.; Woodhead Publishing: Sawston, UK, 2018; Volume 6, pp. 149–186.
11. Zhang, Y.; Chen, C.; Chen, Y.; Chen, Y. Effect of rice protein on the water mobility, water migration and microstructure of rice starch during retrogradation. *Food Hydrocoll.* **2019**, *91*, 136–142. [CrossRef]
12. Man, S.; Liu, T.; Yao, Y.; Lu, Y.; Ma, L.; Lu, F. Friend or foe? The roles of inulin-type fructans. *Carbohydr. Polym.* **2021**, *252*, 117155–117165. [CrossRef] [PubMed]
13. Carocho, M.; Morales, P.; Ferreira, I.C.F.R. Sweeteners as food additives in the XXI century: A review of what is known, and what is to come. *Food Chem. Toxicol.* **2017**, *107*, 302–317. [CrossRef] [PubMed]
14. Saraiva, A.; Carrascosa, C.; Raheem, D.; Ramos, F.; Raposo, A. Maltitol: Analytical Determination Methods, Applications in the Food Industry, Metabolism and Health Impacts. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5227. [CrossRef] [PubMed]
15. Fransvea, A.; Celano, G.; Pagliarone, C.N.; Disanto, C.; Balzaretti, C.; Celano, G.V.; Bonerba, E. Food labelling: A brief analysis of European Regulation 1169/2011. *Ital. J. Food Saf.* **2014**, *3*, 1703. [CrossRef]
16. Sahin, A.W.; Axel, C.; Zannini, E.; Arendt, E.K. Xylitol, mannitol and maltitol as potential sucrose replacers in burger buns. *Food Funct.* **2018**, *9*, 2201–2212. [CrossRef]
17. Adámek, M.; Adámková, A.; Mlček, J.; Borkovcová, M.; Bednářová, M. Acceptability and sensory evaluation of energy bars and protein bars enriched with edible insect. *Potravin. Slovak J. Food Sci.* **2018**, *12*, 431–437. [CrossRef]
18. Małecki, J.; Tomasevic, I.; Djekic, I.; Sołowiej, B.G. The Effect of Protein Source on the Physicochemical, Nutritional Properties and Microstructure of High-Protein Bars Intended for Physically Active People. *Foods* **2020**, *9*, 1467. [CrossRef]
19. Nastaj, M.; Terpiłowski, K.; Sołowiej, B.G. The effect of native and polymerised whey protein isolate addition on surface and microstructural properties of processed cheeses and their meltability determined by Turbiscan. *Int. J. Food Sci. Technol.* **2020**, *55*, 2179–2187. [CrossRef]
20. Pérez-Huertas, S.; Terpiłowski, K.; Tomczyńska-Mleko, M.; Mleko, S. Surface modification of albumin/gelatin films gelled on low-temperature plasma-treated polyethylene terephthalate plates. *Plasma Process. Polym.* **2020**, *17*, 1900171. [CrossRef]
21. Kowalski, S.; Lukasiewicz, M.; Juszczak, L.; Sikora, M. Charakterystyka teksturalna i sensoryczna mas cukierniczych otrzymanych na bazie miodu naturalnego i wybranych hydrokoloidów polisacharydowych. *Żywność Nauk. Technol. Jakość* **2011**, *18*, 40–52.
22. Iannario, M.; Manisera, M.; Piccolo, D.; Zuccolotto, P. Sensory analysis in the food industry as a tool for marketing decisions. *Adv. Data Anal. Classif.* **2012**, *6*, 303–321. [CrossRef]
23. Imtiaz, S.R.; Kuhn-Sherlock, B.; Campbell, M. EFfect of dairy protein blends on texture of high protein bars. *J. Texture Stud.* **2012**, *43*, 275–286. [CrossRef]
24. Novaković, S.; Tomašević, I. A comparison between Warner-Bratzler shear force measurement and texture profile analysis of meat and meat products: A review. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2017; Volume 85, pp. 1–7.
25. Nishinari, K.; Kohyama, K.; Kumagai, H.; Funami, T.; Bourne, M.C. Parameters of texture profile analysis. *Food Sci. Technol. Res.* **2013**, *19*, 519–521. [CrossRef]
26. Fujimoto, K.; Minami, N.; Goto, T.; Ishida, Y.; Watanabe, M.; Nagao, K.; Ichikawa, T. Hardness, Cohesiveness, and Adhesiveness of Oral Moisturizers and Denture Adhesives: Selection Criteria for Denture Wearers. *Dent. J.* **2016**, *4*, 34. [CrossRef] [PubMed]
27. Banach, J.C.; Clark, S.; Lamsal, B.P. Particle Size of Milk Protein Concentrate Powder Affects the Texture of High-Protein Nutrition Bars During Storage. *J. Food Sci.* **2017**, *82*, 913–921. [CrossRef] [PubMed]
28. Hogan, S.A.; Chaurin, V.; O'Kennedy, B.T.; Kelly, P.M. Influence of dairy proteins on textural changes in high-protein bars. *Int. Dairy J.* **2012**, *26*, 58–65. [CrossRef]
29. Hassan, S.K. Quantitative and qualitative effects of proteins and natural sugars on hardening and color of high-protein nutrition bars during storage. *Eur. Asian J. Biosci.* **2020**, *14*, 915–932.

30. Banach, J.C.; Clark, S.; Lamsal, B.P. Texture and other changes during storage in model high-protein nutrition bars formulated with modified milk protein concentrates. *LWT Food Sci. Technol.* **2014**, *56*, 77–86. [CrossRef]
31. Banach, J.C.; Clark, S.; Lamsal, B.P. Instrumental and Sensory Texture Attributes of High-Protein Nutrition Bars Formulated with Extruded Milk Protein Concentrate. *J. Food Sci.* **2016**, *81*, 1254–1262. [CrossRef]
32. Tapia, M.S.; Alzamora, S.M.; Chirife, J. Effects of Water Activity (aw) on Microbial Stability as a Hurdle in Food Preservation. *Water Act. Foods* **2020**, *14*, 323–355. [CrossRef]
33. Tomczyńska-Mleko, M.; Ozimek, L. Ultrasound viscosity measurements allow determination of gas volume fraction in foamed gels. *J. Food Process Eng.* **2013**, *36*, 572–578. [CrossRef]
34. Harwood, W.S.; Drake, M.A. Understanding implicit and explicit consumer desires for protein bars, powders, and beverages. *J. Sens. Stud.* **2019**, *34*, e12493. [CrossRef]
35. Lun, V.; Erdman, K.A.; Fung, T.S.; Reimer, R.A. Dietary Supplementation Practices in Canadian High-Performance Athletes. *Int. J. Sport Nutr. Exerc. Metab.* **2012**, *22*, 31–37. [CrossRef] [PubMed]
36. Khedkar, S.; Bröring, S.; Ciliberti, S. Exploring the Nutrition and Health Claims Regulation (EC) No. 1924/2006: What is the impact on innovation in the EU food sector? *Int. J. Food Sci. Nutr.* **2016**, *68*, 10–17. [CrossRef] [PubMed]
37. Barber, T.M.; Kabisch, S.; Pfeiffer, A.F.H.; Weickert, M.O. The Health Benefits of Dietary Fibre. *Nutrients* **2020**, *12*, 3209. [CrossRef] [PubMed]
38. Gill, S.K.; Rossi, M.; Bajka, B.; Whelan, K. Dietary fibre in gastrointestinal health and disease. *Nat. Rev. Gastroenterol. Hepatol.* **2020**, *18*, 101–116. [CrossRef] [PubMed]
39. Prasad, K.N.; Bondy, S.C. Dietary fibers and their fermented short-chain fatty acids in prevention of human diseases. *Bioact. Carbohydr. Diet. Fibre* **2019**, *17*, 100170. [CrossRef]
40. Gunyaphan, S.; Suttisansanee, U.; Chamchan, R.; Khemthong, C.; Chupeerach, C. Product qualities and sensory evaluation of high protein snack bar incorporated with pea protein isolate. *Food Res.* **2020**, *4*, 51–55. [CrossRef]
41. Faccinetto-Beltrán, P.; Gómez-Fernández, A.R.; Santacruz, A.; Jacobo-Velázquez, D.A. Chocolate as Carrier to Deliver Bioactive Ingredients: Current Advances and Future Perspectives. *Foods* **2021**, *10*, 2065. [CrossRef]
42. Drewnowski, A.; Gomez-Carneros, C. Bitter taste, phytonutrients, and the consumer: A review. *Am. J. Clin. Nutr.* **2000**, *72*, 1424–1435. [CrossRef]
43. Kayaoğlu, B.K.; Öztürk, E. Imparting hydrophobicity to natural leather through plasma polymerization for easy care effect. *Fibers Polym.* **2013**, *14*, 1706–1713. [CrossRef]
44. Ojogbo, E.; Blanchard, R.; Mekonnen, T. Hydrophobic and Melt Processable Starch-Laurate Esters: Synthesis, Structure–Property Correlations. *J. Polym. Sci. Part A Polym. Chem.* **2018**, *56*, 2611–2622. [CrossRef]
45. Huhtamäki, T.; Tian, X.; Korhonen, J.T.; Ras, R.H.A. Surface-wetting characterization using contact-angle measurements. *Nat. Protoc.* **2018**, *13*, 1521–1538. [CrossRef] [PubMed]
46. Wiśniewska, M. Influences of polyacrylic acid adsorption and temperature on the alumina suspension stability. *Powder Technol.* **2010**, *198*, 258–266. [CrossRef]
47. Schellart, W.P. Rheology and density of glucose syrup and honey: Determining their suitability for usage in analogue and fluid dynamic models of geological processes. *J. Struct. Geol.* **2011**, *33*, 1079–1088. [CrossRef]

9. Oświadczenia współautorów prac będących przedmiotem rozprawy doktorskiej

Lublin, 23.05.2022

Oświadczenie autorów publikacji

Niniejszym oświadcza się, że publikacja:

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Małecki Jan - współtworzenie koncepcji pracy, przeprowadzenie analizy danych literaturowych oraz ich interpretacja, napisanie manuskryptu, przygotowanie odpowiedzi na recenzje.

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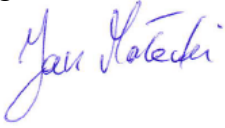
mgr inż. Jan Małecki



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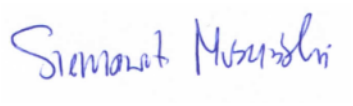

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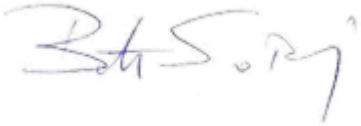

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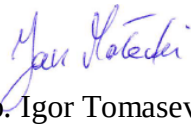
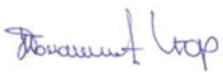
mgr inż. Jan Małecki



Prof. dr hab. Igor Tomasevic



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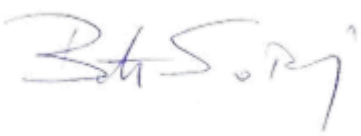

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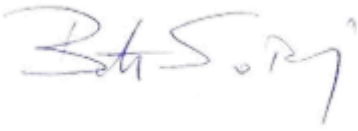
Prof. dr hab. Igor Tomasevic

dr hab. Bartosz G. Sołowiej, prof. UP



Lublin, 23.05.2022

Oświadczenie autorów publikacji

Niniejszym oświadcza się, że publikacja:

Małecki J.; Terpiłowski K., Nastaj M., Sołowiej B. G., 2022, Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used. *International Journal of Environmental Research and Public Health*, 19, 3923.

powstała w wyniku poniżej określonego, indywidualnego wkładu pracy współautorów:

Małecki Jan - współtworzenie koncepcji pracy, udział w opracowaniu metodologii badań, walidacja metod badawczych, przeprowadzenie doświadczeń, zapewnienie materiału do badań, napisanie manuskryptu, przeprowadzenie analizy danych oraz ich interpretacja i wizualizacja, przygotowanie odpowiedzi na recenzje.

Terpiłowski Konrad oraz Nastaj Maciej – udział w opracowaniu metodologii badań, walidacja metod badawczych, nadzór nad przeprowadzaniem doświadczeń, zatwierdzenie finalnego manuskryptu.

Sołowiej Bartosz G. - współtworzenie koncepcji pracy, udział w opracowaniu metodologii badań, walidacja metod badawczych, nadzór nad przeprowadzaniem doświadczeń, zatwierdzenie finalnego manuskryptu, pozyskanie funduszy na opublikowanie artykułu w czasopiśmie, zarządzanie projektem.

mgr inż. Jan Małecki

dr hab. Konrad Terpiłowski, prof. UMCS

dr inż. Maciej Nastaj

dr hab. Bartosz G. Sołowiej, prof. UP

10. Zestawienie dorobku naukowego

RB-XV-18/2022

23.05.2022, Lublin

Biblioteka Główna UP w Lublinie
Bibliografia Publikacji Pracowników Uniwersytetu Przyrodniczego w Lublinie

Raport autora za lata 2019-2022: Jan Małecki

1. Publikacje w czasopismach naukowych

1.1. Publikacje w czasopiśmie naukowym posiadającym Impact Factor IF

Lp	Opis bibliograficzny	IF	Pkt. MNiSW
1.	**Physicochemical, nutritional, microstructural, surface and sensory properties of a model high-protein bars intended for athletes depending on the type of protein and syrup used.** [AUT.] JAN MAŁECKI, KONRAD TERPIŁOWSKI, MACIEJ NASTAJ, [AUT. KORESP.] BARTOSZ G. SOŁOWIEJ. *Int. J. Environ. Res. Public Health (Print)* 2022 Vol. 19 Issue 7 3923, il., bibliogr., sum. DOI: 10.3390/ijerph19073923	3,390	140,00
2.	**The effect of fat replacement by whey protein microcoagulates on the physicochemical properties and microstructure of acid casein model processed cheese. .** [AUT. KORESP.] BARTOSZ G. SOŁOWIEJ, [AUT.] MACIEJ NASTAJ, JAGODA O. SZAFRAŃSKA, KONRAD TERPIŁOWSKI, JAN MAŁECKI, STANISŁAW MLEKO. *Int. Dairy J.* 2022 Vol. 131 Article number 105385, il., bibliogr., sum. DOI: 10.1016/j.idairyj.2022.105385	3,032	100,00
3.	**The influence of the syrup type on rheology, color differences, water activity, and nutritional and sensory aspects of high-protein bars for sportsmen.** [AUT.] JAN MAŁECKI, IGOR TOMASEVIC, [AUT. KORESP.] BARTOSZ G. SOŁOWIEJ. *J. Food Qual.* Volume 2022 Article number 2317676, il., bibliogr., sum. DOI: 10.1155/2022/2317676	2,450	40,00
4.	**Proteins in food systems - bionanomaterials, conventional and unconventional sources, functional properties, and development opportunities.** [AUT.] JAN MAŁECKI, SIEMOWIT MUSZYŃSKI, [AUT. KORESP.] BARTOSZ SOŁOWIEJ. *Polymers (Basel)* 2021 Vol. 13 Issue 15 2506, il., bibliogr., sum. DOI: 10.3390/polym13152506	4,329	100,00
5.	**The effect of protein source on the physicochemical, nutritional properties and microstructure of high-protein bars intended for physically active people.** [AUT.] JAN MAŁECKI, IGOR TOMASEVIC, ILIJA DJEKIC, [AUT. KORESP.] BARTOSZ SOŁOWIEJ. *Foods* 2020 Vol. 9 Issue 10 Article 1467, il., bibliogr., sum. DOI: 10.3390/foods9101467	4,350	100,00
	Suma:	17,551	480,00

1.2 Publikacja w recenzowanych materiałach z konferencji międzynarodowej uwzględnionej w Web of Science

Lp	Opis bibliograficzny	Pkt. MNiSW
1.	**Traditional and regional meat products in Poland.** [AUT.] J. MAŁECKI, B. SOŁOWIEJ. *IOP Conference Series. Earth and Environmental Science* 2019 Vol. 333 012006, il., bibliogr. DOI: 10.1088/1755-1315/333/1/012006	5,00
	Suma:	5,00

2. Monografie naukowe

2.1. Autorstwo rozdziału w monografii naukowej

Lp	Opis bibliograficzny	Pkt. MNiSW
1.	**Biologicznie aktywne peptydy jako prozdrowotne składniki diety (Biologically active peptides as health-promoting components in the diet).** [AUT.] JAGODA SZAFRAŃSKA, JAN MAŁECKI, KATARZYNA KUSIO. W: Żywienie i żywność / redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny Poznań 2021, Młodzi Naukowcy, s.112-117, il., bibliogr., streszcz, 978-83-66743-39-7.	5,00
2.	**Pozyskiwanie, właściwości fizykochemiczne i funkcjonalne inuliny oraz jej wykorzystanie w przemyśle spożywczym, kosmonautycznym i paszowym (Acquisition, physicochemical and functional properties of inulin and its use in the food, aerospace and fodder industries).** [AUT.] JAN MAŁECKI, JAGODA SZAFRAŃSKA, TOMASZ MAŁECKI. W: Nauki przyrodnicze: Fauna i flora. Redakcja naukowa / Jędrzej Nyćkowiak, Jacek Leśny Poznań 2021, Młodzi Naukowcy, s. 112-117, il., bibliogr, 978-83-66743-30-4.	5,00
3.	**Bakterie wykorzystywane w celu tworzenia,biofunkcyjnych i prozdrowotnych produktów mlecznych (Bacteria and yeast used to create biofunctional and health-promoting dairy foods).** [AUT.] JAGODA SZAFRAŃSKA, JAN MAŁECKI, EWA HABZA-KOWALSKA. W: Żywność i żywienie / Redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny Poznań 2020, Młodzi Naukowcy, s. 98-104, il., bibliogr., streszcz, 978-83-66392-82-3.	5,00
4.	**Rola oraz sposoby implementacji błonników w przemyśle spożywczym (The role and methods of fibers implementation in the food industry).** [AUT.] JAN MAŁECKI, JAGODA SZAFRAŃSKA. W: Żywność i żywienie / Redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny Poznań 2020, Młodzi Naukowcy, s. 72-77, il., bibliogr., streszcz, 978-83-66392-82-3.	5,00
5.	**Wpływ błonnika pokarmowego i jego składników na zdrowie człowieka (The effect of dietary fiber and its components on human health).** [AUT.] JAGODA SZAFRAŃSKA, JAN MAŁECKI. W: Żywność i żywienie / Redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny Poznań 2020, Młodzi Naukowcy, s. 91-97, il., bibliogr., streszcz, 978-83-66392-82-3.	5,00
	Suma:	25,00

3. Materiały konferencyjne

Lp	Opis bibliograficzny	Rok
1.	**Rola oraz sposoby implementacji błonników w przemyśle spożywczym.** [AUT.] JAN MAŁECKI. W: Badania i Rozwój Młodych Naukowców w Polsce 2019 : materiały konferencyjne - jesień. Część 3 - Lublin / Redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny s. 50. Poznań 2019, Młodzi Naukowcy, 978-83-66392-58-8.	2019
2.	**The importance of rheology in the confectinery industry.** [AUT.] JAN MAŁECKI. W: Badania i Rozwój Młodych Naukowców w Polsce 2019 : materiały konferencyjne - jesień. Część 3 - Lublin / Redakcja naukowa Jędrzej Nyćkowiak, Jacek Leśny s. 51. Poznań 2019, Młodzi Naukowcy, 978-83-66392-58-8.	2019
	Suma:	2

4. Publikacje popularnonaukowe

Lp	Opis bibliograficzny	Rok
1.	**Apetyt i apatia.** [AUT.] JAGODA SZAFRAŃSKA, JAN MAŁECKI. *Aktual. Uniw. Przyr. Lub.* 2019 R.23 nr 5 (95) s. 21, il.	2019
	Suma:	1

Sumarycznie: IF 17,551, 510,00 pkt. MNiSW

Szczegółowe wyjaśnienia:

Wskaźnik Impact Factor został podany na podstawie bazy Journal Citation Reports (JCR) dla roku wydania publikacji z wyjątkiem publikacji z roku 2022 oraz 2021 gdzie jego wartość została podana na podstawie ostatniej edycji JCR ed. 2020.
- Punktacja została podana na podstawie „Komunikatu Ministra Edukacji i Nauki z dnia 21 grudnia 2021 r. w sprawie wykazu czasopism naukowych i recenzowanych materiałów z konferencji międzynarodowych".
- Punktacja za rozdziały w monografii została przyznana na podstawie „Komunikatu Ministra Edukacji i Nauki z dnia 22 lipca 2021 r. w sprawie wykazu wydawnictw publikujących recenzowane monografie naukowe".

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Katarzyna Brzezińska
/mgr Katarzyna Brzezińska/

Lublin, 17.05.2022

RB-XV-18/2022

Zestawienie wyników cytowań sporządzone przez pracownika Oddziału Informacji Naukowej Biblioteki Głównej Uniwersytetu Przyrodniczego w Lublinie (wg kwerendy na dzień 17.05.2022 r.) dla **Jana Małeckiego**.

Według bazy Web of Science Core Collection – Basic Search	
Liczba prac indeksowanych w bazie	4
Liczba cytowań opublikowanych prac	14
Liczba cytowań opublikowanych prac bez autocytowań	11
Liczba artykułów cytujących	14
Liczba artykułów cytujących bez autocytowań	11
Średnia liczba cytowań na pozycję	3,5
Indeks Hirsha	2
Według bazy Scopus – Author Search	
Liczba prac indeksowanych w bazie	6
Liczba cytowań opublikowanych prac	15
Liczba cytowań opublikowanych prac bez autocytowań	12
Indeks Hirsha	2

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Katarzyna Brzezińska

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