Characterization of plant-based alternative products with consideration of qualitative and nutritional aspects

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List of publications

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Chapter 1

General introduction

1.1 Change in plant-based and meat-based food among consumers and the food industry

Feeding a global population that is expected to grow to 9.7 billion by 2050 without exacerbating the impact on the planet while ensuring health, wellness, and adequate nutrition for all is the greatest challenge that humanity faces this century, especially for the least developed countries (United Nations Population Division, 2019). Significant changes in the global food supply will be required over the next 30 years to provide adequate macro- and micronutrients to people worldwide. Pioneering changes are needed in agriculture and the food industry. The European Commission has set a good example with its "Farm to Fork Strategy" as part of the European Green Deal, focusing on sustainable food production, processing, consumption, and prevention of food loss and waste (European Union, 2020).

Approaches to sustainable diets, where much or all animal-based foods are replaced with plant-based foods, can have positive effects on the environment and concurrent health outcomes worldwide, particularly in high- and middle-income countries (Springmann et al., 2018). The widely cited and debated findings of the EAT-Lancet Commission recommend a global diet for health and sustainability (planetary health diet) to feed the growing population within current planetary boundaries (Willett et al., 2019). For a majority of the world's population, this necessitates a dietary shift to a predominantly plant-based diet that similarly meets the evidence on healthy eating (Willett et al., 2019). In this way, established climate goals can be achieved, and premature deaths from chronic diet-related diseases can be prevented worldwide. In addition, global demand for protein is increasing due to population growth, rising incomes, and a consequently growing middle class (Geraghty et al., 2019; Godfray et al., 2018; Henchion et al., 2021). As part of this trend, there has been an increase in demand for more nutritious foods, mainly of animal-based origin. Bennett's law describes the underlying phenomenon that the positive correlation between increasing wealth leads to a nutrition style with higher consumption of meat and dairy products while consuming less protein from staple foods (cereal-potato foods) (Bennett, 1941; Godfray et al., 2018).

A global shift in the way Western diets shape consumers' food consumption can be perceived (Dagevos, 2021; de Visser et al., 2021). This is facilitated by the spread of information via social media and global campaigns such as "Veganuary" with the challenge not to eat animal-based products for a month (www.veganuary.com) or "Meat Free Monday" where people are encouraged to commit to at least one meat-free day per week (www.meatfreemondays.com). Recent studies show that the young generation is becoming increasingly critical of ethical, environmental, and health issues surrounding our "traditional" food production system (Jürkenbeck et al., 2021; Kemper and White, 2021; Zühlsdorf et al., 2021).

Transforming our food systems and changing current food consumption behaviors with a transition to a more sustainable diet, that is a diet high in plant-based foods, is essential for our future and that of our planet (Kortetmäki and Oksanen, 2021; Nobari, 2021; Ritchie, 2020). A dietary shift away from high consumption of animal-based products, particularly meat and meat products, is necessary to create an environmentally and socially sustainable food system that provides healthy food for a growing population while reducing environmental impacts and not exceeding planetary boundaries (Bonnet et al., 2020; Burlingame and Dernini, 2012; Springmann et al., 2018).

Regulation of meat consumption is the greatest challenge facing developed countries in the coming decades (Willett et al., 2019). In their study, Bonnet et al. (2020) present the main regulatory instruments, such as a tax on meat, so-called fiscal instruments, front-of-pack nutritional labeling, or the "Eat 5 a day" campaign, as an informational instrument that will involve nutritionists and policymakers now and in the future. The problems with the current food system originate in both production and consumption. Therefore, a transformation of the food system and significant supply and demand changes are needed (OECD/FAO, 2021).

Dietary transformation requires that consumers have the necessary knowledge about food and how it is prepared. However, many consumers find it difficult to assess the origin of their food and lack basic cooking skills, as this knowledge and experience is often learned in childhood (Hagmann et al., 2020; Martins et al., 2020). Thus, cooking with meat alternatives is described as an "adventure" and "trial and error" (Kemper, 2020). Plant-based meal preparation is associated with the recreation of traditional dishes, using spices and recipes from other cultures, and trying out new cooking methods (Bernardo et al., 2021; Hartmann et al., 2013; Kemper, 2020). A flexitarian diet represents a relatively easy dietary change to implement and, unlike a more restrictive vegetarian or vegan diet, implies a less strict framework that allows for the consumption of modest amounts of animal-based foods (Dagevos, 2021). In this way, plant-based alternative products can make an important contribution to dietary change (Onwezen et al., 2021; Possidónio et al., 2021). Preparing meals at home is associated with higher-quality diets that are high in fruits, vegetables, and whole grains, low in sugar consumption, and low in ultra-processed foods and fast foods consumption (Bernardo et al., 2021; Hagmann et al., 2020; Martins et al., 2020). Two important issues must therefore be considered. First, efforts must be made to raise consumer awareness to promote behavioral and dietary change away from animal-based foods toward consumption of more sustainable, healthier, plant-based foods (Eisen and Brown, 2021; Springmann et al., 2018; Willett et al., 2019). Second, food manufacturers and product managers must be able to understand consumer attitudes and motivations to more effectively increase sales and demand for plant-based products to serve the market on emerging trends (Bashi et al., 2019; OECD/FAO, 2021).

1.2 What are plant-based products?

Plant-based meat alternative products are often first associated with tofu, although its history is not entirely clear. "Doufu" (the Mandarin Pinyin spelling for tofu) was first mentioned by Tao Ku in Qing Yilu in 965 AD (Shurtleff and Aoyagi, 2014) when in order to promote the virtue of frugality and thrift among people, meat consumption was discouraged, and instead, the sale of tofu was encouraged, called 'mock lamb chops' or 'the vice mayor's mutton.' Over the past 50 years, religious, health, environmental, and technological factors, in particular, have contributed to the development of meat alternatives, aimed to mimic 'real meat' as much as possible, from a plant-based protein through food chemical and industrial processes (Kołodziejczak et al., 2021).

Shurtleff and Aoyagi (2013) have extensively studied the history of plant-based cheese alternatives. For example, the world's first dairy-free cheese-like products were various types of fermented tofu made in China and were first documented during the Ming Dynasty in China around 1500. The first commercial cheese alternative in the Western world was called Nuttose and was developed by John Harvey Kellogg in 1896 (Shurtleff and Aoyagi, 2013). The product was made primarily from peanuts and could also be used as a meat substitute.

The following examples show that plant-based beverages have been produced and consumed in different cultures for a long time. For instance, many different rice-based beverages originated in Asia, such as Sikhye from Korea, which is based on cooked rice, malt extract, and sugar; Atole which is traditionally prepared with corn and originated in Mexico; Bushera is a fermented beverage made from sorghum or millet from Uganda; and from southern Europe (Bulgaria, Albania, Turkey) comes Boza, which is a fermented beverage made from wheat, rye, millet, or corn (Jeske et al., 2018). The first commercially available soy milk product was produced in Hong Kong in 1940 and spread rapidly in the seventies and early eighties in Asia and then in the 1990s and 2000s as a part of a "health trend" in the Western world (Mäkinen et al., 2016).

1.2.1 Plant-based meat alternative products

There is a long history of meat alternative products that have been available on the conventional market for the longest time, with a large variety of products, and there is currently great scientific interest in novel protein sources derived from plants, insects (e.g., mealworms, crickets, silkworm), animal-based cells (i.e., cell-based meat, clean meat, cultured meat), and microorganisms (e.g., microalgae). This section will pay special attention to several categories, namely sensory qualities, health factors, and consumer behavior. Plant-based meat alternatives/substitutes/analogs/replacements consist primarily of one or more protein-rich raw materials (e.g., wheat, legumes, especially soy and pea, mushrooms), water, vegetable fats, structural ingredients (e.g., binding agent), and further additives (e.g., flavorings, colorings), which are then combined to form a new food product (Figure 1). In the 1960s, textured vegetable protein (TVP) was invented, and the concept of plant-based meat alternatives was further advanced when TVP was used as the main ingredient in vegan versions of meat products, such as ground beef and burgers (Riaz, 2011). TVP can be made into different forms by using extrusion technology. The vegetable protein concentrates or isolates from soybean, wheat gluten, and pea are now popular for their useful properties in terms of forming meat-like fiber textures (Yao et al., 2006). With improvements in existing extrusion technology (high-moisture extrusion) and the development of new formulations, a new generation of products has emerged that can convince consumers of all sensory properties, even a bloody appearance, to imitate animal meat. Rügenwalder Mühle™, Beyond Meat™, and The Vegetarian Butcher™ are just a few of the successful companies producing these products. Companies that pioneer the production of these products consider not only vegans and vegetarians but also flexitarians and meat-eaters as their target group. Many of the products that have gained prominence in the media, especially on social media and in food markets, are products designed to imitate processed meat (e.g., ground beef, burger patties, sausages, cold cuts such as mortadella). These products have gained a strong presence in leading fast-food chains as plant-based menu options.

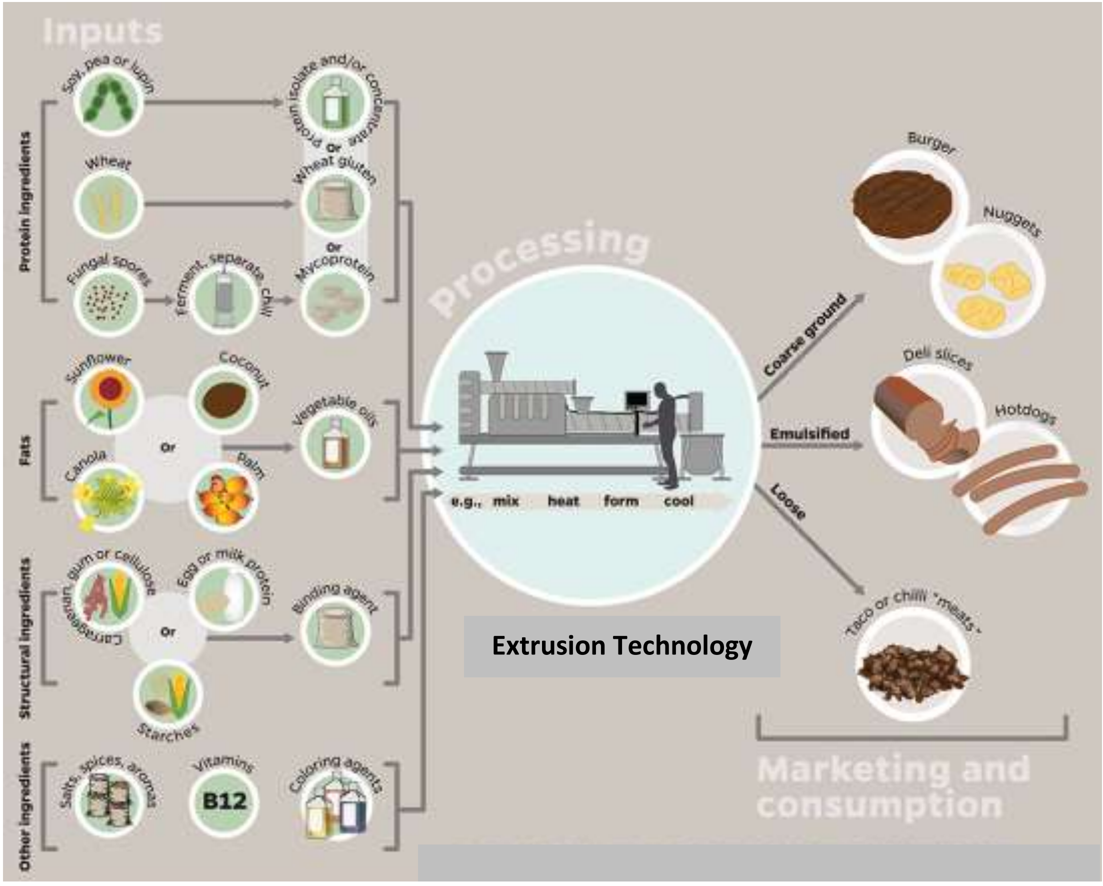

Figure 1: Possible inputs, processes, and end products of plant-based meat alternatives that might be marketed and consumed in this way, based on Santo et al. (2020).

1.2.1.1 Comparison of the health aspects of animal-based and plant-based meat products

Meat and meat products are considered as an excellent source of essential amino acids as well as adequate amounts of various micronutrients, zinc, heme iron, vitamins B_6 and B_{12} (offal such as liver contains reasonable amounts of vitamin D), and unsaturated omega-3 fatty acids (Bohrer, 2017; Kouba and Mourot, 2011). In the U.S., chicken and beef are the main sources of animal protein intake, accounting for about 46% of total protein intake, while only 8% is met through plant sources (Pasiakos et al., 2015). However, in recent years, there has been increasing evidence linking meat consumption, especially processed and red meat consumption, to increased risk of non-communicable diseases (NCDs) such as cancer, cardiovascular diseases (CVDs), Type 2 diabetes, as well as higher overall mortality rates (e.g., Afshin et al., 2019; Maretzke et al., 2020; Sinha et al., 2009; Zheng et al., 2019). Other public health risks attributed to meat production and consumption include increasing antibiotic resistance in humans and risks from pesticide residues and foodborne pathogens (Koch et al., 2019; Santo et al., 2020). Nutrition experts and professional associations have been advocating a reduction in meat consumption, especially processed meat, for years, including the German Nutrition Society, which recommends a guideline value for weekly meat consumption of 300-600 g/week (The German Nutrition Society, 2017). Current consumption data for Germany in 2021 show that per capita consumption will continue to decrease as in the previous year and is currently 55 kg per year (BLE, 2022). Current OECD/FAO data shows that consumption has hardly changed in recent years: per capita consumption worldwide is around 34 kg, in Europe around 63 kg, and the highest in North America at around 97 kg (OECD and FAO, 2021).

Consumer acceptance of plant-based meat alternatives is complex, with the three most important drivers being environmental impact, health and nutritional aspect, and sensory characteristics (de Koning et al., 2020). In recent years, the health benefits of plant-based foods and nutrition styles have been particularly well documented. According to Benatar and Stewart (2018), existing research suggests that a plant-based diet is associated with significant improvement in cardiovascular risk factors and lower incidence and progression of CVDs. A randomized controlled intervention trial by Wright et al. (2017) included patient groups diagnosed with obesity or overweight and at least one of the following: Type 2 diabetes, ischemic heart disease, hypertension, or hypercholesterolemia. The intervention was a plant-based diet accompanied by group discussions. After six months, significant improvements in body mass index (BMI), cholesterol, and other risk factors were observed in the intervention group. Quality of life also showed significant improvements in the intervention group for all measurement periods in the 'physical component summary' and the 'mental component summary' (Wright et al., 2017).

In general, many plant-based alternative products contain comparable amounts of calories, protein, and iron to the meats they are intended to replace, but they have relatively high sodium content compared to unprocessed meats (Bohrer, 2019). A current study shows a significant linear relationship between dietary sodium intake and CVDs, such that the risk for CVDs increased by up to 6% for every 1 g increase in dietary sodium intake (Wang et al., 2020).

Legumes primarily serve as a raw material source for meat alternatives, and it is currently unclear whether products derived from plant-based protein isolates provide similar nutritional benefits or chronic disease reduction as whole legumes (Hu et al., 2019). Protein isolates (> 90% protein content) or concentrates (70-90% protein content) are often the main ingredients of plant-based alternative products (Bohrer, 2019). Evidence shows that processed soy proteins have a higher availability of indispensable amino acids than unprocessed or minimally processed soy proteins (Gorissen et al., 2018; Hughes et al., 2011). Soy isolates can thus be considered a high-quality protein source as they achieve a protein digestibility corrected amino acid score (PDCAAS) value of 1.00, which is the highest PDCAAS value achievable and is comparable to animal foods such as meat, eggs, and dairy products (Hughes et al., 2011; Rutherfurd et al., 2015). Combinations of different plant-based protein isolates can also provide protein properties that closely resemble the typical properties of animal-based proteins (Gorissen et al., 2018). Minimally processed products made from soy (e.g., tempeh and tofu) are rich in proteins, especially essential amino acids, and also have high levels of omega-3 fatty acids and phytochemicals, especially isoflavones (Riciputi et al., 2016). The positive effects of soy products' consumption are described in Santo et al. (2020) as: improved blood lipids, moderately improved measures of bone health, reduced menopausal symptoms, reduced risk of Type 2 diabetes, and moderately reduced risk of breast cancer.

Research gaps exist in comparing the health effects of other plant-based protein sources such as peas, wheat, chickpeas, and animal-based meats. The sustained effects of replacing animal-based proteins with alternative plant-based sources based on longitudinal studies would represent another critical gap in research on the health effects of plant-based meat alternatives and the public health implications in general if these products were to replace a significant portion of current meat consumption. In the randomized crossover trial by Crimarco et al. (2020), participants received plant-based and animal-based products, nutritional guidance, and further medical screening. They were instructed to consume ≥ 2 servings each of plant-based and/or animal-based products per day for eight weeks, with a switch of products consumed after the eight weeks. The plant-based meat alternatives were pea protein-based. All other foods and beverages between the two phases were kept as similar as possible. Results from the 36 participants showed that plant-based meat products improved cardiovascular risk factors and gut microbiome health compared to meat consumption (Crimarco et al., 2020).

1.2.1.2 Consumer acceptance of and preference for plant-based meat alternatives

In recent years, a rising number of research publications have appeared on consumer perceptions and acceptance. Onwezen et al. (2021) conducted a systematic review of 91 articles related to consumer acceptance factors of alternative proteins. In addition to plant-based alternatives to meat, protein sources such as algae, insects, and cultured meat were included in this review because many of the studies on consumer attitudes focused on several new alternative protein sources. Three significant factors influencing consumer acceptance are product-related as well as psychological factors and external attributes such as social environment, trust, and culture (Onwezen et al., 2021; Siegrist, 2008).

The findings of Onwezen et al. (2021) indicate that health, taste, convenience, environmental benefits, and appearance are important product-related factors that promote the acceptance of alternative proteins in general. For plant-based proteins, health motivations play a particularly important role, followed by taste, the two most important factors among product-related factors.

The increasing sensory qualities of meat alternative products in terms of appearance, odor, taste, and texture are becoming more important to consumers (Weinrich, 2018). Sensory methods for evaluating the quality of foods, specifically conventional sensory profiling and consumer-based sensory profiling, are discussed in section 1.3. However, some consumers perceive these products as being inferior in texture and taste compared to meat (Schouteten et al., 2016). Another common reason for not using meat alternatives is that users enjoy the taste of meat (Weinrich, 2018). Therefore, sensory similarity to meat is more important for consumers who eat animal-based products than for those who eat less or no meat or meat products and are familiar with the alternative products (Hoek et al., 2011). Hoek et al. (2011) also found in their study that sensory quality and similarity to meat alone do not lead to a higher willingness to buy, other factors such as familiarity (neophobia), ethical aspects, and personal health are important. Psychological factors that could be a major barrier to acceptance were food neophobia (fear of trying new foods) and disgust (Bryant et al., 2019; de Koning et al., 2020).

In order to explain the external attributes, different studies are presented below. When comparing consumer acceptance in relation to different countries, different motivational reasons such as eating habits, the taste of meat alternatives, and convenience were identified in the three European countries of France, the Netherlands, and Germany (Weinrich, 2018). Regarding socioeconomic status, Gómez-Luciano et al. (2019) found that meat alternatives are more accepted in higher-income countries and suggest that people in lower-income countries place a higher value on meat consumption. A study by Grasso et al. (2019) surveyed over 1,800 older adults aged 65 years or above in five EU countries on the acceptance of alternative protein, with the result that plant-based protein sources were found to have the highest acceptance, followed by a great distance by protein sources based on microorganisms and insects and cultured meat. Younger individuals tend to have fewer reservations about consuming novel products (Hoek et al., 2011). The significance of new meat alternatives for vegetarian men's conceptions of masculinity (new meat alternatives in vegetarian men's 'doing' of masculinity) and the social contexts in which these foods are prepared and enjoyed was examined in a study by Nath (2011). It was found that the Western barbecue is seen as an important site where masculinity is socially calibrated through the consumption of meat, as it is seen as the ritual celebration of the male 'hunter' bond. Here, plant-based products seem to be a good meat-free alternative and offer a gentler entry into usually more difficult terrain. Manufacturers of the "new" generation of meat-alternative products primarily target their marketing to meat-eating consumers and flexitarians, in part to shift dietary habits toward more plant-based food and to raise awareness about meat consumption (He et al., 2020).

A consumer study by Estell et al. (2021) compared the nutritional profiles of plant-based and animal-based meat products. The results identified the motivational reasons as primarily taste and health. Interestingly, participants expected the micronutrient iron and vitamin B_{12} content of plant-based meat alternatives to be comparable to red meat (Estell et al., 2021).

Although consumer desire for more sustainable foods is growing, the price remains a significant barrier (Hawkins, 2012). Many consumers also associate meat alternatives with the negative attribute of being "expensive," so the price is an important factor for many consumers when choosing foods (Elzerman et al., 2013; Santo et al., 2020). Price, for example, remains one of the biggest barriers to widespread adoption of plant-based meat alternatives; they cover only a small share of the market, and the prices of most products are higher than those of animal-based products (Santo et al., 2020). Most studies on consumer perceptions and willingness to pay for meat alternatives focus on burger patties, as they are the dominant product in the market and in media coverage (Tonsor et al., 2021).

1.2.2 Plant-based cheese alternative products

Most commercial plant-based cheese alternatives on the market consist primarily of water and vegetable oil, usually coconut oil, then starch, stabilizers, salt, minerals, vitamins, flavorings, and colorants such as beta-carotene or annatto (Fu and Yano, 2020). Other raw materials used in the production of plant-based alternatives are nuts such as cashews, macadamias, and almonds, which are generally soaked, ground with water, and fermented (Tabanelli et al., 2018). These plant-based products are produced using techniques similar to those used in the production of processed cheese, based on cow's milk (Fu and Yano, 2020). An emulsion of vegetable oils, proteins, and water is produced using emulsifiers and stabilizers. Potato starch has anti-clumping properties, while tapioca starch adds elasticity to the product. Processes such as the application of heat treatments, acids, or enzymes can be used to improve product texture (Boukid et al., 2021; Fu and Yano, 2020). Ingredients such as stabilizers (e.g., carrageenan and xanthan gum) could help improve the texture of alternative cheeses, improving product firmness and minimizing syneresis (Ferawati et al., 2021; Jeske et al., 2018). Plant proteins differ from milk proteins primarily in their structure and functional properties. Because plant proteins have larger molecular sizes and more complex quaternary structures than milk proteins, they cannot form compact gel networks like casein, which is a crucial step in the production of cheese (Bachmann, 2001; Fu and Yano, 2020). Therefore, replacing the functionality of casein with plant proteins is a challenge in the development of plant-based cheese. A positive effect that cheese alternatives based on coconut oil and gluten-free starch have is that the ingredients do not present an allergenic source. The second important advantage of cheese alternatives is that they are free of lactose and cholesterol. However, they often have low protein content and high levels of total fat, saturated fat, and carbohydrates compared to nut-based or cow's milk cheese products (Boukid et al., 2021; Craig et al., 2022; Oyeyinka et al., 2019). A recent consumer study shows that European consumers are often confused about the nutritional disadvantages of these oil- and starch-based alternative products (ProVeg International, 2020). Furthermore, data regarding sensory aspects such as taste and texture of the plant-based alternatives are shown to be very important to consumers, but the products often do not meet their expectations. However, the aroma of dairy cheese is a complex system of different compounds, and especially mature cheeses (e.g., mountain cheese, Gruyère, Comté) have an intense aroma resulting from the cleavage of casein proteins and milk fat into amino acids, amines, and fatty acids (Jeske et al., 2018). Plant-based cheese alternatives are sold in various forms, including slices, chunks, spreads, and grated.

1.2.3 Plant-based milk alternative products

Plant-based milk alternative products can basically be defined as homogenized extracts from plant-based raw materials. A general classification of non-dairy milk divides products into five categories: Cereal-based (e.g., oats, rice), pseudocereal-based (e.g., quinoa, amaranth), legume-based (e.g., soy, pea), nut-based (e.g., almond, coconut), and seed-based (e.g., sesame, hemp) (Aydar et al., 2020; Sethi et al., 2016). The products have a continuous phase consisting of water and a dispersed phase of particles. These particles include protein fractions, starch granules, solid parts of plant matrices, and lipid droplets (Briviba et al., 2016). The process for producing plant-based beverages can vary depending on the raw material and the intended use of the final product, but some steps are common and widely used in manufacturing. Aydar et al. (2020) reported the common process steps and the differences that occur between processes depending on the raw material. For example, the plant material is usually soaked in water to soften it, blanched to deactivate endogenous enzymes, mechanically crushed to break up the plant tissue,

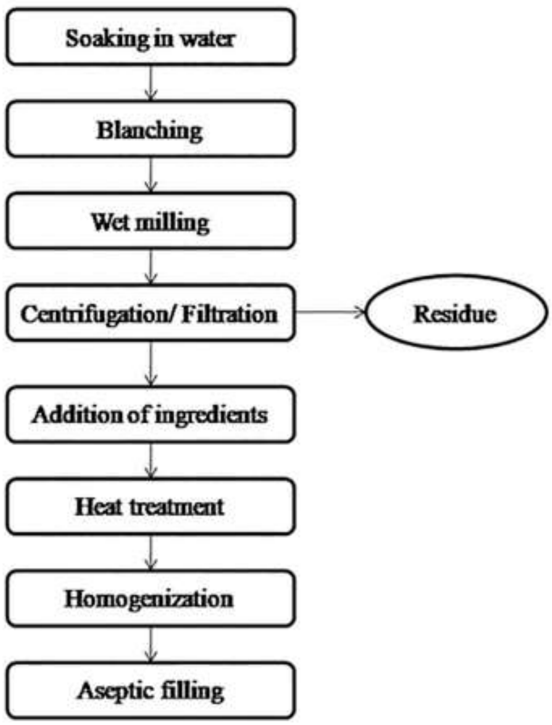

Figure 2: Process steps for the production of plant-based milk alternative, Aydar et al. (2020).

centrifuged or filtered to remove unwanted material, mixed with other ingredients (such as fats, thickeners, stabilizers, colorants, flavorings, and nutrients), thermally processed to destroy perishable or pathogenic microorganisms, homogenized to produce an oil-in-water emulsion using emulsifiers for uniform texture, and then packaged. A simplified figure of the common steps in the production of non-dairy milk is shown in Figure 2.

Pasteurization processes such as heat treatment are widely used to extend shelf life by reducing the number of pathogenic and spoilage microorganisms and inactivating endogenous enzymes. It is a process that increases the microbiological stability of plant-based alternatives, reduces their perishability, and provides pleasant sensory characteristics to the consumer (McClements et al., 2019). However, the use of high temperatures (60°C – 130°C) can also modify the physical, chemical, sensory, and nutritional properties of foods and beverages in undesirable ways (Aydar et al., 2020). New technologies such as ultrasound, pulsed electric fields, ohmic heating, and high and ultrahigh-pressure homogenization are being used to improve stability without additives (Paul et al., 2020). In addition, according to Paul et al. (2020), extraction yield should be improved, and residues should be reduced; recovery of macro-nutrients (fibers, proteins, and sugars) and micro-nutrients (vitamins and minerals) are also important issues, especially where optimal extraction is not achieved by conventional methods and is lost through filtration or centrifugation processes. Besides protein fortification of plant-based milk alternatives, fortification with vitamins and minerals is also an important issue for consumers who prefer plant-based milk alternatives to cow's milk.

In consumer surveys, two main motivators are mentioned: health and environmental aspects, followed most often by animal welfare (Haas et al., 2019; ProVeg e.V, 2019; Schiano et al., 2020). Consumption of cow's milk is linked to the increasing prevalence of health concerns, including milk protein allergy and lactose intolerance, high caloric intake, and hypercholesterolemia (Abbring et al., 2019; Hodges et al., 2019; Sethi et al., 2016). The environmental sustainability of plant-based milk alternatives is rated favorably by consumers compared to cow's milk (McClements et al., 2019). There are several comparative life cycle assessments (LCAs) that point to significantly lower greenhouse gas emissions, eutrophication, water use, and land use impacts during production (Bussa et al., 2020; Grant and Hicks, 2018; Poore and Nemecek, 2018), although some plant-based dairy products such as almond drinks may have a higher environmental impact per kg of protein produced (Grant and Hicks, 2018). Thus, different populations have different concerns about milk and dairy products.

Many consumers have grown up consuming cow's milk and are therefore familiar with its particular physicochemical and sensory properties. It is a liquid with low viscosity, a visually opaque, creamy white appearance, and a characteristic bland tasting profile (Schiano et al., 2017). As a result, consumers often expect plant-based milk alternatives to have fairly similar characteristics. The characteristics of milk depend on many factors, such as the cow's breed, age, health status, the form of its feed as well as further processing and storage conditions (Schiano et al., 2017). The appearance, taste, and mouthfeel of milk depend on its macronutrient composition, particularly fat content, with perceived creaminess increasing with fat content (McCarthy et al., 2017). The sensory properties of milk can be assessed by either a sensory panel or consumer tastings (Alvarez, 2015).

Replacing cow's milk with plant-based drinks depends largely on their appeal and acceptance by consumers (Jeske et al., 2018). To improve the sensory properties of plant-based milk, it is necessary to better understand its sensory perception, especially mouthfeel and taste, through sensory studies. It is often challenging to simulate the unique sensory properties of cow's milk because of its complexity. Some plant-based milk alternative products have characteristic flavors that positively or negatively affect sensory perception, such as almond, oat, bean, malt, or nut flavors (Jeske et al., 2018). Soy milk products often have a beany flavor, while almond milk products have a sweet, nutty flavor (Sethi et al., 2016). Also, some products contain particles that impart an undesirable grainy or chalky mouthfeel. This problem can sometimes be solved by homogenizing the product to reduce the insoluble particles to a size where the tongue no longer perceives them. Further research is needed to remove undesirable flavors or textures from plant-based milk products to make them acceptable to a wider range of consumers. The study by Jeske et al. (2019) compared the sensory characteristics of several plant-based milk products with raw materials from almonds, oats, rice, soy, hemp, and lentils. Consumers rated appearance, odor, taste, mouthfeel, and overall impression. The authors reported that overall preference for these plant-based milk decreased in the following order: Oat, Rice, Almond, Soy, Lentil, and Hemp. Kundu et al. (2018) carried out a consumer comparison of the sensory characteristics of soy and almond drink compared to cow's milk. They were able to reveal that almond milk tasted similar overall to cow's milk, while soy milk scored significantly lower, which was due to poorer ratings of color, taste, and mouthfeel. Despite the motivations behind plant-based alternatives, sensory characteristics may put off some consumers when it does not meet their sensory expectations, meaning that dairy alternatives cannot easily replace milk.

1.2.4 Plant-based alternative products and law in Europe

Vegan and vegetarian foods are regulated by the General Food Labelling Regulation of the European Union (Regulation No 1169/2011). They must be labeled in such a way that consumers can make a qualified choice when shopping and, in particular, are not misled about the characteristics of vegan and vegetarian foods. Plant-based milk alternatives may not be declared or advertised as "milk" because this term is protected by law and, according to the European Union Regulation, only refers to the "product of normal udder secretion obtained by one or more milkings" (Regulation No 1308/2013). Therefore, plant-based milk alternatives are officially called "drink." There are a few exceptions, such as coconut milk. In Germany, the Food Book Commission has described vegan and vegetarian foods in guiding principles. It serves as an important guide and helps to protect consumers from being misled (Deutschen Lebensmittelbuch-Kommission, 2018). Thus, some countries had different labels and laws to inform consumers, but there was no global reference until the publication of the ISO 23662 standard. The international standard (ISO 23662:2021) "Definitions and technical criteria for foods and food ingredients suitable for vegetarians or vegans and for labeling and claims," provides an internationally agreed reference for the food and beverage industry to use when marketing their vegetarian or vegan products.

Meat alternative products often refer to the meat to which it is intended to be an alternative, such as "...-sausage, schnitzel, burger," but the label must clearly state that it is a meatless product. Among the multitude of products on the supermarket shelf, the V-label offers consumers a way to identify vegan and vegetarian options quickly, safely, and transparently. For example, results of an internationally conducted consumer survey show that they view the independent label positively and understand that V-labeled products are plant-based without looking at the ingredient lists (European Vegetarian Union, 2021).

1.3 Conventional and consumer-based sensory profiling

Conventional sensory profiling is a descriptive technique in which trained panelists use the human senses to describe sensory variations (DIN EN ISO, 2016). In performing a quantitative descriptive analysis (QDA), specific rules must be followed. The selection, training, and supervision of a panel of 8–20 raters constitute the first step. Next, product-specific attributes are defined for each project, describing the similarities and differences between the products. For this purpose, panelists are exposed to many different products as well as appropriate reference standards. Training progress and panel performance are measured by consensus and discriminability among panelists and repeatability within each panelist. Quantitative assessment is conducted using 10–15 cm unstructured line scales, with samples scored individually in a sequential, balanced, randomized order (Lawless and Heymann, 2010; Varela and Ares, 2012). Descriptive analysis techniques are useful for revealing sensory-instrumental relationships. This involves describing the product and measuring the intensities of the selected attributes. The obtained data set contains at least duplicate measurements of a product set based on agreed attributes and can then be analyzed.

The financial and time-consuming aspect of training a sensory panel can be a challenge for the food industry and research institutions, so several consumer-based sensory profiling methods have been developed as a faster and more flexible alternative (Varela and Ares, 2012). The check-all-that-apply (CATA) method comes from marketing research and involves multiple-choice questions consisting of a list of words or phrases from which participants are asked to select those they believe apply to answer a particular question (Adams et al., 2007). Adams et al. (2007) suggested using CATA questions as a simple method to collect information about consumer perceptions and sensory characteristics of foods. The use of CATA questions has become established as a quick and reliable method in sensory research and can provide information similar to that obtained through descriptive analysis with trained panelists (Jaeger et al., 2014). The selected products are presented to consumers in balanced rotation order. They are asked to taste the products and answer the CATA questions by selecting all the attributes they consider appropriate to describe the sample. Usually, there are no restrictions on the number of attributes that consumers can select (Varela and Ares, 2012). Moreover, the list of attributes in the CATA questions may relate exclusively to the sensory attributes of the product or may also include terms that relate to non-sensory attributes, such as emotions. The selection of the attribute list is the most challenging part of the methodology. Sensory terms can correspond to the descriptions used by trained panelists to characterize the products, to the results from previous group discussions, or can be selected from consumer studies (Ares et al., 2013). The number of consumer raters needed ranges from 50 to 100 to perform sensory characterization with CATA questions (Varela and Ares, 2012).

However, the binary response of the CATA method does not allow direct measurement of the intensity of the sensory terms evaluated. Ares et al. (2014) explained that a rating-based variant of CATA has been proposed in which participants must rate the intensity of each applicable attribute called rate-all-that-apply (RATA). The RATA method is conducted by asking participants to rate the intensity of terms they had selected (using a 3-point scale with the endpoints "low," "medium," or "high" or with the option on a 5-point scale with the endpoints "slightly applies" and "very applies") (Ares et al., 2014). The idea behind the method is to improve the ability to discriminate between samples that have similar sensory characteristics but differ in the intensity of these characteristics. For this reason, Vidal et al. (2018) compared RATA and CATA in seven consumer studies and concluded that RATA could be recommended for sensory characterization of samples that differ in the intensity of sensory features when these are familiar to consumers.

1.4 Food matrix of highly processed foods and health aspects

Nearly all food is processed in some way. Food is not healthy or unhealthy because it has been "processed." The term "processed food" needs to be defined, especially to examine its impact on human well-being, health, and disease (Moubarac et al., 2014). Increased disease risks with adverse effects on cardiometabolic disease, cerebrovascular disease, depression, frailty, irritable bowel syndrome, and cancer have been associated with ultra-processed foods (UPF), as shown by recent reviews and meta-analyses (Lane et al., 2021; Matos et al., 2021; Pagliai et al., 2021). One of the most important papers here was conducted by Canadian researchers, who analyzed data from 13,608 adult Canadians and established an association between the consumption of UPFs and diet-related diseases (Nardocci et al., 2021). They demonstrated that higher consumption (estimated as a proportion of total daily energy intake) of UPFs was associated with a higher prevalence of obesity, diabetes, and hypertension (Nardocci et al., 2021). The current leading method for classifying food processing is the NOVA system (NOVA is a name, not an acronym) which was first proposed by a team of researchers in 2009

(Monteiro, 2009). Food processing, as defined by NOVA, includes physical, biological, and chemical processes applied to food after it is assembled from its individual raw materials and before it is available for consumers to cook and consume (Monteiro et al., 2019). It further states that the NOVA system classifies foods according to the type, purpose, and extent of processing rather than the composition of the food and nutrients. All foods and beverages are classified into the following delineated four groups (Monteiro et al., 2019):

> Group 1: Unprocessed or minimally processed foods (edible parts of plants (such as fruits, leaves, stems) or of animals (e.g., meat, eggs, milk), as well as mushrooms, algae)
>
> Group 2: Processed culinary ingredients (oils, butter, lard, sugar, and salt)
>
> Group 3: Processed foods (vegetables preserved in brine/sugar/oil, legumes, fruits, fish, processed animal-based foods such as ham, bacon and smoked fish, most baked bread, simple cheeses)
>
> Group 4: Ultra-processed foods (combinations of ingredients that are mostly exclusively industrial, produced by a variety of industrial food techniques and processes)

The NOVA classification is criticized as being too inaccurate and incomplete due to the lack of thresholds for additives and the critical ingredients sugar, saturated fat, and salt (Gibney et al., 2017; Petrus et al., 2021). An advancement is the Siga classification; here the four NOVA groups are combined with four new reductionist subgroups (Davidou et al., 2020). Furthermore, the effects of processing, such as extrusion technologies, on the food matrix are considered, as well as an evaluation of the content of added salt, sugar, and fat. Also, markers for ultra-processing were established as follows: first, substances obtained by chemical synthesis and identical to natural substances, such as isolated proteins, natural flavors, and yeast extracts, and second, substances obtained by artificial chemical synthesis or sequential processes, such as glucose syrup, hydrolyzed proteins, dextrose.

Figure 3 shows schematically how a UPF is generally produced, i.e., by breaking down raw materials into isolated ingredients, which are then combined into artificial food matrixes with the addition of industrial "cosmetic" additives not commonly used in cooking (Aguilera, 2019; Monteiro et al., 2019). Technological processes used to produce UPFs include refining, extraction, extrusion, and hydrolysis (Aguilera, 2019). Industrial additives include sugars such as maltodextrin, dextrose, and malt extracts derived from corn, wheat, rice, and potato; modified oils (hydrogenated or interesterified oils) and processed proteins such as hydrolyzed proteins, isolates from soy, milk, pea, and egg; and gluten and casein (Aguilera, 2019; Fardet and Rock, 2020; Monteiro et al., 2019). In addition to these ingredients, UPFs also contain "cosmetic" additives, meaning the full range of approved additives. These include flavors, enhancers, colors, emulsifiers, emulsifying salts, artificial sweeteners, thickeners, foaming as well as antifoaming agents, fillers, carbonating, gelling, and glazing agents (Monteiro et al., 2019). According to the NOVA criteria, plant-based alternative products can thus be classified as group 3 or 4. The French Open Food Facts database relates data from over 150 countries and is now the most comprehensive, open-access database on packaged foods (https://world.openfoodfacts.org). This database makes it possible to quickly and easily obtain information on different products and producers, in relation to the NOVA classification but also to the Nutri-Score and ECO-Score. Also, numerous new plant-based meat, cheese, or milk products on the market can be compared to this database.

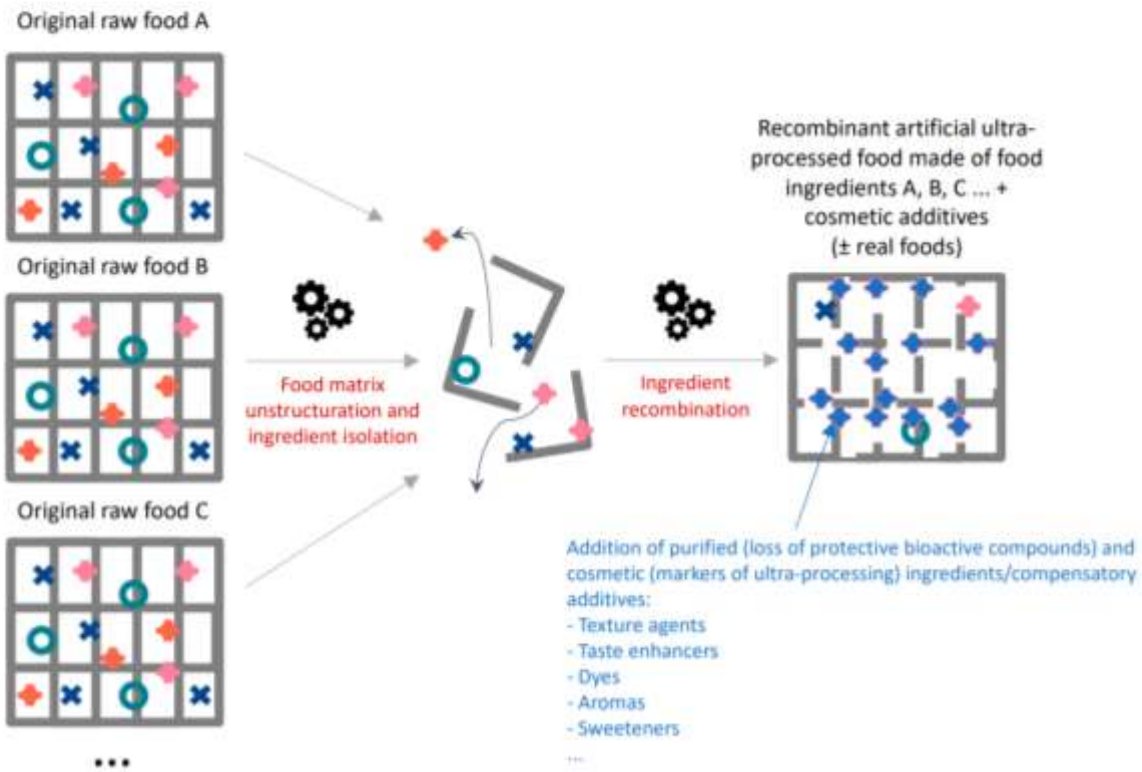

Figure 3: Manufacturing process of UPFs by fractionation of the original raw materials and recombination of the components with "cosmetic" additives, Fardet and Rock (2020).

1.5 Research gaps

Plant-based products that are rich in protein, such as tofu, seitan, or tempeh, are also referred to as "traditional" meat alternative products. Since some of these foods have been consumed for centuries and are not necessarily considered meat alternatives by consumers, they were not explicitly explored in this dissertation. The definition of meat alternatives here is associated with "modern" products, the generation of TVP-based products produced on an industrial scale and commercially available to consumers, particularly in the Western world. Most studies on consumer perception and willingness to pay for meat alternatives relate to burger patties, as they are the dominant product on the market and in media coverage (Tonsor et al., 2021). However, as there is a high diversity of meat alternatives on the food market, the objective of Chapter 2 was to create an overview and a classification of the plant-based alternative products in clusters based on the animal-based original products. Also, a health evaluation based on macro- and micronutrients of the different products as well as the Nutri-Score is a focus of the thesis (Chapters 2 and 3) because currently, there are few sources in the literature. Although most of these studies relate to meat alternatives (e.g., Bohrer, 2019; Curtain and Grafenauer, 2019; Harnack et al., 2021), dairy alternatives are also well researched (e.g., Chalupa-Krebzdak et al., 2018; Silva et al., 2020; Singhal et al., 2017), with the fewest articles on cheese alternatives (e.g., Craig et al., 2022; Fresán and Rippin, 2021; McClements and Grossmann, 2021). The literature often draws relationships and comparisons with animal-based products. As described above, the interrelationship of ultra-processed foods and their health effects on the human organism has been well researched in recent years. Since most of the products studied here can be clearly classified as ultra-processed according to the NOVA classification, reference to this is made in this work.

Much of the literature on consumer motivation is dominated by the sensory attributes (Adise et al., 2015; Elzerman et al., 2011) and environmental impacts (Beacom et al., 2021; de Koning et al., 2020) as well as animal welfare (De Backer and Hudders, 2014; Götze and Brunner, 2021) of meat alternatives. Consumer attitudes toward new plant-based alternative products once confronted with nutritional information and ingredients represent a gap in current research that will be filled in the third study (Chapter 4). Consumers who consume animal-based products are more often not satisfied with the sensory attributes of plant-based alternative products, both for meat and dairy alternatives (Cardello et al., 2022; Wild et al., 2014), which has led to the development of these products in recent years. Therefore, we evaluated sensory data based on nutrition styles, and this additional research point is explored in Chapter 4.

The extent to which sensory perceptions of the trained panel can be compared with data from instrumental sensory measurements is shown in the data in the third chapter. The discussion about the comparability of sensory and instrumental measurements is discussed throughout. Sensory properties, by definition, can never be measured directly by instrumental analyses (Andrewes et al., 2021; Chen, 2020). Measurement of physicochemical properties can only establish relationships with sensory properties, and sensory attribute is measured indirectly. Both studies conclude that technological advancement can improve sensory computation but not perfect it. One trend in this research is the higher sensitivity of sensors, as well as higher variability of data through constructs based on human physiology such as the chewing process, with artificial saliva and heating (Andrewes et al., 2021). When more variables are measured for sensory properties, it becomes less likely that details important to sensory properties will be overlooked, and it makes sense to prioritize the most important and informative variables. Sensory data on plant-based milk alternatives (Chapter 3) were able to show correlations. However, there is no instrumental substitute for good human sensory analysis. The former is a momentary measurement that identifies and quantifies compounds in a product; the latter takes into account the differential temporal release of components from the product and concentration-related changes in perception.

The effects of perceptual changes due to the appearance of plant-based alternative products, including the packaging, the sound when consumed, and when the packaging is opened, are other important aspects to consider in product formulation and optimization. Furthermore, factors regarding the opportunity for consumption, whether alone or in the community, give rise to further questions for consumer research.

1.6 Aim and research questions

The dissertation is integrated into the interdisciplinary joint project "Pflanzlich-orientierte Ernährungsstile als Schlüssel zur Nachhaltigkeit" (short title: Nachhaltige Ernährungsstile, NES) in which representatives of three disciplines of the Georg-August University of Goettingen (Quality of Plant Products, Ecology of Livestock Production, Marketing for Food and Agricultural Products) and of two disciplines of the Leibniz University of Hannover (Food Science and Human Nutrition, Study of Religion) were involved. The project addressed two key research questions. First, to compare different nutrition styles from a comprehensive sustainability perspective, including human health. Second, to analyze the question of whether these nutrition styles are permanently realized by people and thus allow long-term sustainability progress. Seven work packages (WP) were established to address the scientific questions. The focus of the present work was particularly on the commercial availability of plant-based alternative products, the composition of nutritionally relevant ingredients (macro- and micronutrients), the characterizing of sensory properties of these products, and consumer acceptance. The present studies aimed to evaluate the alternative products' sensory quality and gain further insight into the nutrient contents of these plant-based foods, which could have added health and environmental value for consumers compared to conventional animal-based foods. Different food categories of animal-based foods were considered, and plant-based options for meat (hot or cold consumption), cheese, and milk substitutes were included. Visual illustrations of the important aspects of the dissertation are used for orientation (Figure 4). Blue outlines are the anchor points, and green outlines are the methods whereby the market analysis has provided essential information for all three points: Health (Chapter 2) with the further analyses of the mineral and vitamin analytics, the results obtained from the BIG7 as well as the calculation of the Nutri-Score; Quality (Chapter 3) with the data from the sensory panel as well as the instrumental sensory and in cooperation with WP5, the Life-cycle assessment (LCA); finally in cooperation with WP1, the consumer questionnaire and sensory perception (Chapter 4). The arrows are also shown since all methods and anchor points are closely linked. A special feature, for example, was the classification of products into conventional and organic ones, as there were sensory as well as nutritional differences between the products (Figure 4).

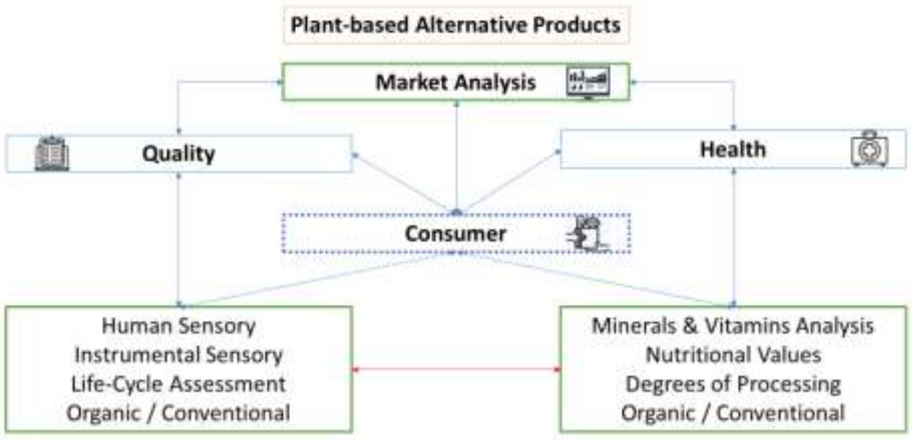

Figure 4: Key anchor points and methods used to orient the work.

The following chapters explore these research questions and objectives:

1. The growing consumer demand for healthy, tasty, and sustainable foods, especially as alternatives to animal-based proteins.
   i. A market analysis of plant-based meat and cheese alternatives was conducted in online stores to get an overview of the variety of products and
   ii. to characterize their nutritional composition, focusing on micronutrients and the Nutri-Score as front-of-package nutrition labeling.

2. Different raw material sources influence sensory parameters and nutritional qualities of plant-based milk alternatives.
   i. Comparison of three different raw material sources (almond, oat, soy) of plant-based milk on micro- and macronutrients compared to cow's milk and
   ii. comparison of the instrumental sensory data with those of the qualitative descriptive sensory data from the panel evaluation.

3. Due to individual nutrition styles, consumers perceive plant-based alternative products differently.
   i. What is the consumers' knowledge and consumption habit regarding plant-based alternative products, identifying the motivating factors that promote consumption and
   ii. linking to the sensory quality of conventional products in the market?

1.7 Thesis structure

After the general introduction in Chapter 1 presenting the background knowledge and literature review of the plant-based alternatives products, the aims and research questions are stated in the subheadings. In order to answer them, the results of three studies corresponding to the following Chapters 2-4 are presented in this dissertation. Finally, Chapter 5 summarizes the main results of the three studies and leads into a general discussion.

Chapter 2: Plant-based alternative products: Are they healthy alternatives? Micro- and macronutrients and nutritional scoring. The study was published in *Nutrients*. In recent years, the product variety for plant-based meat and cheese alternatives has increased immensely. In order to gain an overview of the wide selection, an online-based market analysis for the years 2019 and 2021 was conducted. The products were characterized based on their nutritional value, Nutri-Score, and analysis of micronutrients, so a comparison with the animal-based products was possible. The data on the animal-based products could be obtained from a set of four databases (AUSNUT, Fineli, FoodDATA, Bundeslebensmittelschlüssel) in four different countries (Australia, Finland, USA, Germany). The results show that the number of plant-based products increased in all categories, and the main protein sources in the meat alternatives continued to be soy, wheat, and pea. In general, the meat alternatives contained less energy, total fat, and saturated fat but more carbohydrates and sugars than meat. The protein content of plant-based cheese products was significantly lower than that of cheese and higher in carbohydrate content. The daily requirement for iron was better met by the plant-based alternatives than previously thought, as was the requirement for vitamins E and K. The calculated Nutri-Score was generally lower for the meat alternatives and higher for the cheese alternatives than for the respective animal-based products. Obviously, consumers should increase their intake of plant-based proteins but should limit their consumption of highly processed plant-based alternatives. In this case, the products need to be further modified to provide a health-beneficial alternative to animal-based products for consumers, in particular, reducing the high salt content of the products. Likewise, labeling showing the degree of processing according to the NOVA classification would be helpful for consumers.

Chapter 3: A comparative analysis of plant-based milk alternatives; Part 1: Composition, sensory and nutritional value. The manuscript with the results of the study was submitted to *Sustainability*. Plant-based milk alternatives are increasingly popular with consumers as their interest in reducing animal-based foods grows for health, sustainability, and ethical reasons. Cow's milk is a good source of calcium, meeting the daily requirement, and also the requirements for vitamin B_2 and vitamin B_{12} are adequately met. Therefore, an analysis of the minerals and vitamin contents of almond, oat, and soy drinks was analyzed in this work. A trained panel also carried out a sensory evaluation of these products. Instrumental sensory methods verified the results for basic tastes as well as odor perception. The soy-based drinks met daily micro- and macronutrient nutritional requirements similar to cow's milk, particularly protein content and the three micronutrients mentioned above. All plant-based drinks have significantly lower fat and saturated fatty acid content, and the sugar content of cow's milk is also significantly higher. The sensory panel results show that the two organic products and the two conventional products are similar in terms of their evaluation. One reason for this could be that different additives are approved for organic and conventional products. For example, thickener affects the viscosity of the products and thus also the perceived texture. Organic products were described more frequently with the attributes bitter and astringent, which tend to be viewed negatively by consumers. This could also possibly be related to the different ingredients and additives. The experimentally obtained results confirmed the sensory panel evaluations, therefore, this could be used as a method for a simple and effective evaluation of plant-based milk alternatives. The plant-based milk alternatives evaluated in this study cannot fully replace cow's milk's nutritional and sensory characteristics. They belong to a separate product group and must be evaluated accordingly.

Chapter 4: Plant-based only: Investigating consumers' sensory perception, motivation, and knowledge of different plant-based alternative products on the market. The study was published in *Foods* and belongs to the Special Issue *Sensory Analysis of Plant-Based Products*. Food manufacturers have had to rely on consumers to research and further develop plant-based alternative products. The needs and requirements they demand from the products are multifaceted and include aspects of ecological sustainability, health, and tastiness. In this consumer study with 159 participants, which took place in the sensory laboratory of the University of Goettingen, the research question was how do consumers perceive plant-based milk, cheese, and meat alternatives from a sensory perspective, and what motivations and knowledge do they have. The participants were divided into omnivore, flexitarian, vegetarian, and vegan based on their nutrition styles, and 70% were female, with an average age of 30.1 years. When the BMI was calculated, there was a significant difference; the omnivores had a higher BMI than the vegetarians and vegans. Very few participants had never consumed plant-based alternatives; the frequent users who consumed these products more than five times a week or daily were found in the vegan group. Although motivations differed according to nutrition style, the main factors for all three product groups were animal welfare and the environment. Obviously, a large number of the participants answered "don't know" in the knowledge survey. There were hardly any differences between the nutrition styles in the sensory evaluation of the individual attributes of the three products. However, significantly higher ratings were given to overall liking by vegans compared to the omnivores. Sensory consumer research is considered an important element of product and market research. Here it is evident that consumer information and education regarding plant-based products should be improved. This can be achieved, for example, through standard labeling of the products, such as a front-of-pack label that clearly indicates that the product is vegan or vegetarian (V-label), how it is evaluated in terms of health (Nutri-Score), and what ecological factors play a role (ECO-Score).

Chapter 2

Plant-based alternative products: Are they healthy alternatives? Micro- and macronutrients and nutritional scoring

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Conceived and designed the experiments: M. Pointke, E. Pawelzik

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Article

Plant-Based Alternative Products: Are They Healthy Alternatives? Micro- and Macronutrients and Nutritional Scoring

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Abstract: In recent decades, the demand, supply, and consumption of plant-based (pb) alternative products have increased worldwide. The objective of this study was to characterize pb meat and cheese products and compare them with their respective animal-based products. Data were collected in online market analyses (2019/2021). Nutritional data, Nutri-Score, and analysis of micronutrients are presented in this article. The number of products has grown in all categories, with the largest increase of 110% in pb cheese. The main protein sources in pb meat were soy and wheat, followed by an increasing use of peas. Pb meat generally contained less energy and total and saturated fat, but more carbohydrates and sugars than meat. In pb cheese, the protein content was lower than that of cheese. In 3 of 17 food groups, the salt content of pb alternatives was lower than in animal products. The daily requirement for iron could be covered better by pb alternatives than previously anticipated as well as the need for the vitamins E and K. The calculated Nutri-Score was generally lower for pb meat and higher for pb cheese than for the respective animal products. The trend towards consumption of pb alternative products is increasing, but the high level of processing, wide range of nutrients, and high salt content indicate the need for nutritional guidelines for these products.

Keywords: cheese alternative; meat alternative; micronutrients; Nutri-Score; online market analysis

1. Introduction

From start-ups and leading companies to the world's largest meat corporations, food manufacturers are developing fast-growing innovations in plant-based (pb) foods. This new generation of pb meat, fish, cheese, egg, and dairy products is increasingly competitive with animal products. Market research institutes conduct consumer studies to analyze, among other things, the motivations for consuming pb products. A German online survey [1] clarified that age is essential in individual motivation. More than 32% of the over-60 s stated that health reasons were their main motivation for abstaining from meat, while the 40–49 age group cited animal welfare reasons (27%). In the 18–29 age group, on the other hand, environmental and climate reasons (18%) play an important role. The discussion about reducing the consumption of animal-based foods has increased at many levels in recent years. The publication of the EAT–*Lancet* not Commission, about a global planetary healthy diet [2], was decisive in the scientific field. In its latest report, the OECD/FAO [3] assumes that meat consumption in industrialized countries will continue to rise as environmental and sustainability awareness increases in the population. Younger people, in particular, are increasingly adopting vegan, vegetarian, or flexitarian diets and thus reducing their consumption of animal products. In recent years, pb alternative products have experienced an enormous growth in the German and European food retail sector [4]. In Germany, for example, sales (€) of pb alternative products increased by 97% and sales volume (kg/L) increased by 80% between 2018 and 2020 [4].

Meat alternative products are produced based on proteins from plants (e.g., algae, cereals, legumes, mushrooms) or animal sources (e.g., eggs, insects, milk) [5–8]. Products made from insects currently still play a minor role in Western countries. Despite growing consumer interest in insects, there is still a large gap between curious sampling and actual acceptance. Numerous research groups are currently investigating the complexity of consumer acceptance of insects as food (food neophobia) and how this can be increased in the future [9–11]. Alternative cheese products are "cheese-like" products in which the main ingredient, milk, is replaced by plant components. Besides water, various vegetable edible fats/oils are usually the main ingredients. Other ingredients such as proteins and additives are blended into a homogeneous mixture using heat, mechanical shearing, and emulsifying salts [12,13]. The labeling of pb alternative products is currently being discussed on a social-political level in Europe. There are no specific regulations on these products, so the food information (FIC) regulation [14] applies. The basic principles of product information for consumers must be clear, concise, easy to understand, and not misleading. For better understanding, known products from food groups such as salami or mozzarella are referred to with the addition plant-based (pb) in this manuscript.

The extent to which alternative products can be compared with the respective animal products from a nutritional-physiological point of view is the main objective of the present study. Particular attention was paid to the micronutrients, as these are usually not declared by the manufacturers unless they are explicitly supplemented. With the help of the Nutri-Score, the mandatory information ("Big 7") of the nutrition declaration [14] according to the manufacturer was used to obtain an overview of the macronutrients in the respective product group. With the agreement of numerous stakeholders, the Nutri-Score was introduced as a voluntary consumer information label (front-of-package nutrition labeling (FOPL)) in Germany in November 2020. Recent studies show that FOPL can have positive effects on shopping behavior by leading to, among other things, low consumption of products with a high energy, saturated fat, and sodium content [15–18]. Furthermore, consumers can more easily identify healthier products by replacing foods with red labelling with similar, currently available products without red labeling.

Satisfying the growing consumer demand for healthy, tasty, and sustainable foods, especially healthy alternatives to animal proteins, is a major challenge for the food industry. Therefore, this study aims to (I) provide an overview of the pb meat and cheese alternatives available in online stores in 2019 and 2021, and (II) characterize their nutrient composition, focusing on micronutrients compared to animal-based products, as well as the newly approved Nutri-Score as an FOPL.

2. Materials and Methods

2.1. Online Market Analysis

An online market analysis of pb meat and cheese alternative products was conducted in the first quarter of each of 2019 and 2021. As a result of the global COVID-19 pandemic, studies have shown that the eating habits of many consumers have changed, and meat consumption and overall consumption of animal-based products have decreased [19–21]. First-time buyers of pb meat were consumers who started to become flexitarians in the midst of the pandemic. Therefore, the second market analysis in 2021 will find out if and to what extent the variety of products has changed. Although products were offered directly by the manufacturer or the retailer on the websites, a list of ingredients and nutritional labeling ("Big 7") had to be available there. Therefore, almost exclusively products available on the European market were included, as the legal regulations there are uniform, and the minimum information must be on the packaging [14]. In the internet search, keywords such as "meat alternative", "cheese alternative", "meat substitute", "cheese substitute", "meat-free", "dairy-free", "plant-based", "vegan", and "vegetarian" were used to cover as many available products as possible.

The study included products intended to mimic meat or cheese but made from primarily pb ingredients. The products were categorized according to their similarity to animal-based products. A distinction was also made between organic and conventional products, as there are guidelines for organic products in Europe [22] as to which ingredients may be added to a product. The two main differences in meat alternatives were the criterion of whether the food is eaten hot or cold. The first category (plant-based meat alternatives consumed hot, PBMA-hot) included product groups that were named "fillet", "steak", "schnitzel", "burger", "strips", "minced", "bratwurst", or "sausage" in the product name or sales description. The second category included the following product groups (plant-based meat alternatives consumed cold, PBMA-cold): "meat sausage", "salami", "spreading sausage", and "meat salad" (Table 1). The present study focused on "modern" meat alternative products, so products that did not specifically serve to imitate meat products, such as tofu, tempeh, and granulated products, were not considered. Products that were offered as alternatives to chicken meat or seafood were also not included. These are foods with a high degree of convenience according to the NOVA food classification [23], where consumers only need to perform a few preparation steps at home to consume them. Plant-based cheese alternatives (PBCA) were categorized into the product groups "sliced cheese", "cheddar", "cream cheese", "mozzarella", and "feta". Pure nut products such as cashew and almond, which are fermented, were not included.

Table 1. Classification of pb alternative product categories.

	Category	Description
PBMA-hot	Fillet	Either contains "tenderloin" in the product name or is a meat-free product that appears to imitate beef/pork tenderloin
	Steak	Either contains "steak" in the product name or is a meat-free product that appears to imitate beef/pork steak
	Schnitzel	Either contains "schnitzel" in the product name or is a meat-free product that appears to imitate breaded meat
	Burger	Either contains "burger" and/or "pattie/patty" in the product name or is a meat-free product that appears to imitate beef burger
	Strips	Either contains "gyros", "chunks", and/or "strips" in the product name or is a meat-free product that appears as small thin slices or strips
	Minced meat	Either contains "mince" in the product name or is a meat-free product that appears to imitate minced meat
	Bratwurst	Either contains "bratwurst" or "barbecue sausage" in the product name or is a meat-free product that appears to imitate bratwurst
	Sausage	Either contains "Wiener", "Frankfurter", and/or "Hot Dog" in the product name or is a meat-free product that appears to imitate sausage
PBMA-cold	Meat sausage	Either contains "Lyoner", "Mortadella", and/or "cold cuts" in the product name or is a meat-free product that appears to imitate meat sausage, which can be used in sandwiches
	Salami	Either contains "salami" in the product name or is a meat-free product that appears to imitate salami, which can be used in sandwiches
	Spreading sausage	Either contains "liver sausage" and/or "pâté" in the product name or is a meat-free product that appears to imitate spreading sausage, which can be used in sandwiches

	Meat salad	Meat-free product that appears to imitate meat salad, which can be used in sandwiches
PBCA	Sliced cheese	Either contains "Gouda" in the product name or is a dairy-free product that appears to imitate sliced cheese, which can be used in sandwiches
	Cheddar	Either contains "Cheddar" in the product name or is a dairy-free product that appears to imitate cheddar, which can be used in sandwiches
	Cream cheese	Either contains "fresh" and/or "cream" in the product name or is a dairy-free product that appears to imitate cream cheese, which can be used in sandwiches
	Mozzarella	Either contains "mozzarella" in the product name or is a dairy-free product that appears to imitate mozzarella, which can be used in sandwiches
	Feta	Either contains "Greek style" in the product name or is a dairy-free product that appears to imitate brined cheese or feta, which can be used in sandwiches

PBMA-hot = plant-based meat alternatives consumed hot; PBMA-cold = plant-based meat alternatives consumed cold; PBCA = plant-based cheese alternatives; product name also refers to the sales description.

2.2. Data of Animal Foods from Databases

To make a comparison between plant- and animal-based products, data were collected from the following four national nutrient databases: Food Standards Australia New Zealand, AUSNUT [24]; Fineli, the Nutrition Unit of the National Institute for Health and Welfare in Finland [25]; the US Department of Agriculture (USDA) FoodData Central Data, Food and Nutrient Database for Dietary Studies 2017–2018 [26]; and the Max RubnerInstitute, Federal Research Institute of Nutrition and Food, Bundeslebensmittelschlüssel (BLS) Version 3.02 [27].

2.3. Nutri-Score

FOPL were created by a joint initiative of governments, product manufacturers, and retailers to encourage consumers to make healthier food choices by providing product information at a glance and attract attention [15]. The Nutri-Score is a color-coded, graded FOPL first introduced in France in 2017 [28] and has also been used in Germany on a voluntary basis since 2020. Classified foods can be divided into five categories by a nutritional score (from category A = dark green, indicating high nutritional quality, to category E = red, indicating low nutritional quality) [29]. In this study, the evaluation of nutrients and the calculation of the Nutri-Score were based on the calculation table of the Federal Ministry of Food and Agriculture (BMEL, German translation as of 2021). On a scale from −15 points (A) to +40 points (E), the nutrient content per 100 g of food was evaluated. Positive points (0–10) were assigned for dietary energy, total sugars, saturated fatty acids (SFA), and sodium. Negative points (0–5) were scored for fruits, vegetables, and nuts, fiber, protein, and canola, walnut, and olive oil content.

2.4. Sample Material

All products used for vitamin and mineral analysis in this study were purchased from online stores or local supermarkets. Four products with mostly different protein or fat sources were selected from each of the four product categories (meat sausage, salami, burger, sliced cheese) (Table 2).

Table 2. Pb products for vitamin and mineral analysis.

Category		Product Name (German Name)		Manufacturer or Distributor
PBMA-cold	Meat sausage	Vegan cold cuts	(Veganer Aufschnitt Lyoner Art)	Heirler
		Vegan cold cuts	(Vegan Aufschnitt Natur)	Veganz
		Vegan cold cuts	(Veganer Aufschnitt auf Basis von Pflanzenprotein nach Lyoner Art)	EDEKA
		Vegetarian cold cuts	(Vegetarischer Schinken Spicker Mortadella)	Rügenwalder
	Salami	Vegan salami	(Veganer Aufschnitt Salami Art)	Heirler
		Vegan salami	(Aufschnitt Rustikal nach Salami Art)	Hobelz
		Vegan salami	(Veganer Aufschnitt nach Art Salami)	EDEKA
		Vegetarian salami	(Vegetarische Mühlen Salami Klassisch)	Rügenwalder
PBMA-hot	Burger	Vegetarian burger patty	(Classic Burgers) (frozen)	Quorn
		Vegan burger patty	(Incredible Burger) (chilled)	Garden Gourmet
		Vegan burger patty	(Next Level Burger) (chilled)	Lidl
		Vegan burger patty	(Beyond Burger) (frozen)	Beyond Meat
PBCA	Sliced cheese	Vegan cheese	(Original Geschmack Scheiben)	Violife
		Vegan cheese	(Scheiben Classic)	Bedda
		Vegan cheese	(Natur Genießerscheiben)	SimplyV
		Vegan cheese	(Mr. Berta Schmelz Scheiben)	Soyatoo!

PBMA-hot = plant-based meat alternatives consumed hot; PBMA-cold = plant-based meat alternatives consumed cold; PBCA = plant-based cheese alternatives.

2.5. Mineral and Vitamin Analysis

Freeze-dried material was used for mineral and vitamin analysis; for this purpose, the products had to be cut into pieces and freeze-dried (EPSILON 2-40; Christ, Osterode am Harz, Germany). Subsequently, the samples were ground with a coffee grinder (KSW 3307, Clatronic International, Kempen, Germany) and stored at +4 °C until analysis. Mineral concentrations were determined using a method adapted from that of Wheal et al. [30]. Approximately 100 mg of each sample was digested in 4 mL of 65% (*v*/*v*) nitric acid and 2 mL of 30% (*v*/*v*) hydrogen peroxide for 75 min at 200 °C and 40 bar in a microwave oven (Ethos 660; MWT AG, Heerbrugg, Switzerland). Samples were then made up to 25 mL with distilled water. Mineral concentrations were measured by inductively coupled plasma optical emission spectrometry (Vista-PRO CCD Simultaneous ICP-OES; Varian Inc., Palo Alto, CA, United States). Vitamin analysis of freeze-dried samples was conducted by bilacon (bilacon GmbH, Berlin, Germany, Department of Instrumental Analysis) using standardized procedures of the multi-method for determining water- and fat-soluble vitamins in food by LC-MS/MS (methods: PV-SA-158 and 159, 2019-02).

2.6. Statistical Analysis

SPSS® statistical software (IBM SPSS Statistics, Version 26.0, Armond, NY, USA) and Microsoft Excel® (Microsoft Office Professional Plus, 2013) were used for statistical analysis. One-way and two-way analysis of variance (ANOVA), followed by Tukey's HSD test ($p \leq 0.05$), were conducted to show significant differences.

3. Results

3.1. Market Analysis

In total, data were collected from 150 PBMA-hot products in 2019 and from 236 products in 2021 (+57%). Only a small proportion of this product category was labeled as organic. Compared to the earlier year, there were hardly any changes in organic products in this product category. The largest increase in samples from 2019 to 2021 was seen in the PBMA-cold category (from n = 48 to n = 101 or an increase of 110%). Furthermore, in this product category, significantly more than half of the products were produced conventionally. Overall, 65 cheese alternative products were included in the analysis in 2019 and 123 in 2021, representing an 89% increase in the number of products. The majority of the products available on the market were also not labeled as organic, but produced conventionally. However, the number of organic products increased significantly, by 140%, especially for alternative cream cheese products, by 260% (Table 3).

Table 3. Development of the number and type of products of pb cheese and meat alternatives, and the distribution (%) of products with organic labels between 2019 and 2021.

Category		Pb Products (*n*)				Increase from 2019 to 2021 (%)	
		2019		2021			
		Total	Organic	Total	Organic	Total	Organic
PBMA-hot	Fillet	6	4	6	4	0	0
	Steak	10	8	13	8	30	0
	Schnitzel	16	6	18	2	13	−67
	Burger	34	17	52	14	53	−18
	Strips	23	13	35	16	52	23
	Minced	12	4	29	4	142	0
	Bratwurst	31	13	51	19	65	46
	Sausage	18	7	32	13	78	86
	Total	**150**	**72**	**236**	**80**	**57**	**11**
PBMA-cold	Meat sausage	18	5	57	18	217	260
	Salami	13	6	20	8	54	33
	Spreading sausage	12	6	18	7	50	17
	Meat salad	5	1	6	2	20	100
	Total	**48**	**18**	**101**	**35**	**110**	**94**
PBCA	Sliced cheese	17	4	43	4	153	0
	Cheddar	15	1	13	1	−13	0
	Cream cheese	13	5	38	18	192	260
	Mozzarella	8	3	13	6	63	100
	Feta	12	3	16	7	33	133
	Total	**65**	**15**	**123**	**36**	**89**	**140**

PBMA-hot = plant-based meat alternatives—consumed hot; PBMA-cold = plant-based meat alternatives—consumed cold; PBCA = plant-based cheese alternatives.

The main protein sources of the investigated meat alternatives differed significantly depending on the product (Figures 1 and 2). Soy was the most common protein source, and there was a year-to-year increase from 36.7% to 37.7% in PBMA-hot products and from 27.1% to 38.3% in PBMA-cold products. Wheat protein was the second most commonly used protein source. Overall, there was a clear increase in the use of pea protein, especially in PBMA-hot products, from 6.0% to 19.1%, and a significant decrease in animal proteins (milk protein and egg) in both pb product groups (PBMA-hot and PBMA-cold). Protein combinations were frequently found in the products. As shown in Figure 3, coconut oil was a common fat ingredient in the cheese alternatives. The use of palm oil was significantly reduced in 2021 from 10.8% to 4.1%. There was an increase in the use of cashew nuts, from 7.7% to 10.6%, and almonds, which accounted for 4.1% (Others) in 2021.

3.2. Nutrients and Nutri-Score

Tables 4–6 give an overview of the main nutrients in PBMA-hot, PBMA-cold, and PBCA products that were available as information for each of the categories studied. In addition, the Nutri-Score was calculated for all products. Since consumers can directly substitute animal meat and cheese products with pb alternative products, a comparison of nutrients and Nutri-Score was performed and included in the tables.

In the PBMA-hot product category (Table 4), the average energy value ranged from 152.5 to 244.4 kcal/100 g in 2019 and from 146.5 to 240.7 kcal/100 g in 2021. Fat content varied from 5.05 to 15.98 g/100 g, with sausage having the highest value in both years. The SFA content was 0.92 to 3.40 g/100 g, with the highest value for bratwurst (2019) and burger (2021) categories. Carbohydrate content was in the range from 4.34 to 15.48 g/100 g (2019) and from 4.91 to 16.88 g/100 g (2021), with the highest values in both years for schnitzel. The sugar content was 0.77–2.07 g/100 g in 2019 and 0.88–2.28 g/100 g in 2021, with the highest amounts in burger and steak, respectively. On average, a relatively high protein content, between 14.68 and 21.33 g/100 g, was observed in all product categories. Although the average salt content was generally less than 1.5 g/100 g, there was a wide range in the means of the product groups as well as from year to year, from 1.16 to 1.82 g/100 g, such that several products (2019 n = 7, 2021 n = 9) also contained more than 2.5 g of salt. In six out of a total of seven nutritional categories, fillet and strips had the lowest scores in both years. In the Nutri-Score calculation, fillet scored best, from −2.17 (2019) to −1.17 (2021), thus being in category A (dark green). Bratwurst and steak, on the other hand, achieved the highest score of 8.06 (2019) and 8.85 (2021), respectively, resulting in both of them being in category C (yellow).

Pb meat tends to have a lower kilocalorie content than animal-based meat (Table 4). In three out of eight food groups, namely burger, bratwurst, and sausage, the pb products showed significantly lower values than the animal-based products. A similar difference was found for total fat and SFA: their proportion was significantly higher in the animal-based products, except for minced meat (2021), where the SFA content in the pb products did not differ from that in animal-based products. Although, as expected, pb products contained more carbohydrates and sugars, there were no significant differences in PBMA-hot products compared to the animal variant except for burger. The salt content of pb products was significantly higher than for animal-based products in six out of eight food groups. The reverse was true for bratwurst, and there was no significant difference for meat sausage. The Nutri-Score was significantly better for the pb products in six categories. As with the pb sausage products, the animal-based sausage products received the highest scores, and the animal-based products scored lowest and were in category E (red).

The results for PBMA-cold products (Table 5) were similar, with the content of fat and SFA being significantly higher in animal-based products in two of the four product groups. The carbohydrate and sugar contents were significantly higher in all categories, twice as high for carbohydrates and four times as high for sugar, compared to animal products. The calculated Nutri-Score was overall lower in the pb products, from 7.50 to 14.92 in 2019 and 8.35 to 13.56 in 2021, corresponding to categories C and D (yellow/orange). The scores for meat products are significantly higher here in three out of four food groups.

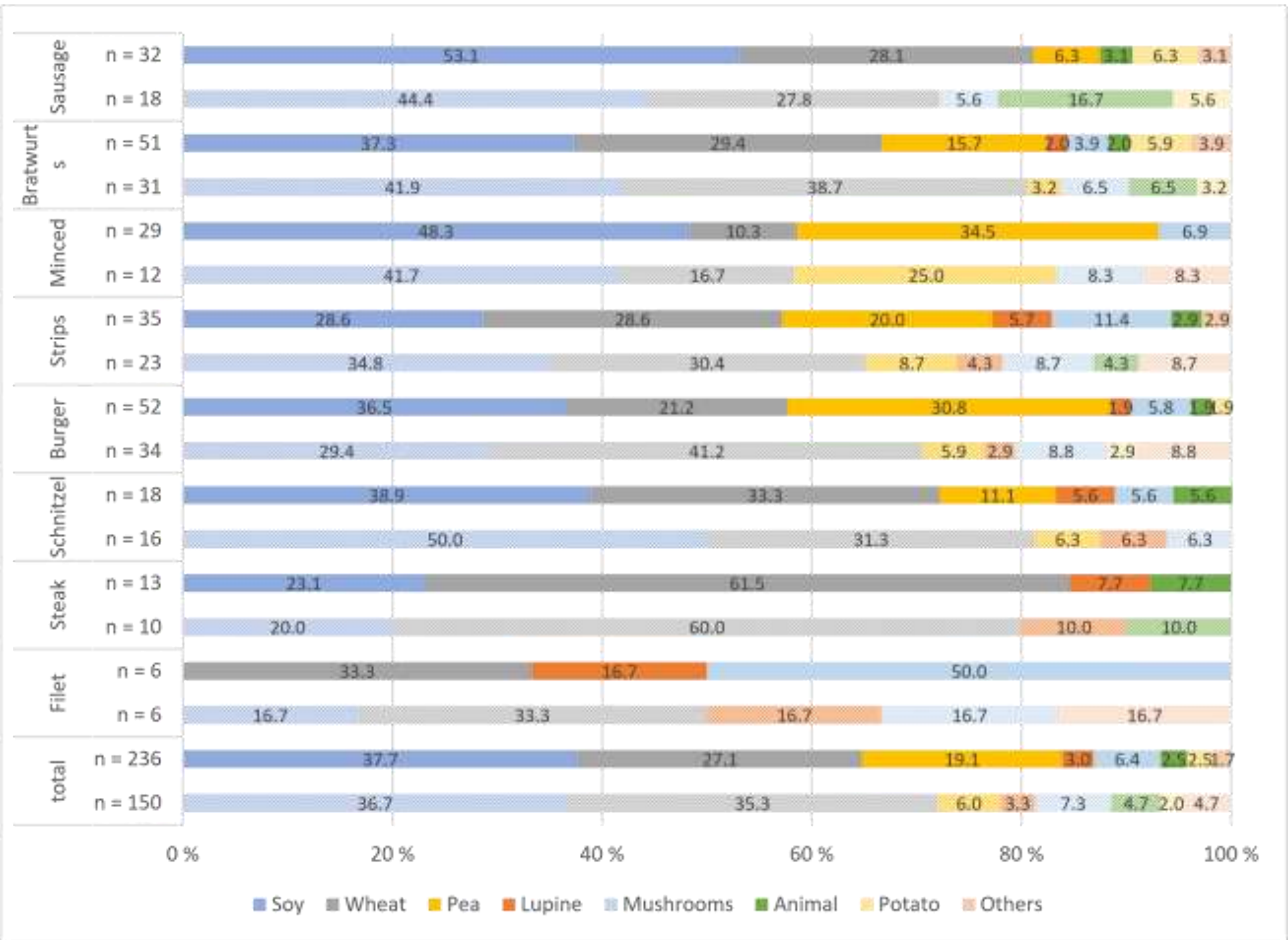

Figure 1. Protein sources used in plant-based meat alternatives (PBMA-hot) in 2019 (patterned color) and 2021 (solid color) (%); *n* = number of products; animal = milk or/and egg protein; others = beans, sunflower and pumpkin seeds.

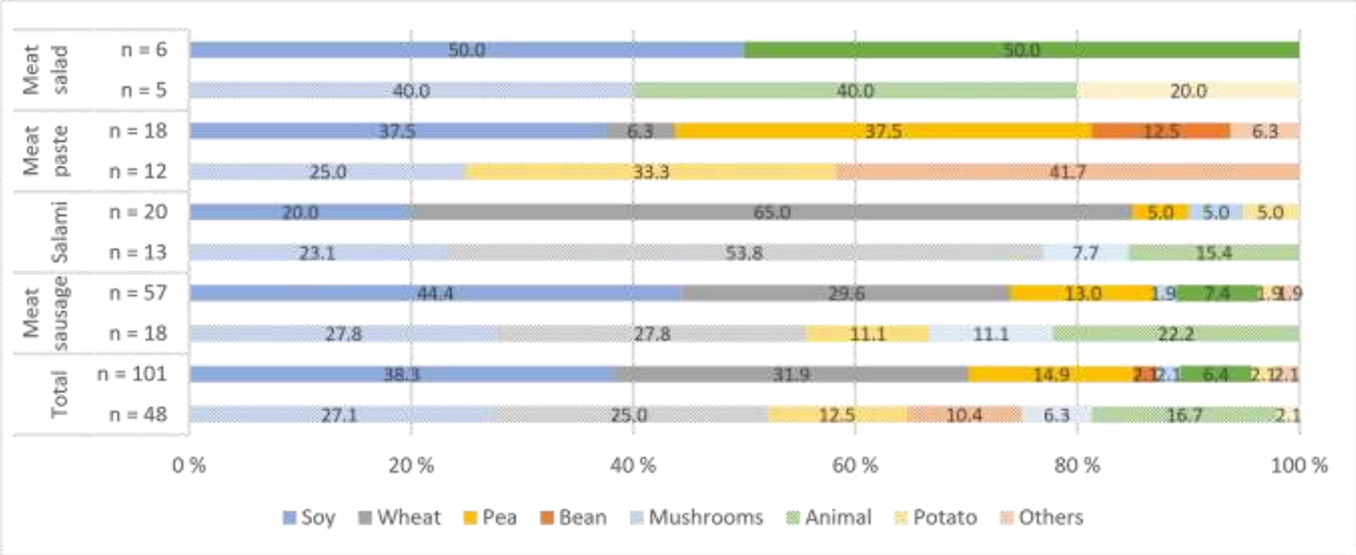

Figure 2. Protein sources used in plant-based meat alternatives (PBMA-cold) in 2019 (patterned color) and 2021 (solid color) (%); *n* = number of products; animal = milk and/or egg protein; others = millet, sunflower seeds.

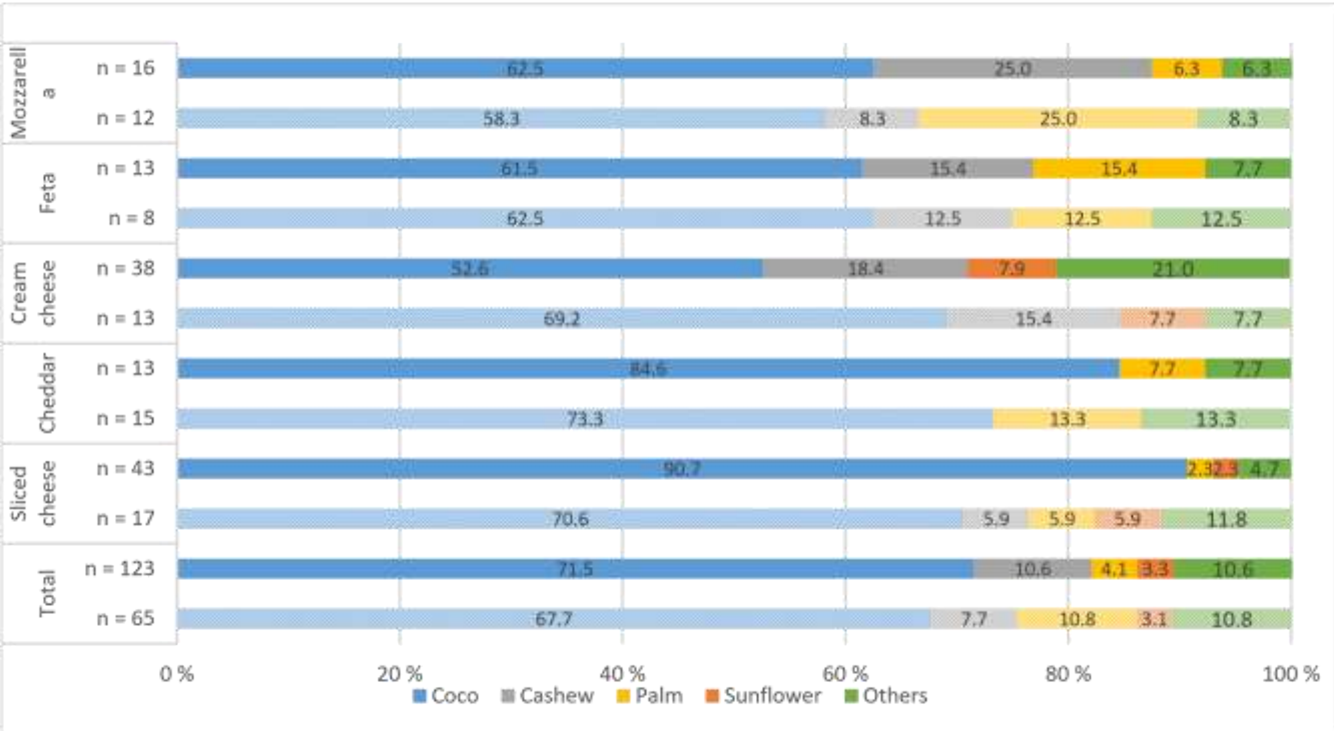

Figure 3. Fat sources used in plant-based cheese alternatives (PBCA) in 2019 (patterned color) and 2021 (solid color) (%); *n* = number of products; others = almond, shea butter, soy, olive, lupine.

Table 4. Nutrients ("Big 7") and Nutri-Score per 100 g of pb meat alternatives and meat (mean and standard deviation) in eight different food groups, compared to animal-based products *.

Nutrient Criteria	Pb Fillet 2019 (n = 6)	Pb Fillet 2021 (n = 6)	Meat Fillet (n = 15)	Pb Steak 2019 (n = 10)	Pb Steak 2021 (n = 13)	Meat Steak (n = 73)	Pb Schnitzel 2019 (n = 16)	Pb Schnitzel 2021 (n = 18)	Meat Schnitzel (n = 19)
Energy (kcal)	152.5 ± 75.6	146.5 ± 63.5	141.6 ± 32.6	188.0 ± 54.9	206.6 ± 54.2	182.4 ± 131.3	244.4 ± 38.8	240.7 ± 41.4	224.3 ± 42.9
Fat (g)	5.58 ± 3.89	5.05 ± 3.81	5.74 ± 3.47	7.52 ± 4.79	9.13 ± 4.30	10.69 ± 16.36	11.98 ± 3.53	11.76 ± 3.95	10.88 ± 4.85
Saturated fat (g)	0.92 ± 0.78	0.92 ± 0.79	2.14 ± 1.21	1.76 ± 2.28	2.75 ± 2.81	4.09 ± 6.34	1.78 ± 1.67 ^{a}	1.34 ± 0.58 ^{a}	3.62 ± 1.62 ^{b}
Carbohydrate (g)	5.67 ± 3.50 ^{b}	5.22 ± 2.55 ^{b}	0.00 ± 0.00 ^{a}	8.14 ± 5.98 ^{b}	8.17 ± 5.53 ^{b}	0.01 ± 0.05 ^{a}	15.48 ± 4.48 ^{b}	16.88 ± 4.78 ^{b}	9.13 ± 5.08 ^{a}
Sugars (g)	0.77 ± 0.75 ^{b}	0.88 ± 0.57 ^{b}	0.00 ± 0.00 ^{a}	1.38 ± 0.86 ^{b}	2.28 ± 1.81 ^{c}	0.00 ± 0.00 ^{a}	1.65 ± 0.79 ^{b}	1.63 ± 1.29 ^{b}	0.44 ± 0.32 ^{a}
Protein (g)	17.52 ± 9.96	18.00 ± 8.15	22.36 ± 2.02	20.46 ± 6.90	20.95 ± 6.58	21.61 ± 4.23	16.69 ± 4.58 ^{a}	14.68 ± 3.75 ^{a}	22.22 ± 2.41 ^{b}
Salt (g)	1.19 ± 0.45 ^{b}	1.22 ± 0.52 ^{b}	0.22 ± 0.24 ^{a}	1.57 ± 0.51 ^{b}	1.82 ± 0.35 ^{b}	0.21 ± 0.31 ^{a}	1.71 ± 0.43 ^{b}	1.55 ± 0.30 ^{b}	0.46 ± 0.27 ^{a}
Nutri-Score	−2.17 ± 7.49	−1.17 ± 9.02	4.33 ± 7.18	3.90 ± 6.84	8.85 ± 7.07	5.37 ± 7.38	4.88 ± 7.02 ^{a}	3.50 ± 5.31 ^{a}	10.47 ± 7.00 ^{b}

Nutrient Criteria	Pb Burger 2019 (n = 34)	Pb Burger 2021 (n = 52)	Meat Burger (n = 26)	Pb Strips 2019 (n = 23)	Pb Strips 2021 (n = 35)	Meat Strips (n = 21)	Pb Minced 2019 (n = 12)	Pb Minced 2021 (n = 29)	Meat Minced (n = 21)
Energy (kcal)	223.0 ± 55.1 ^{ab}	203.5 ± 42.5 ^{a}	236.2 ± 32.7 ^{b}	163.3 ± 68.1	195.2 ± 52.3	205.8 ± 121.1	173.4 ± 56.9	177.6 ± 41.2	199.4 ± 45.6
Fat (g)	9.90 ± 5.13 ^{a}	11.32 ± 4.25 ^{a}	14.32 ± 3.75 ^{b}	6.87 ± 5.45 ^{a}	9.33 ± 4.38 ^{ab}	13.40 ± 13.42 ^{b}	6.44 ± 4.84 ^{a}	8.59 ± 4.36 ^{a}	12.00 ± 4.47 ^{b}
Saturated fat (g)	2.09 ± 2.38 ^{a}	3.40 ± 3.65 ^{a}	5.51 ± 1.28 ^{b}	1.27 ± 1.09 ^{a}	1.78 ± 1.63 ^{a}	4.79 ± 5.76 ^{b}	0.98 ± 1.00 ^{a}	3.26 ± 3.70 ^{b}	4.92 ± 1.75 ^{b}
Carbohydrate (g)	11.42 ± 7.23	8.94 ± 5.83	7.72 ± 8.22	4.34 ± 2.84 ^{ab}	4.91 ± 2.28 ^{b}	2.56 ± 3.96 ^{a}	6.19 ± 4.28 ^{b}	7.76 ± 6.84 ^{b}	1.43 ± 2.61 ^{a}
Sugars (g)	2.07 ± 1.54	1.60 ± 1.54	1.32 ± 1.50	1.10 ± 1.05	1.40 ± 1.22	0.91 ± 1.51	1.34 ± 0.96 ^{b}	1.24 ± 1.28 ^{b}	0.23 ± 0.42 ^{a}
Protein (g)	17.23 ± 8.06 ^{ab}	15.28 ± 5.34 ^{a}	18.82 ± 4.03 ^{b}	19.77 ± 7.99	21.33 ± 6.01	18.43 ± 7.21	21.18 ± 7.88 ^{b}	16.73 ± 4.37 ^{a}	21.24 ± 2.91 ^{b}
Salt (g)	1.48 ± 0.61 ^{b}	1.44 ± 0.41 ^{b}	1.01 ± 0.49 ^{a}	1.16 ± 0.61 ^{ab}	1.47 ± 0.75 ^{b}	0.85 ± 1.20 ^{a}	1.25 ± 0.63 ^{b}	1.26 ± 0.55 ^{b}	0.40 ± 0.39 ^{a}
Nutri-Score	4.50 ± 5.70 ^{a}	5.27 ± 6.75 ^{a}	13.54 ± 6.37 ^{b}	0.61 ± 6.95 ^{a}	3.23 ± 7.82 ^{a}	8.86 ± 8.96 ^{b}	−0.50 ± 6.30 ^{a}	3.03 ± 7.10 ^{a}	8.10 ± 5.76 ^{b}

Nutrient Criteria	Pb Bratwurst 2019 (n = 31)	Pb Bratwurst 2021 (n = 51)	Meat Bratwurst (n = 28)	Pb Sausage 2019 (n = 18)	Pb Sausage 2021 (n = 32)	Meat Sausage (n = 26)
Energy (kcal)	224.7 ± 44.1 ^{a}	218.6 ± 45.0 ^{a}	267.6 ± 41.0 ^{b}	229.1 ± 45.4 ^{a}	224.8 ± 34.8 ^{a}	264.0 ± 67.2 ^{b}
Fat (g)	13.43 ± 5.58 ^{a}	13.62 ± 4.80 ^{a}	22.14 ± 5.00 ^{b}	15.98 ± 4.93 ^{a}	13.97 ± 3.44 ^{a}	21.95 ± 7.94 ^{b}
Saturated fat (g)	2.66 ± 2.23 ^{a}	3.05 ± 2.87 ^{a}	8.84 ± 1.85 ^{b}	1.57 ± 0.77 ^{a}	2.39 ± 2.85 ^{a}	8.47 ± 2.97 ^{b}
Carbohydrate (g)	5.41 ± 2.94 ^{b}	6.00 ± 2.87 ^{b}	2.16 ± 2.40 ^{a}	5.10 ± 2.53 ^{b}	5.32 ± 2.28 ^{b}	2.47 ± 2.55 ^{a}
Sugars (g)	1.46 ± 1.42 ^{b}	1.42 ± 1.22 ^{b}	0.53 ± 0.36 ^{a}	1.04 ± 0.68 ^{b}	1.40 ± 0.90 ^{b}	0.52 ± 0.62 ^{a}
Protein (g)	19.80 ± 6.26 ^{b}	17.12 ± 6.68 ^{ab}	15.08 ± 1.56 ^{a}	15.07 ± 6.96 ^{ab}	18.91 ± 7.50 ^{b}	13.24 ± 2.12 ^{a}
Salt (g)	1.76 ± 0.40 ^{a}	1.66 ± 0.36 ^{a}	1.98 ± 0.37 ^{b}	1.75 ± 0.66	1.77 ± 0.85	1.76 ± 0.40
Nutri-Score	8.06 ± 5.13 ^{a}	7.45 ± 5.68 ^{a}	23.21 ± 4.08 ^{b}	7.67 ± 5.19 ^{a}	7.94 ± 4.72 ^{a}	20.04 ± 3.77 ^{b}

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; $^{a–c}$ values within a food group with differing superscript letters are statistically significantly different ($p \leq 0.05$).

Table 5. Nutrients ("Big 7") and Nutri-Score per 100 g of pb meat cold cuts alternatives and cold cuts meat (mean and standard deviation) in four different food groups, compared to animal-based products *.

Nutrient Criteria	Pb Meat Sausage 2019 (n = 18)	Pb Meat Sausage 2021 (n = 57)	Meat Sausage (n = 37)	Pb Salami 2019 (n = 13)	Pb Salami 2021 (n = 20)	Meat Salami (n = 23)	Pb Spreading Sausage 2019 (n = 12)	Pb Spreading Sausage 2021 (n = 18)	Meat Spreading Sausage (n = 16)
Energy (kcal)	185.4 ± 49.1	198.1 ± 45.6	215.6 ± 84.4	210.3 ± 37.7 ^{a}	218.3 ± 46.9 ^{a}	364.4 ± 75.0 ^{b}	280.7 ± 53.5	276.3 ± 43.0	293.1 ± 72.5
Fat (g)	10.82 ± 5.20 ^{a}	12.05 ± 4.29 ^{a}	16.04 ± 9.48 ^{b}	10.06 ± 3.03 ^{a}	11.83 ± 4.92 ^{a}	30.54 ± 8.65 ^{b}	24.68 ± 7.18	23.32 ± 5.27	24.40 ± 9.87
Saturated fat (g)	2.45 ± 2.91 ^{a}	1.92 ± 1.57 ^{a}	6.00 ± 3.57 ^{b}	1.67 ± 1.31 ^{a}	2.21 ± 2.08 ^{a}	11.23 ± 3.11 ^{b}	11.86 ± 9.10	9.08 ± 8.24	9.53 ± 4.01
Carbohydrate (g)	4.95 ± 3.48 ^{b}	5.21 ± 3.32 ^{b}	2.96 ± 2.89 ^{a}	6.53 ± 2.83 ^{b}	5.86 ± 2.12 ^{b}	0.97 ± 0.94 ^{a}	6.69 ± 3.94	8.11 ± 4.44	3.87 ± 6.57
Sugars (g)	1.85 ± 1.26 ^{b}	1.73 ± 0.94 ^{b}	1.73 ± 0.94 ^{a}	1.88 ± 0.99 ^{b}	2.07 ± 1.20 ^{b}	0.52 ± 0.42 ^{a}	1.91 ± 1.55 ^{b}	1.81 ± 0.85 ^{b}	0.68 ± 0.54 ^{a}
Protein (g)	16.19 ± 9.44	16.34 ± 8.94	14.51 ± 5.43	21.94 ± 9.23	20.44 ± 10.57	21.50 ± 2.56	6.82 ± 2.87 ^{a}	6.61 ± 3.64 ^{a}	14.69 ± 3.87 ^{b}
Salt (g)	1.76 ± 0.81	1.96 ± 0.75	2.23 ± 0.98	2.17 ± 0.74 ^{a}	2.25 ± 0.60 ^{a}	3.47 ± 0.70 ^{b}	1.70 ± 0.34	1.80 ± 0.31	1.71 ± 0.78
Nutri-Score	7.50 ± 8.78 ^{a}	8.35 ± 6.12 ^{a}	19.51 ± 5.02 ^{b}	8.85 ± 5.46 ^{a}	10.45 ± 3.62 ^{a}	25.91 ± 2.98 ^{b}	14.92 ± 7.2 ^{a}	13.56 ± 7.34 ^{a}	20.50 ± 2.85 ^{b}

Nutrient Criteria	Pb Meat Salad 2019 (n = 5)	Pb Meat Salad 2021 (n = 6)	Meat Salad (n = 11)
Energy (kcal)	262.0 ± 27.1	274.2 ± 28.8	237.5 ± 77.5
Fat (g)	24.08 ± 3.71	24.92 ± 4.11	20.38 ± 9.44
Saturated fat (g)	2.28 ± 0.65	5.10 ± 6.34	6.30 ± 3.09
Carbohydrate (g)	5.78 ± 1.36	5.52 ± 0.79	3.14 ± 3.22
Sugars (g)	4.66 ± 1.10 ^{b}	4.70 ± 0.92 ^{b}	0.76 ± 0.64 ^{a}
Protein (g)	4.56 ± 3.33 ^{a}	6.22 ± 3.57 ^{ab}	10.53 ± 4.22 ^{b}
Salt (g)	1.53 ± 0.46	1.26 ± 0.41	1.74 ± 0.80
Nutri-Score	10.00 ± 3.67	10.7 ± 6.02	15.55 ± 5.89

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; ^{a,b} values within a food group with differing superscript letters are statistically significantly different ($p \leq 0.05$).

Table 6. Nutrients ("Big 7") and Nutri-Score per 100 g of pb cheese alternatives and cheese (mean and standard deviation) in five different food groups, compared to animal-based products *.

Nutrient Criteria	Pb Sliced Cheese 2019 (*n* = 17)	Pb Sliced Cheese 2021 (*n* = 43)	Sliced Cheese (*n* = 53)	Pb Cheddar 2019 (*n* = 15)	Pb Cheddar 2021 (*n* = 13)	Cheddar (*n* = 25)	Pb Cream Cheese 2019 (*n* = 13)	Pb Cream Cheese 2021 (*n* = 38)	Cream Cheese (*n* = 32)
Energy (kcal)	286.2 ± 47.2 ^{a}	283.3 ± 13.7 ^{a}	339.4 ± 56.8 ^{b}	279.5 ± 52.5 ^{a}	288.2 ± 21.5 ^{ab}	329.2 ± 72.9 ^{b}	268.5 ± 46.7	267.7 ± 38.4	256.5 ± 73.6
Fat (g)	22.14 ± 4.60 ^{a}	21.62 ± 1.76 ^{a}	26.35 ± 6.51 ^{b}	20.93 ± 4.50	21.92 ± 2.65	24.49 ± 9.13	24.72 ± 5.62	24.78 ± 3.63	22.79 ± 9.24
Saturated fat (g)	16.27 ± 4.67	18.14 ± 3.04	16.77 ± 4.24	15.32 ± 5.69	18.05 ± 3.63	15.73 ± 5.71	15.94 ± 8.73	14.97 ± 8.20	14.45 ± 5.96
Carbohydrate (g)	19.58 ± 4.88 ^{ab}	21.09 ± 2.06 ^{b}	0.78 ± 1.22 ^{a}	20.19 ± 4.86 ^{b}	20.85 ± 2.40 ^{b}	1.83 ± 2.02 ^{a}	4.45 ± 2.89	5.02 ± 3.25	3.95 ± 3.10
Sugars (g)	1.34 ± 4.50	0.30 ± 0.43	0.56 ± 1.05	1.63 ± 5.00	0.07 ± 0.12	1.44 ± 2.00	0.80 ± 0.50 ^{a}	1.18 ± 1.03 ^{a}	3.59 ± 2.62 ^{b}
Protein (g)	1.98 ± 4.09 ^{a}	0.86 ± 1.83 ^{a}	24.56 ± 3.42 ^{b}	1.59 ± 2.84 ^{a}	1.42 ± 2.95 ^{a}	24.81 ± 3.41 ^{b}	4.67 ± 3.64 ^{a}	5.72 ± 3.82 ^{a}	9.13 ± 3.33 ^{b}
Salt (g)	1.70 ± 0.50 ^{a}	2.02 ± 0.26 ^{b}	1.70 ± 0.53 ^{a}	2.06 ± 0.61	2.10 ± 0.36	2.04 ± 1.05	0.80 ± 0.38	1.08 ± 0.37	1.06 ± 0.67
Nutri-Score	19.06 ± 4.10 ^{b}	21.07 ± 1.96 ^{c}	15.17 ± 3.00 ^{a}	20.13 ± 4.27 ^{b}	20.38 ± 2.90 ^{b}	14.96 ± 3.21 ^{a}	11.62 ± 5.28 ^{ab}	14.13 ± 3.81 ^{b}	11.19 ± 3.36 ^{a}

Nutrient Criteria	Pb Feta 2019 (*n* = 8)	Pb Feta 2021 (*n* = 13)	Feta (*n* = 16)	Pb Mozzarella 2019 (*n* = 12)	Pb Mozzarella 2021 (*n* = 16)	Mozzarella (*n* = 15)
Energy (kcal)	276.4 ± 84.3	285.5 ± 91.5	243.6 ± 58.7	269.2 ± 70.4	249.0 ± 50.2	264.3 ± 43.2
Fat (g)	21.85 ± 7.66	24.65 ± 10.04	18.73 ± 7.05	21.11 ± 5.85	20.50 ± 4.13	19.24 ± 3.92
Saturated fat (g)	14.00 ± 8.71	16.65 ± 8.64	11.74 ± 4.30	14.90 ± 5.62	14.92 ± 6.30	12.13 ± 2.54
Carbohydrate (g)	12.70 ± 10.34 ^{b}	9.95 ± 5.74 ^{b}	1.75 ± 1.38 ^{a}	14.56 ± 7.09 ^{b}	13.74 ± 6.58 ^{b}	2.31 ± 2.10 ^{a}
Sugars (g)	0.75 ± 1.09	0.77 ± 1.18	1.65 ± 1.43	0.31 ± 0.65	0.63 ± 1.02	1.03 ± 0.92
Protein (g)	6.84 ± 6.96 ^{a}	5.64 ± 5.49 ^{a}	16.65 ± 2.79 ^{b}	2.87 ± 3.14 ^{a}	1.99 ± 2.30 ^{a}	20.08 ± 5.85 ^{b}
Salt (g)	1.89 ± 0.65 ^{a}	1.93 ± 0.52 ^{a}	2.50 ± 0.47 ^{b}	1.94 ± 1.12 ^{b}	1.56 ± 0.50 ^{ab}	0.96 ± 0.58 ^{a}
Nutri-Score	16.88 ± 6.20	18.69 ± 5.04	15.44 ± 3.08	18.42 ± 5.73 ^{b}	17.25 ± 6.11 ^{b}	11.47 ± 2.59 ^{a}

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; $^{a\text{–}c}$ values within a food group with differing superscript letters are statistically significantly different ($p \leq 0.05$).

Table 6 shows that for all product groups, the pb cheese alternatives had an energy content ranging from 249.0 to 288.2 kcal/100 g in a year-to-year comparison. In both years, the fat content was highest in the pb cream cheese products (24.72–24.78 g/100 g), and the SFA content was highest in the pb sliced cheese (16.27 to 18.14 g/100 g). Carbohydrate content ranged from 4.45 to 5.02 g/100 g in 2019 and from 20.19 to 21.09 g/100 g in 2021. The highest average protein values were found in pb feta in 2019 (6.84 g/100 g) and pb cream cheese in 2021 (5.72 g/100 g). The maximum salt content was calculated as 2.06 g/100 g for pb cheddar in 2019 and 2.02 g/100 g for sliced cheese in 2021. All cheese alternatives performed poorly in the calculated Nutri-Score, with cream cheese having the lowest score (11.62 to 14.13; category D (orange)); 20.13 points for pb cheddar (2019) and 21.07 points for sliced cheese (2021) would result in both being in category E (red). The Nutri-Score was significantly better than in animal products in four out of five product groups, while the protein content of the animal products was significantly higher in all product groups. As expected, the carbohydrate content was also significantly higher in pb products, except for cream cheese. The fat and SFA content did not differ significantly in the four food groups, regardless of whether the product was plant- or animal-based. Therefore, the low energy content in pb products can only be calculated significantly for sliced and cheddar cheese.

3.3. Minerals

Table 7 shows the mean percentage of the recommended daily intake according to the D-A-CH (Germany, Austria, Switzerland) reference values for the determined minerals, separated by gender and different age groups (19–25 years and ≥65 years). If no other recommendations are given for the male gender, the recommendations also apply to the female gender. The different age groups were chosen because the motivation to consume plant products may differ among age groups. The data for the animal products are based on the literature values. For the 19–25 age group (AG1+), zinc and iron in the alternative products were recalculated, a safety factor since it can be assumed that requirements for zinc of up to 50% higher and for iron of even 80% higher have to be met by a vegetarian diet rather than by a non-vegetarian diet [31]. Therefore, the daily requirement for iron, magnesium, copper, and sodium was better covered by pb products than by animal-based products. The same was true for calcium and phosphorus in the meat alternatives but not in the cheese alternatives. In the case of zinc content, the difference in product groups was noticeable. The calcium content by supplementation with calcium citrate was only increased in the product "Bedda"; with an addition of 700 mg/100 g this content is as high as in animal-based cheese products. This could be proven in the analysis. None of the other analyzed products contained any additional minerals.

3.4. Vitamins

The information on the water- and fat-soluble vitamins in Table 8 is to be read analogously to that for the minerals (Table 7). The requirement for vitamins B_1, B_3, and pantothenic acid is covered by all pb alternative products, to a lesser or equal extent than by animal-based products. In contrast, the need for vitamin B_6 is met to a higher or equal extent. Pb cheese cannot meet the requirements for vitamin B_2, folate, or biotin as well as pb meat alternatives. On the other hand, the cheese alternatives can cover up to 65.55% of the daily requirement for vitamin B_{12} and even up to 95.09% of that for vitamin C in females and 82.12% in males. According to the product declaration, only two alternative cheese products (Violife, Bedda) were supplemented with vitamin B_{12}. The enrichment of vitamin B_{12} may explain the high value found. Vitamin C was added to the products in the form of ascorbic acid to extend shelf life. For the fat-soluble vitamins E and K, pb alternative products can cover the daily requirement equally well or significantly better than the animal-based alternatives, while vitamin A, however, was only present in small amounts. The detection of vitamin D was not possible in the group of pb products.

Table 7. Coverage of the daily mineral requirements by pb alternative products compared to animal-based products*. Percentage related to the recommendations of the D-A-CH reference values, given in mg per 100 g of foods, and related to gender and age groups (19–25 Y (years) and ≥65 Y).

				Cheese (*n* = 53)		**Pb Cheese (*n* = 4)**			**Meat Burger (*n* = 26)**		**Pb Burger (*n* = 4)**			**Meat Salami (*n* = 23)**		**Pb Salami (*n* = 4)**			**Meat Sausage (*n* = 37)**		**Pb Sausage (*n* = 4)**		
				Mean (%)					Mean (%)					Mean (%)					Mean (%)				
D-A-CH reference values—female	AG1 [1]	AG1+ [2]	AG2 [3]	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2
Calcium	1000			76.17		31.93			3.18		25.14			1.49		23.35			2.07		20.71		
Copper	1.25			3.02		85.94			7.46		85.43			6.16		75.63			8.96		72.35		
Iron	15	27	10	2.08	3.13	19.53	10.85	29.29	12.98	19.46	29.13	16.18	43.70	5.65	8.48	25.82	14.35	38.73	11.99	17.98	42.28	23.49	63.42
Potassium	4000			2.31		1.41			7.87		11.11			6.05		9.81			8.03		8.13		
Magnesium	310		300	9.21	9.51	14.51		14.99	8.48	8.76	26.48		27.36	5.51	5.70	30.73		31.75	8.29	8.56	29.24		30.21
Sodium	1500			46.08		65.34			26.20		47.80			61.03		92.12			98.57		144.52		
Zinc	8	12		43.70		20.49	13.66		41.95		49.30	32.87		18.61		40.40	26.94		38.59		34.81	23.21	
Phosphorus	700			71.38		15.77			23.76		42.14			22.75		40.02			27.82		38.52		
D-A-CH reference values—male	AG1 [1]	AG1+ [2]	AG2 [3]	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2	AG1	AG2	AG1	AG1+	AG2
Iron	10	18		3.13		29.29	16.27		19.46		43.70	24.28		8.48		38.73	21.52		17.98		63.42	35.23	
Magnesium	400		350	7.13	8.15	11.24		12.85	6.57	7.51	20.52		23.45	4.27	4.88	23.82		27.22	6.42	7.34	22.66		25.90
Zinc	14	21		24.97		11.71	7.80		23.97		28.17	18.78		10.63		23.09	15.39		22.05		19.89	13.26	

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; [1] AG1 = age group 19–25 Y; [2] AG1+ = age group 19–25 Y, recommendation for vegetarian diets due to lower bioavailability [31] calculated for iron +80% and zinc +50%; [3] AG2 = age group ≥ 65 Y.

Table 8. Coverage of the daily vitamin requirements by pb alternative products compared to animal-based products*. Percentage related to the recommendations of the D-A-CH reference values, given in mg[#,##] per 100 g of foods, and related to gender and age groups (19–25 Y (years) and ≥65 Y).

			Cheese (*n* = 53)		**Pb Cheese (*n* = 4)**		**Meat Burger (*n* = 26)**		**Pb Burger (*n* = 4)**		**Meat Salami (*n* = 23)**		**Pb Salami (*n* = 4)**		**Meat Sausage (*n* = 37)**		**Pb Sausage (*n* = 4)**	
			Mean (%)				Mean (%)				Mean (%)				Mean (%)			
D-A-CH reference values—female	AG1 [1]	AG2 [2]	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2
Vitamin B_1	1		3.00		1.62		16.46		5.22		40.24		11.87		32.96		6.90	
Vitamin B_2	1.1	1	32.44	35.69	7.66	8.43	15.61	17.17	18.86	20.74	18.94	20.84	21.42	23.56	14.56	16.02	24.70	27.17
Vitamin B_3	13	11	1.73	2.05	1.35	1.60	40.24	47.56	14.88	17.59	46.10	54.48	12.07	14.27	37.50	44.32	7.96	9.40
Pantothenic acid	6		7.33		1.45		6.25		6.47		6.67		5.22		6.00		3.96	
Vitamin B_6	1.4		4.57		5.74		17.49		38.37		30.06		34.47		21.31		20.51	
Folate [#]	300		8.48		5.04		6.10		19.67		0.91		16.74		1.73		14.98	
Biotin [##]	40		4.90		4.17		10.06		41.47		3.80		57.11		3.85		39.86	
Vitamin B_{12} [##]	4		41.01		65.55		42.25		4.38		40.45		4.99		18.96		2.63	
Vitamin C	95		0.16		95.09		0.69		17.91		2.16		nr		3.83		2.21	
Vitamin A [#]	700		31.79		0.05		2.53		0.11		1.09		0.06		0.94		nr	
Vitamin D [##]	20		1.81		nr		1.43		nr		2.21		nr		1.46		nr	
Vitamin E	12	11	3.42	3.73	4.92	5.37	3.64	3.73	16.50	5.37	4.02	4.38	49.63	54.14	2.90	3.16	61.91	67.54
Vitamin K [##]	60	65	9.67	8.93	5.79	5.34	9.15	8.93	24.92	5.34	6.94	6.41	32.88	30.35	7.68	7.09	38.93	35.94
D-A-CH reference values—male	AG1 [1]	AG2 [2]	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2	AG1	AG2
Vitamin B_1	1.3	1.1	2.31	2.72	1.24	1.68	12.66	14.97	4.02	2.91	30.95	36.58	9.13	10.80	25.35	29.96	5.31	6.28
Vitamin B_2	1.4	1.3	25.49	27.45	6.02	9.62	12.26	13.21	14.82	9.45	14.88	16.03	16.83	18.12	11.44	12.32	19.40	20.90
Vitamin B_3	16	14	1.41	1.61	1.10	2.83	32.70	37.37	12.09	15.56	37.46	42.81	9.81	11.21	30.47	34.82	6.46	7.39
Vitamin B_6	1.6		4.00		5.03		15.30		33.57		26.30		30.17		18.64		17.95	
Vitamin C	110		0.13		82.12		0.60		15.47		1.87		nr		3.31		1.91	
Vitamin A [#]	850	800	26.18	27.82	0.04	0.04	2.08	2.21	0.09	0.10	0.89	0.95	0.05	0.05	0.77	0.82	nr	nr
Vitamin E	15	12	2.74	3.42	3.94	4.92	2.91	3.64	13.20	16.50	3.21	4.02	39.70	49.63	2.32	2.90	49.53	61.91
Vitamin K [##]	70	80	8.29	7.25	4.96	4.34	7.85	6.87	21.36	18.69	5.95	5.21	28.18	24.66	6.58	5.76	33.37	29.20

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; [#] µg equivalents, [##] µg; [1] AG1 = age group 19–25 Y; [2] AG2 = age group ≥ 65 Y; nr = not reported.

4. Discussion

Various studies have extensively proved that meat consumption has an impact on human and environmental health [2,32–38]. However, a conversion of Western nutrition habits, with a high portion of meat, on a global level would be possible over a longer period of time. Though the meat consumption per capita in Germany decreased overall by 750 g in 2020 compared to the previous year, especially for pork and beef, it still remains at a high level of 57.3 kg [39]. Different strategies for change are conceivable, such as smaller portions of meat from sustainable farming ("less, but better") as well as greater consumption of vegetable proteins, where alternative products are relevant. Venti and Johnston [40] presented a vegetarian food pyramid with a subheading "Beans & Protein Foods", in which they also mention meatless burgers and chicken and "nondairy" foods. In addition to soy milk and yogurt, soy cheese was also named [40]. The Giessen Vegan Food Pyramid also includes milk and yogurt alternatives, as well as "legumes and other protein sources", which include tofu, lupine, and pea protein products [41]. Although pb foods such as tofu have been available for many years, they are currently not considered explicitly in country-specific guidelines [42] or documents such as that produced by the EAT–*Lancet* Commission [2].

4.1. Market Analysis

The data from the market analysis showed that the availability of pb alternative products has increased, and consumers are presented with a new variety of products when choosing their food. Especially with the rapid increase in new pb meat and cheese alternative products available, as shown in the market analysis (Table 3), the importance of these products in consumers' daily food choices has increased. Recent studies have shown that shifting to a diet with a reduction or elimination of animal-based products to more whole-grain foods and pb foods has been one of the most important dietary strategies on a global scale for both the planet and human health [32–35,43]. A study by Kemper and White [44] showed that the pb product category's dietary implications and individual diversity have gained importance as more people adopt flexitarian, vegetarian, and vegan dietary styles. Sundar and Kardes [45] described the "health halo effect", through which consumers automatically perceive the variety of pb alternative products as healthier. The results of the present study, though, cannot confirm such theory, as the products studied here and most of the foods found in the market analysis have to be classified as ultraprocessed foods according to the NOVA classification (Group 4) of Monteiro et al. [23]. These food products contain various ingredients, particularly additives such as dyes and other colors, flavors, flavor enhancers, and emulsifiers, and are produced through a number of different industrial processes. They are usually ready to heat and eat and are enticingly packaged and intensively marketed [23]. Gehring et al. [46] found in their study that a significant avoidance of animal foods was associated with greater consumption of ultraprocessed foods. Thus, vegetarian/vegan diets are not necessarily beneficial to health, as studies have shown that consumption of ultra-processed foods can potentially negatively affect the nutrient quality and, thus, health outcomes [23,47]. The most important criteria for consumers in their purchasing and consumption decisions for meat alternatives were their sensory characteristics and the availability of the products, and only secondarily do animal welfare and environmental as well as health aspects influence consumers [48]. The number of alternative products has increased significantly from 2019 to 2021: by 57% for PBMA-hot, by 110% for PBMA-cold, and by 89% for PBCA. During this time, the products have evolved from niche products to mainstream products in German supermarkets, which often place them close to animal products. Dutch [49] and Australian [50] consumer studies investigated motivations for eating pb meat substitutes. They found that for switching to a pb sustainable diet, alternative products can be a valuable aid. Considering cultural and social factors, especially at family gatherings or other occasions where animal-based products are consumed, pb foods can provide a good alternative for consumers who prefer them [49,50]. Interestingly, consumer studies have shown that meat alternatives primarily appeal to consumers who want to replace meat in their meal, rather than consumers who identify themselves as vegetarians and vegans and are more likely to question the purpose of eating meat-like foods [50,51].

4.2. The "Big 7" of the Plant-Based Alternative Products

Considering the categorization of foods by their energy content (low: ≤150 kcal/100 g; medium: 160–240 kcal/100 g; high: ≥250 kcal/100 g [52]), only the product group "fillet" had a low energy content in 2021. In the PBMA-hot category (Table 4), all other product groups had a medium energy content (160–240 kcal/100 g). A high energy content (≥250 kcal/100 g) was observed in two of the four PBMA-cold product groups (Table 5). For the PBCA category (Table 6), all products had a high energy content. However, compared to the animal-based products, in the three categories (PBMA-hot, PBMA-cold, PBCA), the energy content of the alternative products was significantly lower in burger, bratwurst, sausage, salami, sliced cheese, and cheddar. Since the global obesity epidemic is linked to excessive daily energy intake [53], low energy density foods should also be consumed to prevent secondary diseases such as cardiovascular diseases (CVDs) or cancer [36,54].

The total fat and SFA content in the meat alternatives was not substantial or significantly lower than in the animal products. It was noticeable that the amount of fat can vary considerably within all product categories. A high proportion of ultra-processed foods with a high energy density can also be associated with excessive fat intake in the long term [23]. In both years, the market analysis for pb cheese in Figure 3 shows that the main fat source for all products was coconut oil: 76.7% in 2019 and 71.5% in 2021. The high content of SFA in coconut oil may have implications for elevated blood concentrations of total and LDL cholesterol. Associations between coconut oil consumption and the risk of CVDs are controversially discussed in studies [55,56].

The present study shows that the main protein sources in meat alternatives are soy, wheat, and pea (Figures 1 and 2). The quality of dietary proteins can be determined by the protein digestibility corrected amino acid score (PDCAAS). The PDCAAS for milk and whey protein concentrate, soy protein isolate, and egg were rated at the highest possible score of 1.0, whereas pea protein concentrate was rated at 0.89. Wheat and wheat gluten had the lowest scores with 0.51 and 0.25, respectively. In comparison, red meat was rated at 0.92 [57,58]. Proteins of plant origin are often deficient in one or more essential amino acids. They are less digestible in their natural form than animal proteins due to antinutritional compounds, such as phytic acid [59]. Nevertheless, dietary intake of plant protein may be more positively evaluated than that of animal protein due to its potential health benefits. The studies by Shang et al. [37] and Song et al. [38] showed that a higher intake of plant protein tends to be associated with a low risk of type 2 diabetes and of all-cause and cardiovascular mortality. Accordingly, the protein quality of pea-, soy-, milk-, and/or eggbased meat alternatives was comparable to that of beef in terms of essential amino acids, but wheat- or gluten-based products had a lower protein quality than comparable meat products. In addition, many products contain combinations of multiple protein sources, and thus protein quality can be improved. The protein content of each meat alternative product, as well as of each category, sometimes differs significantly. For example, two PBMA-hot categories (bratwurst, sausage) had a considerably higher protein content than the respective animal category. On the other hand, the protein content in all five cheese groups was substantially lower than in the animal-based products (see Table 6), so that pb cheese products currently do not offer an adequate protein alternative.

The results of the market analysis showed that the salt content in pb meat alternatives was significantly higher than in the respective meat product. Recommendations for salt reduction explicitly for meat alternatives were presented by Public Health England in 2020 [60]. Three subgroups were classified from that study [60] and recommendations for the salt content were made based on 100 g of product as follows: "plain meat alternatives" (e.g., fillets, mince) with a low salt content of 0.63 g/100 g, "meat-free products" (sausage, burger) with a medium salt content of 1.19 g/100 g, and "meat-free bacon" (cold cuts) with a high salt content of 1.78 g/100 g. Comparison of the product categories showed that all PBMA-hot products were above the maximum recommended value. In the PBMAcold category, there were three products in 2019 and one in 2021 that did not exceed the value of 1.78 g/100 g (Table 5). The mineral analysis (Table 7) found significantly higher sodium levels in all the pb products analyzed here, compared to the data from the food databases [24–27] for the animal-based products. Especially in the products pb salami and pb sausage, the recommended daily intake was covered or even exceeded with 100 g of food. However, it should be noted that the consumer adds salt or sodium-containing seasonings to the less processed animal-based product (e.g., fillet, steak, minced meat) but not to the pb convenience product. Because of such additions, similar high sodium levels could be achieved as in the vegetable alternatives in this study. These results indicate the need for industry guidelines.

4.3. Nutri-Score

On calculating the Nutri-Score for alternative and animal-based products, significant differences were found. In PBMA-hot (Table 4) and PBMA-cold (Table 5), significantly higher scores were calculated for the meat products in nine of the twelve product groups, mainly due to the high proportion of SFA and salt. The results for cheese alternatives were the opposite; in four out of five product groups (Table 6), the pb alternatives had a higher Nutri-Score than the animal products. This can be explained by the very low protein content of pb products. That the Nutri-Score can be an effective tool to inform consumers and make healthier purchasing decisions has been shown in recent studies [15,16]. Therefore, manufacturers should increasingly declare this FOPL on their products. The Nutri-Score is colored like a traffic light and makes it easy for consumers to understand which product is the "healthier" one. However, it is not able to reflect the degree to which the products are processed. As shown by Romero Ferreiro et al. [61], there were ultra-processed foods in each Nutri-Score category (A–E), oriented according to the NOVA classification. According to their results, in category B, more than half (51.5%) of the products were highly processed foods. The prospective French cohort study, NutriNet-Santé, was able to show that ultraprocessed foods have negative effects on various diseases, such as associations with a higher risk of CVD [62] and depressive symptoms [63], and Schnabel et al. [47,64] observed effects with gastrointestinal disease and an overall higher risk of mortality. Given the negative impact that consumption of ultra-processed foods has on various aspects of health, FOPL with the Nutri-Score should be followed with at least additional labeling indicating the degree of processing, such as the NOVA classification. In this way, it becomes clear that each pb alternative product has individually different product characteristics and these different aspects have to be evaluated in order to classify a food as "healthy".

4.4. Micronutrients of the Plant-Based Alternative Products

The enrichment of pb foods with micronutrients is also becoming increasingly important. The more products are offered and the greater their acceptance among consumers, the more important it becomes to have a uniform European regulation to achieve nutritional equivalence compared to animal-based products in order to avoid possible deficits in calcium, iron, zinc, and vitamin B_{12} in certain population groups [65]. The mineral and vitamin analyses in Tables 7 and 8 show that most of the pb cheese and meat alternatives meet the daily nutritional recommendations for single micronutrients.

Iron in plant foods has generally a lower bioavailability than iron in meat, because some of the iron in meat is bound to hemoglobin (heme iron), which is a more bioavailable form of iron than non-heme iron [31,66]. In the present study, the iron content of the plant alternatives was higher than the reference data from the literature [24–27] for animal products. Even after calculating a safety factor of +80%, the results are the same or higher. The same results can be seen in Table 7 for the male gender and the age groups (AG1, AG1+). As the D-A-CH reference values for iron in older women (≥65 years) are lowered, the daily recommendations can be reached faster (AG2). Thus, the products selected here may provide a good alternative.

In contrast, except for the salami alternatives, the zinc content of the products was significantly lower than the average literature references for animal-based products from the databases [24–27] and, thus, did not represent an adequate zinc alternative, especially when the safety factor was taken into account. In addition, antinutritional substances such as phytic acid may reduce zinc absorption in pb alternatives [67,68].

In an omnivorous diet, milk and dairy products, especially hard cheese, are an essential source of calcium [68]. The results of the present study showed that on average 100 g of sliced cheese covers 76% of the requirement, whereas the vegetable alternatives provide only 32% (Table 7). Such a high content can only be achieved if the manufacturer fortifies the product with calcium. On the other hand, meat alternatives also appear to be a source of calcium, as they can cover the requirement much better than meat-based products. Other important sources of calcium are green leafy vegetables and calcium-rich mineral water [68].

Vitamin B_{12} was found exclusively in animal products. Vegetarians who consume milk, cheese, and eggs can get a sufficient supply. Vegans rely on enriched foods or supplements such as toothpaste containing vitamin B_{12} to meet their needs [69,70]. However, only conventional foods can be supplemented with vitamins because it is not legally permitted for organic products in Europe [22]. Therefore, it would be beneficial if pb alternative products contained this nutrient. In the present study, only the cheese alternatives were able to meet the recommended daily intake to the same extent as the animal-based products, as the meat alternatives contain only very low levels of B_{12}. The reason for this was the producer adding vitamin B_{12} to the PBCA.

To our knowledge, the present study was the first to focus solely on pb products available in online stores and to compare them with animal-based products and calculate the Nutri-Score for these products. However, due to the large number and variety of "modern" pb alternative products on the market, the results obtained in this study cannot be generalized in principle. Nevertheless, the selection of products from online stores represents a broad part of the market for meat and cheese alternatives, so that information and recommendations can be derived from it.

5. Conclusions

The trend towards pb alternative products is rising, especially in the Western world. These alternative products mainly provide high-quality vegetable protein. The present study showed that the content of fat, SFA, and salt in the pb products varied considerably. These nutrients are related to the most important dietary factor in the global burden of disease. The results of the micronutrient assessment show that the relationship to the reference values for the recommended daily intake is meaningful. In this way, deficiencies and surpluses of vitamins and minerals can be made clear. Due to the high degree of processing of the foods studied here, they can nevertheless not be recommended for the daily diet, even if they have a low Nutri-Score. However, consumers should also pay attention to the nutrition labeling of the individual alternative products, as these do not automatically represent a healthier alternative to an animal-based product. Therefore, intervention studies would be of particular interest to clarify whether substituting animalbased foods with pb alternatives has an impact on health. Furthermore, consumers need guidance on how to compose a balanced pb diet.

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Chapter 3

A comparative analysis of plant-based milk alternatives
Part 1: Composition, sensory, and nutritional value

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A Comparative Analysis of Plant-Based Milk Alternatives Part 1: Composition, Sensory, and Nutritional Value

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Abstract: Consumers are becoming increasingly interested in reducing the consumption of animal-based foods for health, sustainability, and ethical reasons. The food industry is developing products from plant-based ingredients that mimic animal-based foods' nutritional and sensory characteristics. In this study, the focus is on plant-based milk alternatives (PBMAs). A potential problem with plant-based diets is the deficiency of important micronutrients, such as vitamin B_{12}, B_2, and calcium. Therefore, an analysis of micronutrients in PBMAs was conducted to assess their nutritional value. The second main focus was on the sensory description of the PBMAs, done by a trained panel, and instrumental assessment to characterize the sensory attributes. Almond drinks met the daily micronutrient requirements the least, while soy drinks came closest to cow's milk in macro- and micronutrients. The experimentally determined electronic tongue and volatile compound results confirmed the sensory panel's evaluations and could therefore be used as a method for easy and effective assessments of PBMAs. The PBMAs evaluated in this study could not completely replace cow's milk's nutritional and sensory properties. They are products in their own product group and must be evaluated accordingly. Given the variety of products, consumers should experiment and make their decisions regarding the substitution of cow's milk

Keywords: almond drinks; micronutrients; milk substitutes; non-dairy beverages; oat drinks; sensory evaluation; soy drinks

1. Introduction

Worldwide dietary recommendations published on homepages and in reports and guidelines are based on established scientific evidence recommending a predominantly plant-based diet [1–5]. For the most part, it consists primarily of vegetables and fruits, complemented with whole grain products, adequate protein from plant and animal sources, and vegetable fats. Meat and meat products, as well as foods that are high in sugar, salt, and saturated fats, should be consumed only in moderate amounts. The increasing demand for a Western-style diet is exerting pressure on the global food supply. The high consumption of animal products, especially beef and milk, is one of the main reasons contributing to the negative impact of the modern diet on global and individual health [6,7]. Therefore, there is great interest in shifting to a more plant-based diet when it comes to, for example, environmentally friendly or balanced nutrition to support public health at all levels of society–personal, community, national, regional, global, and planetary health. Indeed, our food system in its current form contributes significantly to the climate crisis, resource depletion, and loss of intact ecosystems, especially through intensive livestock farming [8–10]. There is significant interest in the development of plant-based milk alternatives (PBMAs) to cow's milk. Consumers are looking for specific functions in these beverages that are part of their lifestyle and meet different needs. One of these important functional requirements for PBMAs is primarily to address health aspects such as the problems of cow's milk allergy, lactose intolerance, high caloric intake, and prevalence of hypercholesterolemia [11]. Concerning lactose, it should be noted that approximately 75% of the world's adult population cannot digest this carbohydrate or can only partially digest it [12]. Ethnic origin influences the frequency of lactose intolerance. In Europe, people in Great Britain, The Netherlands, and Scandinavia have a low level of intolerance (1–15%), while people in Asian countries, such as China, Thailand, and Southeast Asia, have very high intolerance (95–98%) [12].

The consumption of PBMAs has increased in Europe from 2018 to 2020 [13] because they contain no lactose and no milk protein, are cholesterol-free, contain no trans-fatty acids, and are low in calories, making them suitable not only for special populations but appealing to a broader population. In addition to the health aspect, a recent study [14] conducted in an online survey of young adults from Germany shows that awareness of a climate-conscious diet is growing. The same authors concluded that the trend of vegetarian, vegan, and flexitarian diets is increasing, and plant-based alternative products are popular among the respondents, especially PBMAs are well-perceived. Another online survey of young adults grouped as "Future-Oriented Climate Protectors" is noticeably open to plant-based alternatives [15]. For example, they appreciate that many more alternative products are available and would like to see an even wider range in supermarkets. Another current study by Turnwald et al. [16] analyzed data from social media personalities with high followings who post nutrition messages and found that posts with "healthier" foods were associated with fewer "likes" and comments, suggesting lower user approval. The authors of this study suggest that the representation of the consumption of "unhealthy" foods and beverages in social media can lead to a sociocultural problem, especially in the dietary habits of children and adolescents. Considering data on PBMAs from an economic point of view, based on global and European surveys, these show that these products have gained acceptance in the market and among consumers. The global market development for PBMAs is anticipated to grow at a compound annual growth rate (CAGR), a percentage indicating how much the value under consideration is increasing on average per year, of 12.5% from 2021 to 2028, and is expected to reach a value of US $20.5 billion [17]. According to a study by the Smart Protein Project [13], the market for PBMAs in Europe is growing both in sales value in euros and sales volume in liters. For example, data for Austria show that PBMAs had the highest-value sales (€37 million) and the highest volume sales (19 million liters) compared to those of other plant-based products. The segment of plant-based beverages is dominated by oats, almonds, and soy, which are currently the main raw materials and are dominant but may vary slightly in their ranking depending on the country [16].

The general classification of PBMAs according to the raw materials (legumes, nuts, cereals, pseudocereals, oilseeds) into five categories is currently applied in the literature [11,18–21]. PBMAs are liquids extracted by crushing plant material in water and designed by homogenization to be quite similar to cow's milk in appearance, mouthfeel, taste, and shelf life so that they can be used for similar applications [11,18,19]. Since the sensory properties play a crucial role in the consumption of plant-based beverages, undesirable off-flavors should be reduced. Off-flavors often described include a beany taste in soy-based products, a high degree of bitterness, and impaired textural quality, for example, due to a high starch content [11,22]. Furthermore, off-flavors can be caused by volatile compounds formed during the oxidation of lipids, such as hexanal, hexanol, and pentanal [22,23].

According to the NOVA classification (which is not an acronym), a categorization of foods and beverages based on degrees of processing, PBMAs are classified in NOVA group 3 (processed foods) or 4 (ultra-processed foods, UPFs), whereas fresh and pasteurized cow's milk belongs to natural and minimally processed foods (group 1) [24,25]. UPFs are classified as follows: synthetic ingredients are added to the usual high-tech, industrial processes such as additives, flavorings, as well as vitamins and minerals. Although the term "milk" for plant-based alternatives is controversial in many countries, as in Europe, the term for cow's milk is protected by legislation [26]. PBMAs are often marketed in German food retailing by naming the raw material base and adding "drink." In the United States, the Food and Drug Administration recently investigated whether beverage manufacturers of PBMAs may use the term "milk", and guidance on labeling is expected in 2022 [27].

In this study, PBMAs were analyzed, and their composition was discussed from a nutritional and sensory perspective. The main objective was to investigate the micronutrients of conventional PBMAs from different raw material sources in order to compare their nutritional values with that of cow's milk and assess whether there are health benefits. In addition, a complete overview of the macronutrients ("Big 7") was given to gain a better overview of the PBMAs related to their feedstock and to be able to benchmark these products against cow's milk. For the comprehensive sensory evaluation of PBMAs, qualitative descriptive panel work and instrumental sensory data were used in this paper.

2. Materials and Methods

2.1 Plant-based Milk Alternative Samples and Data from Databases

Fifteen commercially available PBMAs were selected for the study, five of each of the three raw materials: almond, oat, and soy (Table 1). They were purchased in local grocery stores and online. For each product, samples with the same best before dates were used both in the sensory tastings and the analytical procedures to ensure the product itself was of the same batch. For the sensory evaluation and the analysis of volatile compounds and vitamins, fresh samples were used. For the assessments with the electronic tongue (e-tongue) and mineral analysis, freeze-dried material (freeze-dryer, EPSILON 2-40, Christ, Osterode am Harz, Germany) was used, which had previously been ground with a coffee grinder (KSW 3307, Clatronic International, Kempen, Germany) and stored at +4 °C until analysis. For comparison between the analyzed data and existing literature values of PBMAs and cow's milk, data were collected from the following four national nutrition databases: Food Standards Australia New Zealand, AUSNUT [28]; Fineli, the Nutrition Unit of the National Institute for Health and Welfare in Finland [29]; the US Department of Agriculture (USDA) FoodData Central Data, Food and Nutrient Database for Dietary Studies 2017–2018 [30]; and the Max Rubner-Institut, Federal Research Institute of Nutrition and Food, Bundeslebensmittelschlüssel (BLS) Version 3.02 [31].

2.2 Nutri-Score

The nutritional evaluation of PBMAs was performed according to the front-of-pack labeling rating system accepted and voluntarily applied in Germany since 2020 [32]. The Nutri-Score classifies foods into five categories according to nutritional quality (from category A, indicating higher nutritional quality, to category E, indicating low nutritional quality). These categories are additionally highlighted with a five-color traffic light labeling (from A being green to E being red). According to the current version of the Santé Publique France brand statutes, plant-based alternative beverages are treated as cow's milk, thus, the calculation of the Nutri-Score score is not according to beverages but is based on the calculation for solid products [33]. Nutrients were evaluated using the Nutri-Score system on a scale from −15 points (A) to +40 points (E) by the nutrient content per 100 g. Positive points (0–10) are determined for energy, total sugars, saturated fatty acids, and sodium, and negative points (0–5) are granted for fruits, vegetables, legumes, nuts and rapeseed, walnut and olive oils, dietary fiber, and proteins [33].

Table 1. Mean values of nutritional composition in g/100g, energy in kcal/100g, and Nutri-Score of tested plant-based milk alternatives and data from food databases[#].

Abbreviation[$]	Supplements	Raw material (%)		Energy	Fat	SFA	Carbohydrate	Sugar	Fiber	Protein	Salt	Nutri-Score
JA	Z	2.0	Almond	14	1.2	0.1	0.1	0.0	0.4	0.4	0.12	B
AA	W,X,Y,Z	2.3	Almond	13	1.1	0.1	0.0	0.0	0.3	0.4	0.14	B
ALA*		7.0	Almond	36	3.3	0.3	0.5	0.5	0.7	1.1	0.14	B
RA*		3.5	Almond	22	2	0.2	0.0	0.0	0.4[##]	0.9	0.12	B
ABA**	Z	2.5	Almond	24	1.2	0.1	2.6	2.5	0.3	0.5	0.08	B
OO	W,X,Y^1,Z	10.0	Oat	46	1.5	0.2	6.7	4.1	0.8	1.0	0.10	B
AO	W,X,Y,Z	9.8	Oat	44	1.5	0.1	6.8	3.3	1.4	0.3	0.09	A
KO*		11.3	Oat	44	1.1	0.2	7.6	4.5	0.6	0.7	0.10	B
BO*		11.0	Oat	46	1.4	0.2	7.6	5.2	0.9[##]	0.7	0.13	B
ABO**		12.0	Oat	47	1.3	0.5	8.1	3.9	0.8	0.3	0.09	B
JS	X,Y,Z	7.1	Soy	38	1.7	0.2	2.5	2.4	0.5	3.0	0.09	A
AS	W,X,Y,Z	5.6	Soy	28	1.2	0.2	1.7	1.5	0.9	2.1	0.11	A
ES*		9.4	Soy	53	2.6	0.4	2.9	2.7	0.7[##]	4.1	0.15	A
BS*		11.0	Soy	28	1.5	0.3	0.9	0.7	0.7[##]	2.6	0.08	A
ABS**	W,X,Y,Z	8.7	Soy	42	1.9	0.3	2.7	2.5	0.6	3.3	0.10	A
Almond drink, Database (mean, *n* = 6)				24.0	1.39	0.07	2.26	1.89	0.27	0.57	0.15	B
Oat drink, Database (mean, *n* = 11)				51.7	1.39	0.17	7.86	2.83	1.27	1.24	0.09	A
Soy drink, Database (mean, *n* = 38)				44.0	1.69	0.28	3.62	2.02	0.83	3.15	0.10	A
Cow´s milk, Database (mean, *n* = 55)				53.1	2.14	1.41	5.06	4.99	0.0	3.37	0.11	B

Note: nutritional properties defined on the packaging of the products; [$] description of the abbreviations: the first letter stands for the product name, last letter stands for the raw material A = almond, O = oat, S = soy, with three letters the letter B stands for barista-style; [#] calculated mean values from AUSNUT, Fineli, USDA, BLS databases; [##]Nutri-Score calculated, for missing values calculation means; * organic; **barista-style; SFA = saturated fatty acids; W = 0.21 mg vitamin B_2, X = 0.38 µg vitamin B_{12}, Y = 0.75 µg vitamin D, Y^1 = 1.1 µg vitamin D, Z = 120 mg calcium.

2.3 Micronutrient Analysis—Vitamins and Minerals

Finely ground, freeze-dried material was used for mineral analyses and stored at +4 °C until analysis. Mineral concentrations were determined using an adapted method of Koch et al. [34]. Approximately 100 mg of each sample was digested in 4 mL of 65% (*v*/*v*) nitric acid and 2 mL of 30% (*v*/*v*) hydrogen peroxide for 75 min at 200 °C and 40 bar in a microwave oven (Ethos 660; MWT AG, Heerbrugg, Switzerland). The samples were then made up to 25 mL with distilled water. Mineral concentrations were measured by inductively coupled plasma optical emission spectrometry (Vista-PRO CCD Simultaneous ICP-OES; Varian Inc., Palo Alto, CA, USA). For the vitamin analyses, refrigerated 250 mL of fresh sample material was sent to the bilacon food laboratory (bilacon GmbH, Berlin, Germany, Department of Instrumental Analysis). The lab services performed the analytics according to standardized and accredited procedures of the multimethod to determine water- and fat-soluble vitamins in food by LC-MS/MS (Method: PV-SA-158 and 159, 2019-02).

2.4 Sensory Evaluation

All training and evaluation sessions took place in the sensory lab of the Georg-August-University Goettingen, Germany, which complies with the international standard ISO 8589 [35]. Due to the COVID-19 pandemic (SARS-CoV-2) in 2020, a special hygiene concept had been developed, and the number of panelists had to be reduced to 8 (6 female/2 male). The panel met twice a week for a maximum of 120 min, and during the sessions, each panelist sat isolated in individual booths in daylight conditions. According to ISO 8586 guidelines [36], the panelists were selected and declared their agreement before participation. Training under DIN 10969 standards [37] took place to obtain significant data because descriptive analysis was used for the qualitative description of the samples and the quantification of the intensities and the degree of the sensory perceptions [38]. According to Lawless and Heymann [39], descriptive sensory analyses were subject to three main steps, which were also relevant for this work: the determination of sensory attributes, the training of panelists, and the sample characterization. The panel leader was the moderator for the panel to structure and guide the sessions. The first step was to find attributes, which were developed to describe the plant-based alternative products in appearance (_A), odor (_O), taste (_T), and texture (_TX). In total, 23 attributes were defined for all PBMAs (Table 2). The same evaluation form was used for all sensory sessions to ensure comparability of the results. The panel leader screened vocabulary for the attributes found through research to save time during training. The assessors generated the final list of descriptors through consensus. During the training, samples from other food and the sample set were served to demonstrate the common vocabulary and the meaning of each food product attribute [40]. The panelists decided on the references, the definitions, and the order of rating in consensus. In the training sessions, the assessors learned to assign each sample to the attribute and rate it on an unstructured scale with the endpoints 0% (not perceptible) to 100% (strongly perceptible) in relation to the reference. The training focused on the differentiation between samples, the consensus among panelists regarding samples, and the ability to repeat the products' evaluation. Sample preparation for the sensory evaluation of PBMAs was performed as follows: The samples were stored at 7 °C and brought to room temperature one hour before the start of the tasting, which was 20 ± 2 °C, before being presented to the panelists. The PBMAs were shaken vigorously by hand in their packaging to ensure that a homogeneous liquid was obtained. The odorless and transparent sample cups were always filled with 20 mL of the product and labeled with a three-digit random code. For data collection, the sample set was rated duplicated by each panelist in a randomized order and blinded by three-digit codes. After evaluating each sample, the panelists were invited to neutralize their sense of taste with water and white bread as well as coffee beans to neutralize their sense of smell, and then waited 2 min before beginning to evaluate the next sample. Data recording and analysis were performed with the software EyeQuestion® (Version 4.11.57, EyeQuestion®, Elst, The Netherlands).

Table 2. Sensory attributes, scales, reference products and definitions, and the assessment of the attributes used to evaluate plant-based milk alternatives.

Attribute	Abbreviation	Scale (from-to)	Reference / Definition[1]	Assessment
		Appearance		
Consistency	Con_A	Liquid-Viscous	Water = 0, Whipping cream = 80	Standard daylight in the booths
Intensity	Int_A	White-Brownish	Sample hue	
		Odor		
Overall	Over_O	Not perceivable-Strongly perceivable	All perceptible odor	Sample odor, holding it 2 cm under the nose, and sniffing three times
Cereal	Cer_O		Damp mixture of oats, wheat, rye, barley, spelt (Kölln Multikorn-Flocken)	
Nutty	Nut_O		Shredded nut mixture of cashew, walnut, hazelnut, almond (Seeberger)	
Cardboard	Card_O		Soaking square of cardboard in water for 30 min	
Milk	Milk_O		Fresh cow's milk, fat content 3.5%	
Cooking	Cook_O		Whole milk heated to steaming and cook 10 min	
Vanilla	Van_O		Pure vanilla extract diluted with water in a ratio of 1:8	
		Taste		
Overall	Over_T	Not perceivable-Strongly perceivable	All perceptible taste	Taste intensity after the first swallow
Bitter	Bit_T		Caffeine solution: 0.17 g/l (medium perceivable)	
Salty	Sal_T		Sodium chloride solution: 0.98 g/l (medium perceivable)	
Sour	Sou_T		Citric acid solution: 0.31 g/l (strongly perceivable)	
Sweet	Swe_T		Sucrose solution: 4.32 g/l (weakly perceivable)	
Cereal	Cer_T		Damp mixture of oats, wheat, rye, barley, spelt (Kölln Multikorn-Flocken)	
Nutty	Nut_T		Shredded nut mixture of cashew, walnut, hazelnut, almond (Seeberger)	
Milk	Milk_T		Fresh cow's milk, fat content 3.5%	
Cooking	Cook_T		Whole milk heated to steaming and cook 10 min	
Vanilla	Van_T		Pure vanilla extract diluted with water in a ratio of 1:8	
Aftertaste	After_T		Intensity overall	Intensity of aftertaste in total, 5 seconds after swallowing
		Texture		
Astringent	Ast_TX	Not perceivable-Strongly perceivable	Chemical sensitivity factor on the tongue / oral cavity described as dry or astringent 0.1% Alum solution	

Viscosity	Vis_TX	Liquid-Viscous	Viscid appearance is perceived when flowing as the product moves over the tongue and palate. Water = 0, Whipping cream = 100	Texture intensity after the second swallow
Chalky	Chal_TX	Not perceivable-Strongly perceivable	Mealy, powdery sensory impression Calcium carbonate tablets ground into powder and blended with water at a ratio of 1:10	

[1] The definition was suggested and accepted by the panelists; abbreviations: _A = appearance, _O = odor, _T = taste, _TX = texture.

2.5 Electronic Tongue

This study used an electronic tongue (e-tongue) α-ASTREE Liquid Taste Analyzer (Alpha M.O.S., Toulouse, France) with an autosampler with 16 sample positions. The e-tongue consists of an array of seven different liquid sensors mounted around an Ag/AgCl reference electrode [38]. A sensor set consisting of seven sensors was used, which was developed to analyze food (coded: AHS, PKS, CTS, NMS, CPS, ANS, SCS). According to the manufacturer, three tests ("conditioning," "calibration," and "diagnostic") must be passed in order to acknowledge that all sensors are working properly. Before the analysis, these three tests were performed on each new food product. The "conditioning" and "calibration" steps were performed using an aqueous solution of 0.01 mol/L hydrochloric acid. For the last step, "diagnostic," sodium-L-glutamate (0.01 mol/L), sodium chloride (0.01 mol/L), and hydrochloric acid (0.01 mol/L) solutions of ultrapure water were prepared. For the measurements, the sensors ran into the sample solution for 120 s, and the last 20 s of the analysis were used for statistical evaluation. After each measure, the sensors were cleaned in a beaker with ultrapure water for 10 s [41,42]. This collection method was looped 12 times for each sample, with the first two measurement results being omitted during the evaluation process. All PBMA sample solutions were prepared from freeze-dried material with ultrapure water (1% w/v), filled in centrifuge tubes, heated in a water bath to 95 °C for 10 min, and centrifuged at 9000 rpm for 10 min at 20 °C (Heraeus Megafuge 16R Centrifuge, Thermo Fisher Scientific, Waltham, United States). The clear liquid was collected and filtered (615 ¼ filter, Macherey-Nagel, Düren, Germany) before being analyzed.

2.6 Volatile Compounds

The beverages were shaken in their original packaging and then poured into 50 mL centrifuge tubes and stored at −20 °C until the analyses. The samples were defrosted overnight at 5 °C for analysis. Subsequently, 2 mL were pipetted into a 20 mL glass vial already filled with 4 g of NaCl for saturation, closed with a polytetrafluoroethylene (PTFE)-coated silicone rubber septum. The volatiles were extracted by headspace solid-phase-micro-extraction (HS-SPME) with a 100 mm polydimethylsiloxane (PDMS) fiber (PAL System, CTC Analytics, Zwingen, Switzerland). Before sampling, the incubation time was 30 min at 60 °C, with an agitator speed of 500 rpm. The sample extraction time was 40 min at the same temperature and in shaking mode. Thermal desorption in the injector was performed for 3 min at 250 °C (splitless mode), followed by 9 min in split mode (split ratio 1:10). Each sample was analyzed in duplicate. The GC-2010 Plus (Shimadzu Deutschland GmbH, Duisburg, Germany) was used for the separation and identification of the analytes. Helium was used as a carrier gas at a 1 mL/min flow rate. The column temperature program was as follows: 40 °C initial temperature held for 5 min, raised to 100 °C at a rate of 10 °C/min in the same shaking mode, further raised to 220 °C at a rate of 5 °C/min held for 5 min and finally raised to 250 °C at a rate of 15 °C/min. The total analysis time was 44 min. Analyte desorption took place in the GC injection port at 250 °C for 3 min in splitless mode, and the fiber was kept in the injection port for 5 min more for cleaning. The mass analyzer was set on scan mode, and the recorded ions were m/z: 35 to m/z: 350. MS source and MS Quad were operated at 250 and 130 °C, respectively. There were 366 compounds identified with the National Institute of Standards and Technology 14 library (NIST, MD, United States). The evaluation of the results was performed through databases PubChem [43]; Food Flavourings Version 3.3, an informational tool on the flavoring substances approved for use in food in the EU [44]; and the database of food compounds, the FooDB, Version 1.0 [45], which is the largest public repository of food compounds and contains a large set of ca. 26,000 molecules.

2.7 Statistical Analyses

The data from the study were statistically analyzed using SPSS® statistical software (IBM SPSS Statistics, Version 26.0, Armonk, NY, USA) and Microsoft Excel® (Microsoft Office Professional Plus, 2013). The results of the instrumental sensory and human sensory evaluations were analyzed using one-way and two-way analysis of variance (ANOVA), followed by Tukey's post hoc test ($p < 0.05$). Correlation analysis was conducted to determine the relationships among the attributes (Pearson correlations). Principal component analysis (PCA) was performed for the sensory evaluation and volatile compound analysis using Statistica version 13.3 (TIBCO Software Inc., Chicago, IL, USA). PCA was used to identify redundant terms and determine which terms best described each sample. The PCA biplots provided a visual representation of which terms were related and described the samples. Only GC-MS data were incorporated for which databases could substantiate odor-active key compounds ($n = 43$).

3. Results

3.1. Macronutrients (Big 7) and Nutri-Score

The list of nutritional labels, the so-called "Big 7," which the manufacturer must indicate on the product, was used to compare the products with regard to their macronutrients. In the case of missing information, such as dietary fiber, which is not part of the mandatory information but is important for the calculation of the Nutri-Score, the mean value was generated from the available product data, denoted by ## in Table 1.

The comparison of the energy content of the different PBMAs showed that almond drinks had on average the lowest energy content, with an average of 21.8 kcal/100 g compared to 24.0 kcal/100 g given in the database. Soy and oat drinks followed, while cow's milk had the highest with 53.1 kcal/100 g (Table 1). Total fat and SFA contents were lower in PBMAs than in cow's milk. Both carbohydrate and sugar content in cow's milk was about 5.0 g/100 g. For PBMAs, the oat drinks showed the highest proportion of both macronutrients with 7.36 g/100 g and 4.2 g/100 g, and 7.86 g/100 g and 2.83 g/100 g, respectively, among the products in the databases. In particular, the almond drinks had the lowest carbohydrate and sugar contents with 0.64 g/100 g and 0.6 g/100 g, respectively. Here, a wide variety of products is shown, for example, four almond drinks had a low content of carbohydrates and sugars, but in one product (ABA), the content was quite high. The highest levels of dietary fiber could be found in oat drinks. The average protein content of the soy drinks was 3.02 g/100 g, and 3.15 g/100 g among the products in the databases, which was close to that of cow's milk at 3.37 g/100 g. The other PBMAs, especially the almond drink, had on average significantly lower protein contents (Table 1).

The calculation of the nutritional properties of the PBMAs demonstrated that the soy-based beverages had the best Nutri-Score with a score A (Table 1). Four of the five oat drinks had score B, one had score A. The oat products from the database received an average of score A, though. The highest Nutri-Score was observed in almond drinks (score B). The data from the database for cow's milk also gave a score B.

3.2 Vitamins and Minerals Evaluations

Table 3 shows the mean percentage of the recommended daily intake according to the D-A-CH (Germany, Austria, Switzerland) reference values for the determined water- and fat-soluble vitamins as well as the minerals, separated by gender and different age groups (19–25 years and ≥65 years). If no other recommendations were given for the male gender, the recommendations for the female gender should apply. The different age groups were chosen, because the motivation to consume PBMAs may vary by age group. Database values for PBMAs and cow's milk were based on information from the databases referenced.

PBMAs could meet the daily requirements for fat-soluble vitamins D and E equally well or significantly better than cow's milk, regardless of age group or gender (Table 3). For water-soluble vitamins, almond drinks were generally lower than oat and soy drinks. The database values were higher than the values determined for the soy drinks. Cow's milk better covered the need for vitamins B_2, B_3, and B_6. Here, the values obtained by PBMAs were lower than those in the PBMAs database, although the soy beverages scored the highest values compared to those of the other two plant-based alternatives. The analyzed products covered the vitamin B_{12} requirement better than those in the database. The exception was the almond drinks, which showed lower contents.

Compared to cow's milk, the mineral requirement was similarly well-covered by soy drinks. The higher copper (Cu) levels were analyzed in the oat and soy drinks. In addition, the iron (Fe) content in the database values of the PBMAs was higher than that of cow's milk. The database values for the calcium (Ca) requirement of the PBMAs were also higher than the analyzed values, except for the soy drinks (Table 3).

Table 3. Coverage of the daily vitamin and mineral requirements by PBMA drinks compared to database values*. Percentage based on D-A-CH reference value recommendations, per 100 g of food, and related to gender and age (19–25 years and ≥65 years).

			Almond * *n* = 6 [%]	**Almond** *n* = 5 [%]	**Oat *** *n* = 11 [%]	**Oat** *n* = 5 [%]	**Soy *** *n* = 38 [%]	**Soy** *n* = 5 [%]	**Cow's milk *** *n* = 55 [%]
				D-A-CH reference values female, 19–25 years					
Vitamin D	20	µg	4.50	nd	2.64	3.00 [a]	1.58	2.38 [b]	2.71
Vitamin E	12	mg	20.18	8.75	4.04	5.26	6.72	2.38	0.53
Vitamin B_1	1	mg	2.66	0.32	2.73	3.05	5.95	2.08	2.10
Vitamin B_2	1.1	mg	10.86	7.37	9.27	8.99	14.61	8.86	17.30
Vitamin B_3	13	mg	0.84	0.95	2.32	0.44	2.87	0.88	2.58
Vitamin B_6	1.4	mg	0.64	0.52	6.54	1.00	7.80	2.06	2.57
Folic acid	300	µg	0.33	1.34	1.94	1.98	8.11	3.06	3.09
Vitamin B_{12}	4	µg	11.04	6.55 [b]	4.55	11.45 [b]	8.03	12.92 [c]	11.12
Na	1500	mg	4.09	3.71	2.34	2.74	2.60	3.47	2.91
K	4000	mg	1.09	1.22	0.86	0.72	4.11	4.61	3.90
Mg	310	mg	2.59	2.57	4.00	1.09	6.00	6.76	3.71
Ca	1000	mg	14.67	10.26	8.70	4.77	9.31	11.01	12.06
Fe	15	mg	1.56	0.12	2.52	nd	3.77	1.99	0.73
P	700	mg	1.63	7.30	5.38	6.20	8.29	12.97	13.32
Cu	1.3 (1.0–1.6)	mg	1.92	3.91	1.54	10.33	8.67	17.48	0.77
Zn	8.5 (7–10)	mg	1.75	1.26	3.34	0.89	1.74	4.45	4.79
				D-A-CH reference values female, ≥65 years					
Vitamin E	11	mg	22.02	9.55	4.41	5.73	7.34	2.59	0.58
Vitamin B_2	1	mg	11.95	8.11	10.20	9.89	16.07	9.75	19.02
Vitamin B_3	11	mg	0.99	1.12	2.75	0.52	3.40	1.04	3.05
Mg	300	mg	2.68	2.66	4.13	1.12	6.2	6.99	3.84
Fe	10	mg	2.35	0.18	3.78	nd	5.65	2.99	1.1
				D-A-CH reference male, 19–25 years					
Vitamin E	15	mg	16.14	7.00	3.23	4.20	5.38	1.90	0.43
Vitamin B_1	1.3	mg	2.05	0.24	2.10	2.35	4.58	1.60	1.62
Vitamin B_2	1.4	mg	8.54	5.79	7.28	7.06	11.48	6.96	13.59
Vitamin B_3	16	mg	0.68	0.77	1.89	0.35	2.34	0.72	2.10
Vitamin B_6	1.6	mg	0.56	0.45	5.73	0.88	6.82	1.80	2.25
Mg	400	mg	2.01	2.00	3.10	0.84	4.65	5.24	2.88
Fe	10	mg	2.35	0.18	3.78	nd	5.65	2.99	1.10
Cu	1.25 (1.0–1.5)	mg	2.00	4.07	1.60	10.74	9.01	18.18	0.80
Zn	13.5 (11–16)	mg	1.10	0.80	2.11	0.56	1.10	2.80	3.02
				D-A-CH reference male, ≥65 years					
Vitamin E	12	mg	20.18	8.75	4.04	5.26	6.72	2.38	0.53
Vitamin B_1	1.1	mg	2.42	0.29	2.48	2.78	5.41	1.89	1.91
Vitamin B_2	1.3	mg	9.19	6.24	7.84	7.61	12.36	7.50	14.63
Vitamin B_3	14	mg	0.78	0.88	2.16	0.40	2.67	0.82	2.39
Mg	350	mg	2.30	2.28	3.54	0.96	5.31	5.99	3.29

* Calculated mean values from AUSNUT, Fineli, USDA, and BLS databases; recommendations for vitamin D, folic acid, B_{12}, and Na, K, Ca, P correspond to both genders; [a] n=1, [b] n=2, [c] n=3, nd = not detected.

3.3 Sensory Evaluation

Raw material sources significantly influenced the sensory quality for all three product groups (almond, oat, soy). Considering all 23 attributes evaluated by the sensory panel, out of the total 15 PBMAs, five per product group, significant differences could be calculated for eight attributes, as shown in Figure 1A. As mentioned, the intent was to use the same evaluation form for several beverages. However, some of the uses of the various attributes differed significantly, such as the nutty odor and taste of the almond drinks to those of the other products, indicating that some terms were more product-specific. Figure 1B–D gives a more detailed overview of the significantly different sensory attributes of the selected products based on the raw material sources almond, oat, and soy.

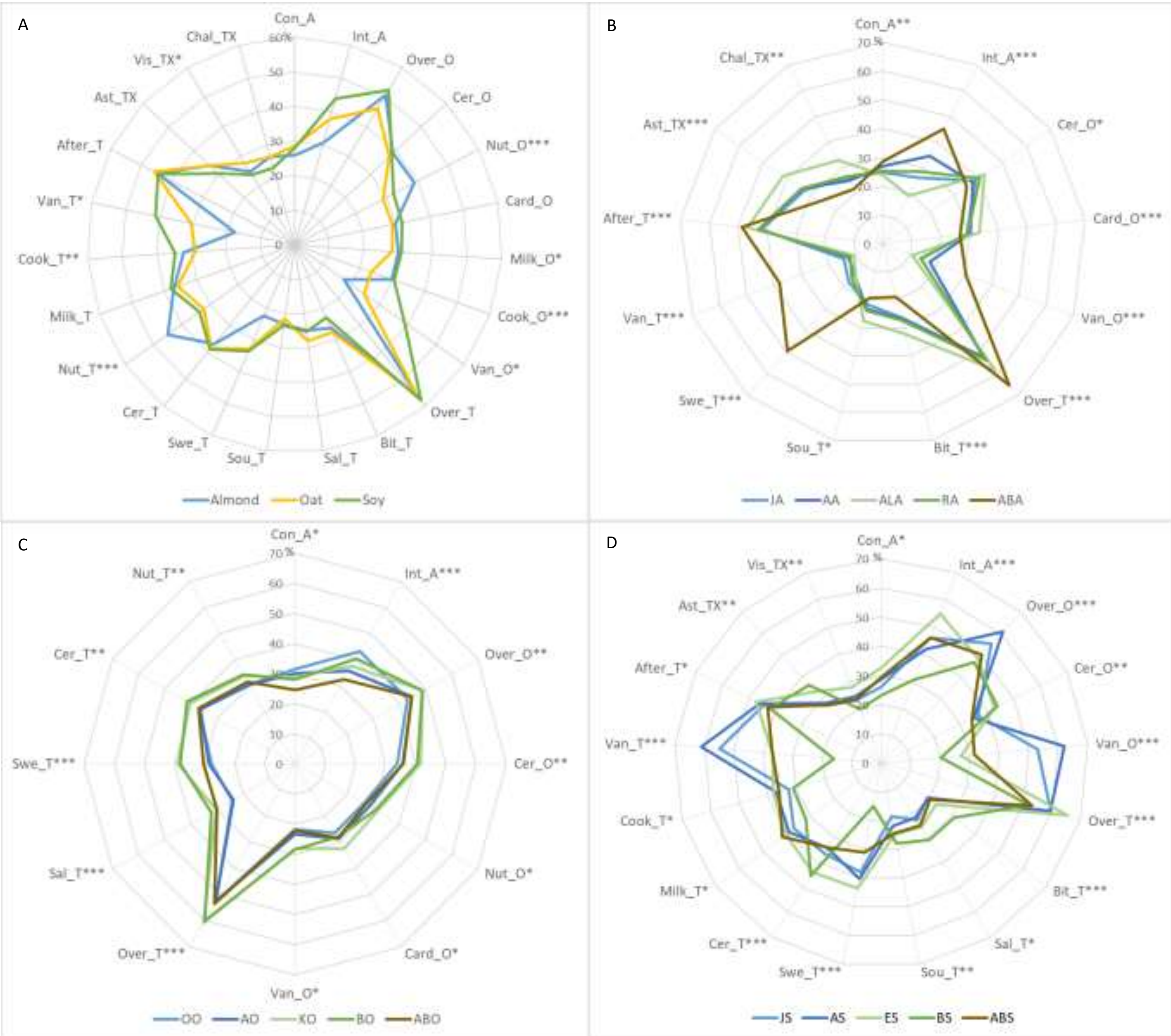

Figure 1. Spider diagram for sensory evaluation using quantitative descriptive analysis (QDA) of PBMAs; it shows the comparison of three raw materials with five products each, here with all attributes (**A**), and the significant attributes of almond drinks (**B**), oat drinks (**C**), and soy drinks (**D**); blue lines—conventional products, green lines—organic products, brown lines—barista-style products; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; for abbreviations of the products, see Tables 1 and 2.

For the five almond drinks (Figure 1B), 13 significantly different attributes were assessed, with two products differing strongly. On the one hand, the barista-style product (BS) was perceived as significantly darker (Int_A) and rated higher than the other products in the attributes of sweetness (Swe_T) as well as vanilla odor (Van_O) and taste (Van_T). On the other hand, the product ALA was perceived as the lightest (Int_A) and rated the highest in bitter taste (Bit_T) as well as astringent and chalky mouthfeel.

The evaluation of the oat beverages showed significantly different attributes. The two organic products were scored very similarly as well as the two conventional products, except for the attributes for appearance. The oat-based barista-style product was evaluated between these two product categories (Figure 1C). Both organic products were almost consistently evaluated higher on the rating scale than the conventional products. In addition to higher cereal and nut notes (Cer_O, Nut_O, Cer_T, Nut_T), the drinks had stronger overall odor and flavor (Over_O, Over_T) and higher sweetness and saltiness (Swe_T, Sal_T). Oat drinks tended to have a watery texture (Vis_TX) compared to that of the two other product groups. In addition, these products were often characterized by their darker, browner, and grayer appearance (Int_A) (Figure 1A).

Soy drinks had the most diverse sensory attributes and showed the most significant differences in 17 out of 23 attributes. Like the oat drinks, the panel evaluation showed a distinction between organic and conventional product categories for several attributes, most significantly for vanilla odor and flavor (Van_O, Van_T) (Figure 1D). The organic products were rated the highest in the attributes cereal note (Cer_O, Cer_T) as well as the basic tastes of bitter (Bit_T), salty (Sal_T), and sour (Sou_T), and the mouthfeel astringent (Ast_TX). The BS product further stood out with a low rating of vanilla note (Van_O, Van_T) and sweet taste (Swe_T). Interestingly, soy-based beverages were more associated with a milk odor and taste (Milk_O, Milk_T) than the other two product groups and were characterized by a darker, reddish- to brownish-colored appearance (Int_A) (Figure 1A).

3.4 Comparison of E-Tongue Results and Sensory Evaluation

The e-tongue measured taste in relation to the five basic human sensory tastes (sweetness, sourness, bitterness, saltiness, and umami) in the PBMAs. The e-tongue results for sweetness, sourness, and saltiness were compared to the perceived results of the trained sensory panel. The sensory panel results and the e-tongue measurement data showed a significant positive correlation for sweetness, sourness, and saltiness for all PBMAs (Figure 2).

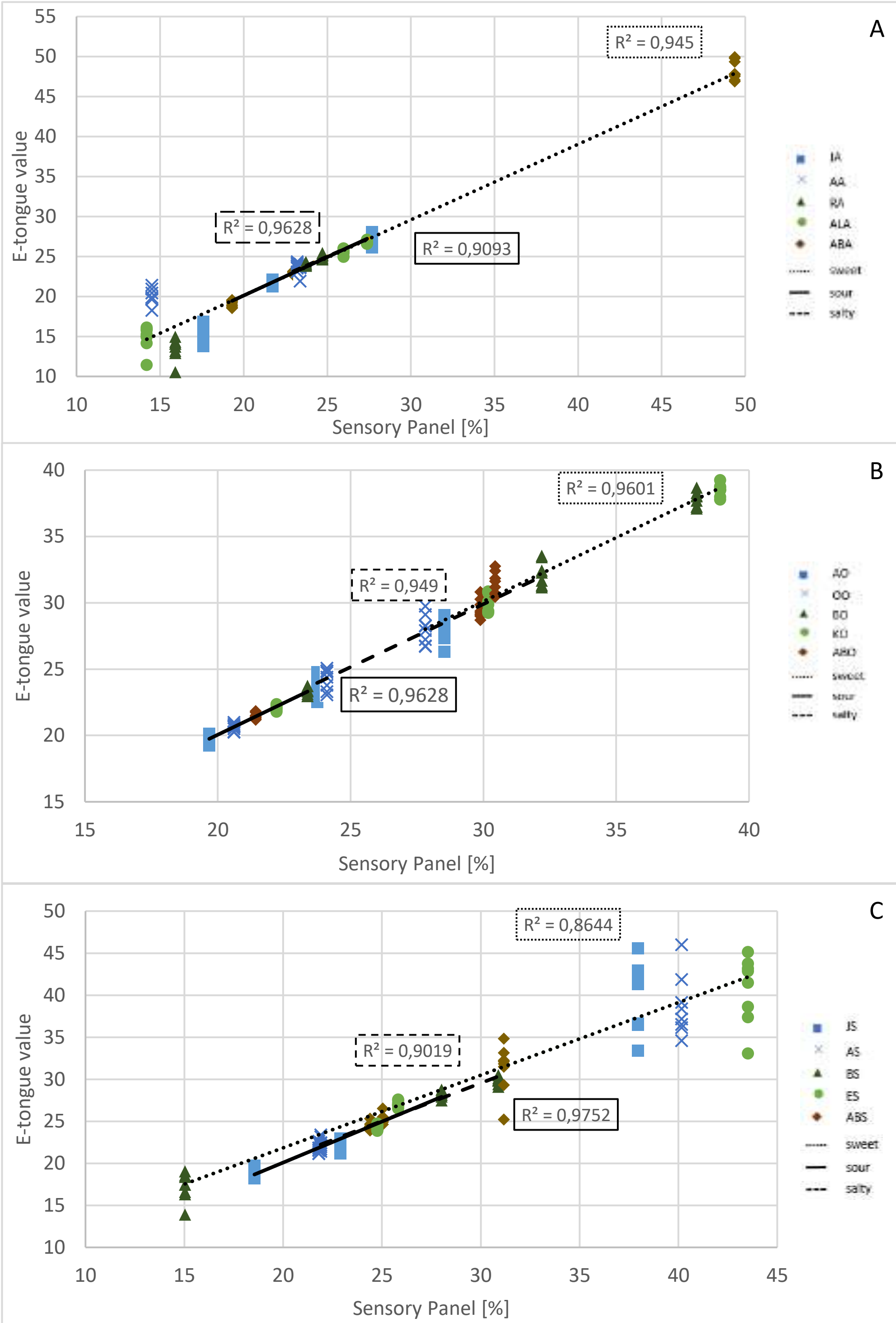

Figure 2. Comparison of sensory results and e-tongue values for the attributes sweet, sour, and salty (Pearson correlation) in almond drinks (**A**), oat drinks (**B**), and soy drinks (**C**); blue symbols—conventional products, green symbols—organic products, brown symbols—barista-style products; correlations were significant with $p < 0.05$.

3.5 Volatile Profile of PBMAs

A total of 366 volatile compounds were detected by GC-MS, of which 94 compounds had ≥75% qualitative similarity and were present in FooDB [45]. These identified compounds belonged to different chemical classes, which were classified into the following groups: alkanes (26%), acids (19%), aldehydes (18%), alcohols (11%), organic compounds (11%), aromatic/cyclic compounds (6%), furans (4%), pyrazines (3%), and esters (2%). When comparing specific compounds, some were found in all raw material groups, such as hexanal, acetic acid, pentanal, and furan, 2-pentyl-. The number of compounds in the different substance classes of volatile compounds and their percentage content within each raw material group as well as the average percentage qualitative similarity of the compounds are presented (Table 4). The almond drinks had the highest content of aldehydes and alkanes, and the highest percent similarity was in the pyrazines with 93%, which, however, only occurred once here. In oat drinks, most substances were found in the groups of acids and alkanes. The qualitative similarity was <90% in all groups, except for the alkanes with 94.8%. Organic compounds, alkanes, and acids were the chemical classes that occurred most often in soy drinks. Here, a qualitative similarity of >90% was found in five of the total nine classes. Of these substances, 43 odor-active key compounds were identified in the databases of PubChem [43] and FooDB [45] as well as in studies [23,46–51] (Table 5).

Table 4. The number of compounds in the different substance classes of volatile compounds, their percentage content within each raw material group, and the average percentage qualitative similarity (≥75%) of the compounds.

	Acids	**Alcohols**	**Alde-hydes**	**Alkanes**	**Aromatic/ Cyclic compounds**	**Esters**	**Furans**	**Organic compounds**	**Pyrazines**
Almond (*n*/%)	3/8.6	6/17.1	8/22.9	8/22.9	4/11.4	2/5.7	1/2.9	2/5.7	1/2.9
%-Qualitative similarity	84.7	91.7	87.9	92.1	83.3	76.0	76.0	82.0	93.0
Oat (*n*/%)	6/24.0	1/4.0	4/16.0	9/36.0	1/4.0	0/0	2/8.0	2/8.0	0/0
%-Qualitative similarity	87.3	88.0	86.3	94.8	83.0	0	85.5	85.0	0
Soy (*n*/%)	9/26.5	3/8.8	5/14.7	7/20.6	1/2.9	0/0	1/2.9	6/17.6	2/5.9
%-Qualitative similarity	88.8	92.0	87.6	91.0	97.0	0	97.0	80.5	92.0

Table 5. Odor-active compounds (n=43) with a percentage qualitative similarity of ≥75% in the PBMA drinks.

Class	Compound	Odor impression[a]	Described in PBMA[b]	Almond					Oat					Soy				
				AA	JA	ALA	RA	ABA	AO	OO	BO	KO	ABO	AS	JS	ES	BS	ABS
Acids	Tetradecanoic acid	Burnt, cheese, harsh									83	84		89	93	93	92	93
Acids	Dodecanoic acid	Coconut, fatty, metal													89	89		
Acids	Oleic Acid	Fatty												89	89	89		87
Acids	Hexadecanoic acid	Fatty							81		85	89	94	95	95	95	94	95
Acids	Acetic acid, methyl ester	Honey, fruity, green	5					86										
Acids	Acetic acid	Sour, fruity, vinegar		98		97	91	98	98	95	97	98	98	97	86	95	97	93
Acids	Pentadecanoic acid	Waxy							80					89	91	90		91
Alcohols	1-Butanol, 3-methyl-	Banana, floral, fruity, malt, wheat				91											82	
Alcohols	1-Octanol	Bitter almond, fatty, green, rose	3			96												
Alcohols	1-Heptanol	Coconut, green, mushroom, nutty, woody	1, 2, 3, 4			91												
Alcohols	1-Hexadecanol	Flower, wax										88						
Alcohols	1-Pentanol	Fruity, green, grain, mushroom, vanilla	1, 2, 3, 4			93												
Alcohols	1-Hexanol	Green, beany, fruity, grain, nutty, wheat	3, 5, 4, 1, 2			84										96	97	
Alcohols	1-Octen-3-ol	Mushroom, cooked bean, fatty	1, 2, 3, 4, 5, 6													88	97	
Alcohols	Phenylethyl Alcohol	Rose, floral, fruity, honey	5			95												
Aldehydes	2,4-Decadienal	Citrus, fatty, green	2, 3, 4, 5, 6			87					87						89	
Aldehydes	Nonanal	Almond, fatty, green, lemon, rose, soapy	1, 2, 3, 4, 5			90												
Aldehydes	Benzaldehyde	Almond, malt, woody	2, 3, 4			97		91										
Aldehydes	Piperonal	Anise, coconut, flower, vanilla												93				
Aldehydes	Benzaldehyde, 3-methoxy-	Anise													82			
Aldehydes	Benzaldehyde, 4-methyl	Cherry, fruity, sweet	2, 3						83									
Aldehydes	Octanal	Citrus, fatty, green, soap	2, 3, 4, 5			96												
Aldehydes	Hexanal	Green, fruity, leafy	1, 2, 3, 4, 5, 6	75		96					90						93	88
Aldehydes	Hexanal, 3-methyl-	Green			78													

Aldehydes	Pentanal	Green, almond-like, cooked beans, nutty	1, 2, 3, 4, 5			93			82				85		81			
Aldehydes	Heptanal	Green, citrus, nutty, rancid	1, 2, 3, 4, 5			89												
Alkanes	Eicosane	Waxy						82										83
Alkanes	Heneicosane	Waxy									95			90		93	88	89
Alkanes	Tetradecane	Waxy, sweet, fusel-like	3, 4	95		96	96	95	96	96	97	80	97	96	96	95	95	96
Alkanes	Pentadecane	Waxy		96	96						95	96				95	95	
Aromatic/Cyclic compounds	D-Limonene	Citrus, mint, fruity	2, 3					95										
Aromatic/Cyclic compounds	3-Carene	Lemon	9			77												
Aromatic/Cyclic compounds	Phenylephrine	Bitter				81												
Aromatic/Cyclic compounds	Acetylbenzoyl	Savory, buttery, honey						80										
Aromatic/Cyclic compounds	Vanillin	Vanilla	5								79	83	81	97	95			
Ethers	1,1-Dimethoxydecane	Citrus, green, herbal			77													
Furans	Furan, 2-pentyl-	Bean, floral, fruity, green	2, 3, 4, 5			76					94					95	97	
Organic compounds	gamma.-Dodecalactone	Apricot, floral, fruity, peach															80	
Organic compounds	9-Octadecenal	Dairy, fatty														79		
Organic compounds	Octadecanoic acid	Fatty												88	86	79	89	86
Organic compounds	Propyl propionate	Fruity, pineapple, banana													78			
Pyrazines	Pyrazine, 2,5-dimethyl-	Nutty, chocolate-like	2, 4, 5											91				92
Pyrazines	Pyrazine, 2,6-dimethyl-	Nutty	9					93										93

[a] Odor impression was described in PubChem or FooDB; [b] References that have described compounds and odor impression in PBMA: 1—Xia et al. [46], 2—Manousi et al. [47], 3—Klein et al. [48], 4—Pérez-González et al. [23], 5—Nedele et al. [50], 6—Kaneko et al. [51]; blue highlighted—conventional products, green highlighted—organic products, brown highlighted—barista-style products; the color scale ranges from 75% (red) to 98% (dark green) and corresponds to qualitative similarity.

Combining the data from the sensory panel with those from the analysis of volatile compounds showed which compounds influenced the odor and taste of certain products (Figure 3). The highest content of aldehydes characterized the almond beverages, including the benzaldehyde characteristic of almonds (Table 4). A relatively high number of alcohols were also detected in almond drinks, e.g., phenylethyl alcohol, 1-heptanol, and 1-octanol were identified only in almond drinks (Table 5). These results are confirmed by Pérez-González et al., which states that the aroma profile of almond beverages is mainly composed of aldehydes, ketones, and alcohols [23]. The results from the sensory analysis showed that these compounds led to a nutty taste and odor. The oat beverages generally differed from other beverages by a higher number of alkanes compounds (Table 4). Thus, many compounds from this chemical group were associated with waxy attributes (Table 5). Overall, few volatile compounds were found in these PBMAs. Overall, oat beverages showed great homogeneity in the sensory description (Figure 3). The soy beverages had high acids levels (Table 4), although they were found in slightly smaller amounts in the other raw materials groups. These compounds often had an acidic odor, which is probably why they led to the odor attributes milk (Milk_O) and cooked (Cooked_O) in soy beverages (Figure 3). Vanillin was detected in the highest qualitative similarity and quantity in soy beverages, overlapping with the sensory evaluation (Vanilla_O, Vanilla_T).

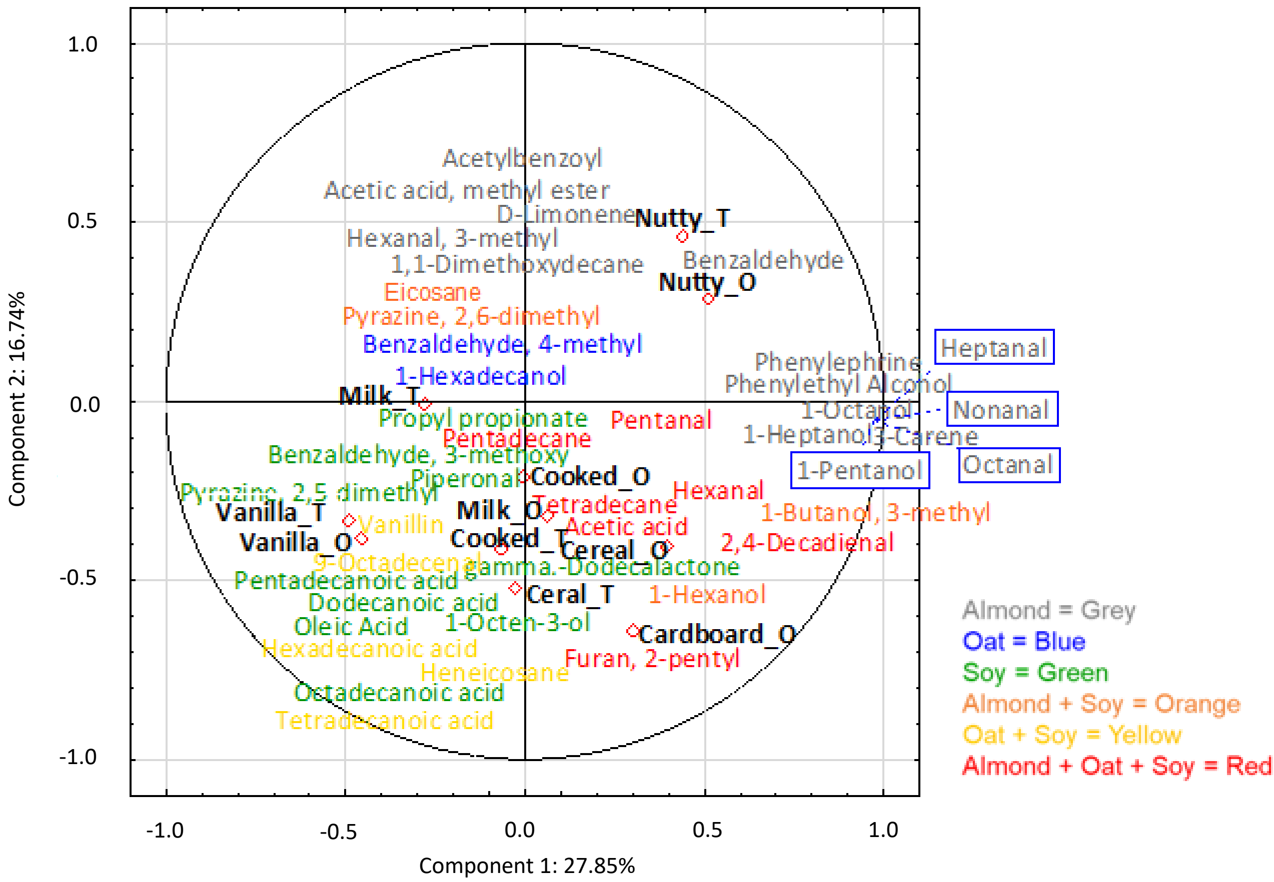

Figure 3. PCA results for the volatile compounds ($n = 43$) compared with the mean sensory data, including odor (_O) and taste (_T) attributes (black text, red squares); the volatiles are shown in different colors depending on the source of the raw materials in which they could be detected. For a description of odor impressions, see Table 5.

4. Discussion

4.1 Nutritional Properties

The nutritional properties of a variety of PBMAs and cow's milk were compared for macronutrients (Table 1) and micronutrients (Table 3). This comparison showed significant differences in the nutritional value of the various beverages. Soy drinks had a similar protein content to that of cow's milk, whereas almond and oat drinks had much lower values. There were also differences in amino acid composition between the different plant-based raw materials and cow's milk. The study by Gorissen et al. [52] showed the essential amino acid content of raw plant material in total 13.7 g/100 g in oats, 19.9 g/100 g in soy, and 30.3 g/100 g in cow's milk, with similar differences for non-essential amino acids. Considering that in PBMAs the raw material content was between 2% and 12%, this could have nutritional effects when regularly consumed. Therefore, combinations of different plant-based protein isolates are useful, as they could increase the evaluation of the amino acid profile, "protein digestibility-corrected amino acid score" (PDCAAS) of the product, which was close to that of cow's milk. Some commercial oat beverages were currently already supplemented with pea isolates because they were rich in essential amino acids (30.3 g/100 g) and non-essential amino acids (38.6 g/100 g) [52].

Based on the D-A-CH reference values, there were significant differences in the various plant-based beverages in the coverage of the daily requirement of vitamins and minerals (Table 3). Reference was made explicitly to the different age groups and gender, as the motivations for consuming these plant-based drinks often differed. Thus, on the one hand, the potential benefit for the environment [7] and, on the other hand, health aspects [19]. When comparing the data shown here with results from other studies [53–57], the same results are obtained with slight variations. Cow's milk is a rich source of fat- and water-soluble vitamins and compared to PBMAs, it contains higher amounts of vitamins B_2, B_3, and B_6. Fortified alternative products could be an important source of vitamins if they achieve levels similar to those of cow's milk. A study by Scholz-Ahrens et al. [58] shows the major importance of vitamin B_{12} supply for bone health and neuronal function and that people over the age of 60 are at an increased risk of having a deficiency.

Cow's milk often has a higher mineral content than the plant-based beverages analyzed here. Therefore, supplementation was applied to most products [59], except for products produced according to organic certification [60]. The supplementation with minerals increases the nutritional value of these products. Astolfi et al. [55] found that cow's milk has higher Ca, P, Mg, Na, and K content than PBMAs do. For Ca and P, this was also confirmed by the analyses shown here (Table 3).

In addition to the low mineral content, legume-based beverages may contain antinutrients such as phytic acid, oxalates, lecithin, and saponins. These reduce the body's absorption and digestibility of essential minerals such as Ca, Fe, Mg, Zn, and Cu. Beyond that, they bind these compounds and form insoluble complexes [19,20]. The study by Borin et al. [61] focused on the risk factors for kidney stones and chronic kidney diseases concerning PBMAs. The authors were able to show that oat, rice, and soy drinks are comparable to milk in terms of kidney stone risk factors, while almond and cashew drinks had a potentially higher stone risk factor, as the highest oxalate concentration was found in almond drinks. For patients with chronic kidney disease, coconut beverages are a good milk alternative because they are low in oxalate and contained low K and Na levels [60].

Another undesirable property is the allergic potential, especially in soy and almond drinks [19,21,61]. The proteins that could trigger allergies, especially tree nuts and soy, are among the eight most common food allergens [21]. Furthermore, the authors wrote that almost 14% of people allergic to cow's milk also report reactions to soy protein. The presence of gluten in PBMAs, in oat and other cereal-based beverages, is tolerated by most people but may have adverse health consequences in people with gluten intolerance, especially celiac disease [62]. Pea allergies are rare and therefore not extensively studied, so there is limited information on this [63].

Among PBMAs, legume-based beverages have a protein content comparable to that of milk and the highest PDCAAS, which is related to protein digestibility and indicates the quality of the protein profile [20]. Furthermore, soy drinks have a good ratio of micro- to macronutrients and are closest to the values of cow's milk. Therefore, people who include more plant-based foods in their diets should take special care to maintain a balance of essential vitamins, minerals, and amino acids. Unfortunately, there are very few comprehensive or no long-term studies on the health effects of PBMAs, but studies on the raw material showed some health benefits, such as for oats and almonds [64].

In accordance with the NOVA classification, PBMAs could also be categorized as organic products (NOVA group 3) or conventional products (NOVA group 4) [24,25]. Products with an organic label can only be produced according to the guidelines for organic products in Europe, which also regulate the use of additives or flavorings [59]. In the production of PBMAs, as with UPFs, natural raw materials are broken down, and the processing changes the food matrix. Depending on the raw material, different processing steps are required, such as crushing, separation, enzymatic or chemical hydrolysis, blanching, thermal processes, homogenization, and formulation with the addition of functional ingredients such as flavors, colorants, preservatives, stabilizers, thickeners [7,11,58]. The processing steps necessary for almond drinks are described in a study by Grundy et al. [65]. The modified matrix is recombined, and additives are used, which affects the availability of nutrients, energy, secondary phytochemicals, and digestibility [65,66]. A study by Drewnowski [67] showed that out of the total 641 PBMAs, 90% could be classified as UPFs. It should be noted that only data from the USDA Agricultural Research Service database were taken here. On average, the products had a much higher Nutri-Score of 9.63 (score C) than the products in this study, where the evaluated products had a Nutri-Score of –0.5 (score A/B). This shows that there were many different products in an expanding market and that the product groups and the products are very heterogeneous. Increased disease risks with negative effects of cardiometabolic diseases, cerebrovascular diseases, depression, frailty, irritable bowel syndrome, and cancer were associated with UPFs, as shown by recent reviews and meta-analyses [68–70].

In a study by Romero Ferreiro et al. [71], it was clarified that the Nutri-Score classifies foods according to their nutritional quality but does not consider aspects such as degree of processing. Thus, the authors could find UPFs in all Nutri-Score categories, for example, 26% with a Nutri-Score A and 51% with a Nutri-Score B. Therefore, a complementary label indicating the degree of processing would be helpful for the consumer.

4.2 Sensory Characteristics

More than 40 years ago, the first sensory studies on legume-based beverages were conducted, with the results that the products were similar to cow’s milk in color and viscosity, but were all deficient in odor and taste [72]. Of the ten legume species at that time, lima, mung, and pea bean were rated equally high, and soybeans scored significantly lower. There have been further developments in many areas, from breeding to food technology. Thus, soy products are gaining importance today due to their high-quality protein and are in high demand by consumers worldwide. Chambers et al. [73] developed a lexicon through a descriptive analysis with a trained sensory panel that can be used to characterize soy drinks. However, the authors discuss that their study results cannot be considered exhaustive due to the variety of products on the growing market and the continuous development of products.

Figure 1A shows the comparison of three raw materials (almond, oat, soy) with five products each, here with all sensory panel attributes requested. Since there were only a few significant differences here, it is again clear that the products should be evaluated according to the raw material source since there is a high degree of heterogeneity. Figure 1B–D show that there were significant differences between organic and conventional PBMAs. It is also shown here that more negative attributes such as bitterness and astringency were associated with organic products. A recent study by Hoppu et al. [74] cites several consumer studies [75–77] asking whether there are sensory differences between organically and conventionally grown vegetables or their products. None of these studies measured significant differences. The masking of bitterness has been studied the most in consumers with high sensitivity to bitter taste. Hoppu et al. [73] pointed out studies in which taste interactions in vegetables and their products, and aqueous solutions with salts, sucrose, and sweeteners, can significantly mask bitterness.

In soybean beverages, bitterness and astringency were also considered negative properties [78,79]. Furthermore, Torres-Penaranda and Reitmeier [78] found that adding sugar resulted in desirable flavor changes by reducing the attributes of bitterness and astringency. In the results for almond drinks (Figure 1B), this was again evident, as “sweet” products were rated less “bitter” and “astringent.” For the soy drinks (Figure 1D), similar conclusions could be reached only for the product “ES,” which was rated high in sweetness and also in bitterness and astringency, so the masking did not seem to work optimally. Here, the organic products had highest soybean content with 11.0% and 9.4%, so this could be related to the more negative attributes (astringent, bitter).

A study by Yang et al. [80] clearly shows that cultural influences are also decisive for the product development of PBMAs, especially in soy beverages. The authors found that the typical bean-like taste of soy milk is important for “traditional” soy consumers from Asia and is strongly associated with the product. PBMAs are composed of a complex of proteins, lipids, and carbohydrates combined with several micro-components, making these products a heterogeneous food matrix.

4.3 Comparison of the Results of Electronic Tongue and Sensory Evaluation

An e-tongue was used to classify basic flavors in PBMAs and compare the results with those of the sensory panel. This automatic, qualitative analysis of highly complex samples rapidly detected product-specific and characteristic properties. As the results of the study by Pascual et al. [81] showed, it is possible to make a distinction between

PBMAs based on different raw materials and through different manufacturing processes (handmade or industrial).

Since sweetness is a very relevant parameter in plant-based drinks and soy drinks are generally associated with the attribute "salty," it received in this study as well as in the study of Pascual et al. [81] lower values for the parameter "sweet." Almond drinks received the highest ratings for sweetness in both studies, with the oat drinks falling between the two drinks. When adding the product data of the Big 7 from Table 1, there were many similarities of the results between the sensory panel and e-tongue. The organic oat drinks had the highest sugar and salt content, and both the panel and e-tongue confirmed this. Pascual et al. [81] found for tiger nuts that the origin of the raw material seems to be an important factor in the data values. According to the manufacturer, the barista-style product was the only one in the group of almond drinks where sugar and natural flavors were added. This explains the high sugar content in the Big 7, it was rated sweetest by the sensory panel (Figure 1B), with the e-tongue analysis showing the same results (Figure 2A). The flavors explain the high score for vanilla odor and taste. The promising results indicate that the use of an e-tongue serves as a practical and suitable tool for classifying PBMAs since the system could be used to present a fast and straightforward sensory evaluation of the basic flavors.

4.4 Comparison of Volatiles' Profile and Sensory Evaluation

Some generalizations could be made about the different product types, which were also supported by other studies. The heat treatment of the products for shelf life (ultra-high-temperature processing) is often responsible for characteristic aromas [48,82]. Almond drinks were characterized by their high content of benzaldehyde and nonanal, which were key compounds and could also impart a sweeter taste [23,47]. The presence of pyrazines in raw almonds and soybeans may be directly related to the roasting process [83,84]. Erten and Cadwallader [83] showed that the content of pyrazines depends on the roasting type (dry, oil roasted) and temperature and time.

HS-SPME could detect the high content of alcohols in soy drinks in the results shown here, as in the study by Achouri et al. [49]. In addition, typical leguminous, beany, and earthy notes may be related to the high levels of pyrazines, furans, and alkanes found in legumes [51,85].

Oats possess a unique aroma with grainy, nutty, hay-like, and grassy sensory characteristics, which were contributed by the volatile key compounds from aldehydes and ketones [86]. Consequently, oat drinks were able to show the fewest compounds in this analysis and those with the lowest percentage in qualitative similarity.

One of the main problems with the acceptance of PBMAs as cow's milk alternatives is that these products often had undesirable sensory characteristics. According to previous findings, the formation of hexanal, hexanol, and pentanal is often a result of lipid oxidation [22,23,49,51]. The previously mentioned volatile compounds induce off-flavors, such as beany and earthy flavors found in legume-based beverages [84].

The green off-flavor of soy beverages could be reduced by fermentation processes [50]. The authors significantly reduced the green odorants (hexanal, 2,4-decadienal, 2-nonenal) of a soy beverage, with hexanal falling below its odor threshold. The first two substances mentioned could also be determined in the soy drinks analyzed here. Therefore, it could be hypothesized that vanillin is used as a flavoring to hide the deficiencies of soy-based products, as they tend to taste like beany and earthy notes, sometimes with an astringent mouthfeel.

Due to the high variability, it was a challenge to generalize the sensory properties of plant-based beverages from different raw materials. Differences were evident between different product categories and within the same product type. The described characteristics of the product probably depended on the origin of the raw material and the production technology. Therefore, raw material variability should be considered in the production and development of PBMAs.

5. Conclusions

The increasing popularity and consumption of PBMAs among consumers show a shift in dietary styles in the Western world. In the present study, plant-based milk beverages, based on almond, oat and soy, from the German food market were sensory-evaluated, micronutrients were analyzed, and macronutrients' and health evaluation by the Nutri-Score were carried out. Food manufacturers could develop products that meet the sensory characteristics of PBMAs desired by consumers, i.e., with reduced off-flavors, but are not recommended from a nutritional and health perspective because of high sugar content and additives. On the other hand, products with high health value, for example, with high fiber content and no additives, come in with bitterness and astringency and are therefore not preferred by consumers. It turns out that the balance of these two important product characteristics is crucial. Plant-based products have naturally lower levels of proteins, minerals, and vitamins compared to those of cow's milk. Therefore, the content of essential amino acids and the PDCAAS in the products is lower than that in cow's milk, except in products based on legumes or in combinations of an oat-based drink with the addition of pea protein, for example. As a result, PBMAs are not nutritionally comparable or equivalent to cow's milk. However, if they are fortified with nutrients, the evaluation may be more positive. This means an adequate supply of micronutrients can be ensured if cow's milk is replaced by plant-based alternatives. Due to the wide range of products on the market, consumers need to consider the nutritional values and ingredients when choosing a product.

To encourage the consumption of plant-based milk, information on health aspects must be available to consumers. Research results published in scientific articles have to find their way to their application in relevant, everyday contexts. The identification of relevant target groups as well as communication channels is important to support a healthy diet with more plant-based and fewer animal-based foods.

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Chapter 4

Plant-based only: Investigating consumers' sensory perception, motivation, and knowledge of different plant-based alternative products on the market

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Plant-Based Only: Investigating Consumers' Sensory Perception, Motivation, and Knowledge of Different Plant-Based Alternative Products on the Market

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Abstract: Consumer acceptance and product development of sustainable, healthy, and tasty plant-based alternative products (PBAPs) are closely interlinked. However, information on consumer perceptions of the sensory profile of plant-based meat, cheese, and milk remains scarce. The study aimed to investigate German consumers' (1) sensory evaluation of PBAPs and (2) consumers´ motivations and knowledge underlying the purchase of such products. This was analyzed in relation to different dietary styles of consumers (omnivore, flexitarian, vegetarian, vegan). A sample of 159 adults completed two tasks: first, a sensory test in which participants tasted and rated three different PBAPs in two consecutive sessions, and second, a questionnaire on consumption behavior, motivation, and knowledge. Results show few differences between nutrition styles in sensory evaluation of individual product attributes. However, overall liking was rated significantly higher by vegans than by omnivores. All dietary styles reported animal welfare and environmental aspects as the main motivations for consuming PBAPs. Most participants acknowledged that meat and cheese alternatives are highly processed foods and not a fad but are not automatically healthier or more environmentally friendly than their animal-based counterparts. Future research should focus on emerging product segments such as plant-based cheeses to better understand how consumers evaluate PBAPs.

Keywords: cheese alternative products; meat alternative products; milk alternative products; consumer research; consumer profiling; sensory characterization; RATA

1. Introduction

Reducing the global consumption of animal-based products and changing to a predominantly plant-based diet are necessary approaches for a sustainable diet that simultaneously has positive environmental and human health and public health impacts [1]. An unbalanced diet low in fruits, vegetables, nuts, and whole grains, high in red and processed meats, with a high sodium intake, is responsible for the greatest health burden worldwide [2]. The EAT Lancet Commission's published planetary health diet states that meat and dairy constitute important parts of the diet but in significantly smaller proportions than plant-based foods [3]. Additionally, according to the recommendations of the German Nutrition Society, a reduction in meat consumption in particular is necessary. With a per capita consumption of 57.3 kg for the year 2020 [4], meat consumption is still significantly above the recommended consumption levels, requiring many people in the Western world to make far-reaching changes to their eating habits. Meat has long been an integral part of traditional German meals and, for many, an important part of their food culture. Although there has been increasing interest in reducing meat consumption in Germany, many social and personal barriers prevent this dietary change, as meat is often perceived as a status symbol [5]. Other reasons are taste preferences, enjoyment and habit [6,7], the social environment, or a lack of awareness of the link between climate change and food consumption [7–9]. A 2020 online survey of German young adults showed that just under 13% abstained from meat, which is about twice as many as in the overall German population [10]. Spiller et al. [10] showed that giving up meat was a trend among the survey respondents, as around one-third of those who ate a vegetarian or vegan diet had switched to a meat-free diet only a year earlier.

In making a dietary change to reduce animal-based product consumption, plant-based alternative products (PBAPs) can make an important contribution to managing those changes within the familiar structure of meals and existing cooking skills, but also increase product variety as well as availability, which can otherwise be considered barriers to dietary change [11–13]. PBAPs are products composed of predominantly plant-based proteins, such as legumes, grains, nuts, seeds, mushrooms, and fats. They have slowly but steadily increased their market share in Germany, with many supermarkets and discount stores increasing the range of available products [14]. The goal of alternative products is to mimic the animal-based product as closely as possible, so the sensory evaluation effort often aims to assess the similarities between these products and their traditional animal-based product. Consumer studies are necessary to evaluate the sensory characteristics and the perception during consumption in order to achieve sensory acceptability. However, there are currently limited data on which sensory aspects are important to consumers, particularly in the area of plant-based cheese alternatives and the most commonly used substitutions. Process optimization and new technologies to utilize and improve novel plant proteins are driving product development of PBAPs, but at the same time require constant evaluation of sensory properties from a consumer perspective.

While sensory research is an important tool for analyzing consumer preference and acceptance, it is also insufficient because sensory acceptance is only one factor that influences food choice and consumption [15]. Among various key determinants in the decision-making process, cognitive factors are considered critical to sustainable diets, as the shift to more sustainable lifestyles must take into account not only consumers' individual needs and preferences but also their attitudes and knowledge about health and environmental values [16]. Studies suggest that PBAPs are more often perceived as being environmentally friendlier and, partly, healthier than their animal counterparts [17–20]. However, there is little research on what consumers actually know about the sustainability of PBAPs. In terms of environmental aspects, alternative products are likely less detrimental to the environment than most meat production due to refinement losses within the animal production line [21,22]. However, as PBAPs are often ultra-processed foods, the extensive processing required uses energy and resources and leads to losses during the transformation from the raw material into final products [22,23]. From a nutritional perspective, reduced consumption of red and processed meat and partial replacement of the original amount of meat with plant-based meat alternatives has been shown to have a beneficial effect on the intake of unsaturated fatty acids and dietary fiber [24,25]. Moreover, PBAPs represent an important source of vegetable protein [26]. Yet, these new food matrices are created from raw materials by adding other ingredients through food technology processes, so PBAPs often contain high levels of salt, sugar, and saturated fat, as well as flavorings and other additives [27–29]. Consumers have limited access to reliable scientific publications or the ability to evaluate robust scientific data. Their knowledge of sustainability-related properties of PBAPs depends on claims made by manufacturers and internet searches that generally do not provide clear, validated evidence for specific features. Several studies point out that relevant knowledge is a prerequisite to enabling consumers to make environmentally friendly choices [14,30,31]. Thus, it is important to better understand consumer knowledge related to sustainability-related attributes (e.g., environmental impact, health, degree of processing) of PBAPs.

This paper also attempted to determine whether consumers' knowledge and motivation influence sensory evaluation. Some studies have shown that extrinsic factors, such as packaging, brand, information, emotion, and social environment, influence sensory perception [32–34]. Information focused on sustainability can especially influence consumers' liking of food, as shown with various commodities, such as chocolate, coffee, and lamb [35], but has so far been little studied in relation to PBAPs. We intended to investigate whether information about the sustainability of PBAPs—which is conveyed along with consumer knowledge and motivation—acts as a cognitive impulse, thereby inducing a change in sensory perception. The research project in which this study was conducted focused on comparing different nutrition styles from a comprehensive sustainability perspective. For this reason, the participants were grouped according to their dietary preferences (omnivore, flexitarian, vegetarian, and vegan), and the data were analyzed accordingly. The primary focus was to determine the prevalence and acceptance of different plant-based foods in German diets. This research project investigated the existing range of PBAPs from three different product groups (plant-based salami cold cut, plant-based cheese, and plant-based oat drink) in food retail from a consumer perspective regarding availability and sensory quality. An assessment of PBAPs may be helpful for further development in product research and thus for a better understanding of the acceptance of such products. Specifically, the following questions arise: (i) How do consumers evaluate the sensory quality of products on the market, and does information on sustainability characteristics influence the sensory perception? (ii) What is the consumption pattern for these products? (iii) What knowledge and (iv) what motivations support the current products offered? These questions will be analyzed by comparing different dietary groups (omnivores, flexitarians, vegetarians, vegans).

2. Materials and Methods

2.1 Procedure

The study was conducted in January 2020 in the sensory laboratory of the Georg-August University of Goettingen. During the evaluation, each participant sat in a separate booth designed according to the specifications of ISO 8589 [36]. This study received ethical approval from the Ethics Committee of the University of Goettingen. All participants received an information letter stating the conditions for participation in the study and signed an informed consent form. Each participant received a EUR 5 expense allowance for their participation in a session of approximately 60 min. After receiving a short welcome and introductory information, the participants were seated in the booths. The products were tasted twice, in two successive sessions, with a 15 min break between sessions. During this break, sociodemographic variables (age, gender, education, and household income), frequency of, and motivation for, the consumption of plant-based alternative products, and knowledge of the sustainability features of such foods were obtained by questionnaire. This questionnaire served as a way to measure the influence of information on sensory perception. Thus, the questionnaire was intended to reveal a possible influence on the sensory evaluation of the second session. Data recording was performed with the software EyeQuestion® (version 4.11.57, EyeQuestion®, Elst, The Netherlands) under white lighting, controlled temperature (20 °C ± 1 °C), and airflow conditions.

2.2 Sample Recruitment

Participants were recruited via notices posted at the University of Goettingen and via various social media channels. A sample size of 160 people in total participated; however, complete data from the sensory testing and survey were only received from 159 participants and included in the analysis (Table 1).

Table 1. General characteristics of the study sample by nutrition style.

		All	Omnivore	Flexitarian	Vegetarian	Vegan	*p*-Value
	n	159	36	62	44	17	
	%		22.6	39.0	27.7	10.7	
Gender	Female	69.8	55.6	61.3	84.1	94.1	
	Male	30.2	44.4	38.7	15.9	5.9	0.002 [1]
Age	18–24 years	53.5	27.8	50.0	75.0	64.7	
	25–29 years	22.6	30.6	24.2	11.4	29.4	
	30–39 years	12.6	22.2	12.9	9.1	0.0	
	40–70 years	11.3	19.4	12.9	4.5	5.9	0.008 [1]
Age	Mean (SD)	30.13 (10.18)	33.03 (10.98) [b]	32.29 (12.25) [ab]	26.41 (4.91) [a]	25.82 (4.77) [a]	<0.001 [2]
Education [3]	Low	3.1	2.8	4.8	2.3	0.0	
	Medium	62.3	47.2	51.6	77.3	94.1	
	High	34.6	50.0	43.5	20.5	5.9	0.005 [1]
Net household income per month	< EUR 600	37.7	36.1	29.0	40.9	64.7	
	> EUR 600–1800	37.7	19.4	46.8	45.5	23.5	
	> EUR 1800–3600	15.1	27.8	12.9	9.1	11.8	
	> EUR 3600	9.4	16.7	11.3	4.5	0.0	0.013 [1]
Body mass index	<18.4	5.7	5.6	4.8	4.5	11.8	
	18.5–24.9	75.5	52.8	82.3	88.6	64.7	
	25.0–29.9	13.8	33.3	8.1	4.5	17.6	
	>30	5.0	8.3	4.8	2.3	5.9	0.012 [1]
Body mass index	Mean (SD)	22.59 (3.75)	23.94 (4.31) [b]	22.38 (3.40) [ab]	22.12 (3.68) [a]	21.97 (8.86) [a]	0.009 [2]

[a,b] Values with the same superscript letter within the row indicate statistically nonsignificant differences between nutritional styles based on the Kruskal–Wallis rank test, and when differences existed,

they were determined using the Bonferroni correction two-sample test, $p < 0.05$. [1] Pearson chi-square. [2] Kruskal–Wallis rank test. [3] Education classification: Low (secondary school certificate), Medium (high school graduation), High (completed studies).

2.3 Description of the Plant-Based Alternative Products

Participants sampled three different plant-based product groups (milk, cheese, and salami). These were purchased from the local supermarket, and each had only minor variations in the best-before date of one week or less, so it can be assumed that no change in the formulation had occurred.

The plant-based milk alternative (PBMiA) was an oat drink from the company Alpro with the caption "Oats; purely vegetable, no added sugar" (Alpro GmbH, Duesseldorf, Germany); Alpro is the European market leader for soy-based foods and dominates the German food market [37].

SimplyV Natur, "Vegane Genießerscheiben," a non-dairy sliced cheese with the sales description "Bread topping with almond produce" (E.V.A. GmbH, Oberreute, Germany), was used for the tasting as a plant-based cheese alternative (PBCA). This company is the market leader in Germany, and according to a representative Forsa survey, about 6.8 million consumers in Germany have already tried the product [38].

The plant-based meat alternative (PBMA) tasted was "Vegetarian Mühlen Salami, classic" from the manufacturer Rügenwalder Mühle (Bad Zwischenahn, Germany) with the sales description "Vegetarian product in the style of a salami based on wheat, cooked." Rügenwalder Mühle is a traditional meat-processing company that has been very successful in the vegetable protein sector for several years selling many food products in the German market. In July 2020, their vegetarian and vegan product sales share was greater than the share of their animal-based products for the first time [39,40].

2.4 Sensory Evaluation

The rate-all-that-apply (RATA) questionnaire is a variant of check-all-that-apply (CATA). This method consists of asking participants to rate the intensity of the sample's attributes. Its purpose is to increase the ability to discriminate between samples with similar sensory profiles but different intensities of certain attributes [41]. The inclusion of attribute intensity scaling improves the accuracy of descriptive profiling and leads to better product differentiation than the CATA questionnaire [42,43]. According to Ares et al. [44], the selected terms can be rated on a 5-point scale (from "slightly applicable" to "very applicable") according to applicability. Participants were asked to leave the scale blank for terms that did not apply. In addition, the overall liking of the product was ranked here on a vertical 9-point hedonic scale, with endpoints of "dislike extremely" (1) and "like extremely" (9). A trained panel (n = 10) from the University of Goettingen, Germany, developed an initial list of attributes. For this purpose, the trained assessors evaluated all samples in consecutive sessions and wrote down all the attributes they could think of to describe the samples, considering all relevant modalities. The sensory attributes mentioned most frequently and for which a reference or standard definition could be identified were selected for inclusion in the RATA ballot. The final lists of terms included 14–15 terms (see Supplementary Materials Table S1). During sensory testing, the attributes appeared in a fixed order. To help participants quickly find the appropriate response, the order corresponded to the expected "dynamics of sensory perception" [43,45]: appearance, odor, flavor/taste, and texture. Participants were provided with water and unsalted crackers (P. Heumann's Matzen, Germany) to neutralize their senses.

2.5 Questionnaire

Participants provided initial information on sociodemographics, including gender, age, education, and household income (Table 1). Information on height and weight allowed us to draw inferences on the body mass index (BMI, kg/m^2) of the participants.

Participants indicated that they followed an omnivorous, flexitarian, vegetarian, or vegan diet. Omnivorous and flexitarian diets were determined by reporting their meat consumption (e.g., "I eat meat regularly," "I deliberately eat less meat"). This was verified or adjusted by asking about the consumption frequency for meals containing meat and meat products, on a 7-point scale from "never" to "more than five times a week," as well as the type of animal-based product consumed. Accordingly, participants who consumed meat and/or meat products 3 or more times a week were classified as omnivores. Participants who consumed meat and/or meat products but no more than 1–2 times per week were classified as flexitarians [46]. Participants who did not eat meat and/or meat products but did eat other animal-based products were assigned to the vegetarian diet (no fine-grained distinctions of lacto-ovo vegetarian, pescetarian, etc.), and participants who did not eat meat or meat products or animal-based products were assigned to the vegan diet.

For each plant-based product group (i.e., PBMA, PBCA, and PBMiA), consumption characteristics were examined in more detail: (a) the frequency that participants consumed alternative products, on a 7-point scale from "never" to "more than five times a week," adapted from Hoek et al. [47]; (b) what food or raw material the products were based on (e.g., grains, legumes, seeds); and (c) where they were purchased (e.g., discount store, supermarket, organic food store).

Ten items were used to assess participants' motivation for consuming plant-based alternatives. Based on earlier work [6,48–51], the items related to health, environment, animal welfare, social setting, product lifestyle, sensory appeal, and convenience. Further items were developed by discussing, adjusting, and reflecting on current motivations for food choice motives (e.g., "I am interested in the advertising and the product design") (see Appendix A, Table A1). The item on "convenience" was surveyed for PBMAs only, against the background that many PBMA products are ready-to-heat or prepared as ingredients for further processing. Participants responded to these items on a scale from 1, "totally disagree", to 5, "totally agree". The scale offered a "don't know" response option.

Seven items for PBMAs and PBCAs and six items for PBMiAs related to sustainability characteristics of the products were used to assess the participants' objective knowledge (e.g., plant-based meat alternatives are a source of vegetable protein) (see Appendix B, Table A2). Information on PBMAs was based on research by Huber and Keller [26], Nijdam et al. [52], Mejia et al. [53], Leitzmann [54], Joshi and Kumar [55], and Klementova et al. [56]. Findings on PBCAs came from the studies of Jeewanthi and Paik [57] and Masotti et al. [58], and data for PBMiAs originated from research by Röös et al. [59] and Poore and Nemecek [60]. Participants were asked to indicate the extent to which they agreed with the items on a scale of 1, "strongly disagree", to 5, "strongly agree". The knowledge questionnaire included a "don't know" response option so that participants could use this option instead of guessing [61,62]. One of the items in the questionnaire contained a negative meaning; the remaining items were worded positively. The values of the negatively worded item were recoded in the data analysis so that the highest score represented the highest possible agreement, indicating correspondingly greater knowledge. Responses were averaged for the sustainability characteristics: health, environment, ultra-processed food (UPF), additives, and consistency.

2.6 Data Analysis

The questionnaires were recorded using EyeQuestion® software (Elst, The Netherlands), and the extensive data set could be easily linked and processed with SPSS® statistical software (IBM SPSS Statistics, Version 26.0, Armonk, NY, USA) and Microsoft Excel® (Microsoft Office Professional Plus, 2013). Sociodemographics, motivation, and knowledge were analyzed using simple descriptive statistics to report percentages, means, and standard deviations. Differences between dietary styles were tested using the Kruskal–Wallis rank test and chi-square for percentages and mean values. When differences existed, they were determined using Bonferroni correction two-sample test. Analysis of variance (ANOVA) was performed in SPSS® for all RATA questions as well as for the hedonic question on overall liking on the 9-point scale; these were subdivided by dietary styles (i.e., omnivore, flexitarian, vegetarian, vegan). Fisher's Least Signifi-cant Difference (LSD) multiple comparison test with α = 0.05 was used for mean com-parisons. A p-value < 0.05 indicated statistical significance.

3. Results

3.1 Study Characteristics

The characteristics of the study sample are shown in Table 1, further classified by dietary styles. Of 159 participants, about 70% were female, and almost 54% were 18–24-years-old, thus belonging to Generation Z [63]. Although the mean age of the respondents was 30.1 years (Generation Y), there were significant differences between the nutrition styles. Omnivore participants were on average older, 33.0 years, than vegetarians at 26.4 years, and vegans at 25.8 years. The above-average education is also an indicator that this study took place at a university, so 50.0% of the omnivores indicated having completed their university study. The BMI results should provide an indicator of the participants' health status; these data are based on self-reporting. Nutritional status is based on WHO criteria, with a BMI 18.5–24.9 indicating a normal weight. Overweight is defined as having a BMI of 25 or more, and obesity is defined as having a BMI of 30 or more. With a BMI of 22.6, this cohort was within the normal weight range. With a BMI of 23.9, the omnivores had a significantly higher BMI than the vegetarians with 22.1 and vegans with 22.0. The high percentage (11.8%) of underweight vegans should be noted.

3.2 Sensory Consumer Profiling and Overall Liking

The sensory profiles of the three plant-based alternative products differed in scoring before and after the information treatment in the form of the questionnaire (Table 2–4). The attributes the participants were able to select for the products can be found in the Supplementary Materials (Table S1). The frequency of selection of sensory terms varied according to the nutrition styles. Significant differences were found between different sensory modalities for the oat drink: appearance ("beige" and "viscous"), odor ("cereal"), taste ("nutty" and "sweet"), and texture ("viscous" and "oily"); for plant-based cheese: appearance ("yellow"), odor ("cheesy," "nutty" and "brothy" and taste ("milky" and "umami"); for plant-based salami: taste ("meaty" and "sweet").

The oat milk data show the most significant differences between dietary groups, but they were not present in both sessions (Table 2). Thus, for the attribute "viscous appearance" and "viscous texture," significant differences could be found in the second session; as the omnivores voted this the lowest in the first session, only tendencies can be shown for this. However, it is noticeable for this product that the attributes "bitter taste" and "sour taste" were not used by the vegans in the first and second rounds.

For the plant-based cheese, the "cheese smell" was perceived at a significantly higher rate by the flexitarians; for the "cheese taste," there was a tendency, and this was true for both sessions (Table 3). On the other hand, the "broth odor" was rated significantly lower by the omnivores in the first sitting. In the second sitting, there was also a tendency. Analogously, the attribute "umami taste" was perceived at a significantly lower rate by the omnivores in both sittings.

In the case of the plant-based salami, there were only two significant differences; the "meat taste" was rated lowest by the omnivores in the first session, and there was also a trend in the second session for the attribute "meat smell," which was also rated lowest by the omnivores (Table 4).

Significant differences were found in consumers' overall liking of the products in the dietary forms and in the two sessions, except in the second round for the plant-based salami product (Table 5). In general, it is noticeable that the products were rated relatively high on the nine-point scale. The plant-based salami never received the lowest rating from the omnivores, with a mean of 5.24 and 5.52. The other products were also generally rated lower by the omnivores than by the representatives of the other diet styles. Vegans rated the oat drink and the plant-based cheese the highest.

Table 2. RATA attribute evaluation of plant-based oat drink in two sessions on a 5-point scale, with different shares of 159 participants. Significant differences could be calculated for the attributes in **bold**.

		1st Session				2nd Session			
Attribute *		**Omnivore**	**Flexitarian**	**Vegetarian**	**Vegan**	**Omnivore**	**Flexitarian**	**Vegetarian**	**Vegan**
Beige_A	N (% of total)	32 (20.8)	63 (40.9)	44 (28.6)	15 (9.7)	32 (20.8)	64 (41.6)	43 (27.9)	15 (9.7)
	Mean (95% CI)	4.41 (4.08–4.73) ^{b}	4.21 (3.98–4.44) ^{ab}	3.93 (3.64–4.22) ^{a}	4.20 (3.77–4.63) ^{ab}	4.28 (3.95–4.61)	4.13 (3.88–4.37)	4.23 (4.01–4.45)	4.00 (3.49–4.51)
Grey_A	N (% of total)	7 (29.2)	10 (41.7)	6 (25.0)	1 (4.2)	10 (32.3)	12 (38.7)	9 (29.0)	0
	Mean (95% CI)	2.00 (1.08–2.92)	3.20 (2.32–4.08)	3.00 (1.01–4.99)	4.00	2.50 (1.53–3.47)	2.83 (1.79–3.88)	3.00 (1.85–4.15)	
Viscous_A	N (% of total)	13 (17.1)	32 (42.1)	25 (32.9)	6 (7.9)	12 (15.6)	31 (40.3)	29 (37.7)	5 (6.5)
	Mean (95% CI)	3.31 (2.59–4.02)	3.41 (3.00–3.81)	3.48 (2.97–3.99)	3.83 (2.80–4.87)	2.33 (1.65–3.02) ^{a}	3.26 (2.78–3.73) ^{b}	3.17 (2.68–3.66) ^{ab}	3.60 (2.49–4.71) ^{ab}
Cereal_O	N (% of total)	13 (13.8)	43 (45.7)	27 (28.7)	11 (11.7)	17 (16.8)	42 (41.6)	32 (31.7)	10 (9.9)
	Mean (95% CI)	3.23 (2.44–4.02) ^{a}	3.81 (3.44–4.19) ^{ab}	4.00 (3.69–4.31) ^{b}	3.73 (3.05–4.41) ^{ab}	3.47 (2.76–4.18)	3.98 (3.66–4.30)	3.91 (3.50–4.31)	3.60 (2.76–4.44)
Milky_O	N (% of total)	11 (19.6)	25 (44.6)	19 (33.9)	1 (1.8)	10 (20.0)	23 (46.0)	14 (28.0)	3 (6.0)
	Mean (95% CI)	3.45 (2.76–4.15)	3.48 (3.07–3.89)	3.42 (2.91–3.94)	5.00	2.60 (1.83–3.37)	3.39 (2.84–3.94)	3.14 (2.51–3.78)	4.00
Nutty_O	N (% of total)	14 (19.7)	30 (42.3)	19 (26.8)	8 (11.3)	13 (19.1)	30 (44.1)	22 (32.4)	3 (4.4)
	Mean (95% CI)	3.50 (2.79–4.21)	3.43 (3.02–3.85)	3.63 (3.14–4.12)	4.13 (3.59–4.66)	3.46 (2.78–4.14)	3.10 (2.63–3.57)	3.68 (3.29–4.08)	3.33 (0.46–6.20)
Bitter_T	N (% of total)	6 (31.6)	7 (36.8)	6 (31.6)	0	4 (12.1)	15 (45.5)	14 (42.4)	0
	Mean (95% CI)	1.67 (1.12–2.21)	4.14 (3.79–4.49)	2.67 (0.95–4.38)		3.75 (1.75–5.75)	2.93 (2.22–3.64)	3.43 (2.65–4.20)	
Cereal_T	N (% of total)	27 (18.2)	62 (41.9)	44 (29.7)	15 (10.1)	29 (19.1)	64 (42.1)	42 (27.6)	17 (11.2)
	Mean (95% CI)	4.26 (3.90–4.62)	4.29 (4.07–4.51)	4.20 (3.94–4.47)	4.33 (4.06–4.60)	4.31 (3.93–4.69)	4.31 (4.10–4.53)	4.36 (4.12–4.59)	4.06 (3.67–4.44)
Nutty_T	N (% of total)	26 (22.4)	49 (42.2)	34 (29.3)	7 (6.0)	25 (23.4)	44 (41.1)	30 (28.0)	8 (7.5)
	Mean (95% CI)	3.27 (2.73–3.81) ^{a}	3.84 (3.57–4.10) ^{b}	3.88 (3.54–4.22) ^{b}	3.86 (3.03–4.69) ^{ab}	3.72 (3.17–4.27)	3.57 (3.24–3.90)	3.60 (3.23–3.97)	3.75 (3.16–4.34)
Sour_T	N (% of total)	2 (14.3)	5 (35.7)	7 (50.0)	0	6 (26.1)	7 (30.4)	10 (43.5)	0
	Mean (95% CI)	2.50 (1.96–2.65)	3.00 (1.24–4.76)	3.71 (2.55–4.87)		2.83 (1.44–4.23)	3.29 (2.13–4.45)	3.20 (2.09–4.31)	
Sweet_T	N (% of total)	26 (19.3)	54 (40.0)	39 (28.9)	16 (11.9)	27 (18.6)	61 (42.1)	40 (27.6)	17 (11.7)
	Mean (95% CI)	3.85 (3.38–4.31)	3.83 (3.60–4.07)	3.82 (3.51–4.13)	4.06 (3.57–4.56)	3.41 (2.94–3.88) ^{a}	3.80 (3.56–4.05) ^{ab}	3.90 (3.60–4.20) ^{b}	4.24 (3.95–4.52) ^{b}
Astringent_TX	N (% of total)	9 (26.5)	14 (41.2)	10 (29.4)	1 (2.9)	12 (29.3)	17 (41.5)	12 (29.3)	0
	Mean (95% CI)	2.89 (1.91–3.86)	2.93 (2.13–3.73)	3.40 (2.50–4.30)	4.00	2.67 (1.84–3.49)	2.47 (1.81–3.13)	3.50 (2.62–4.38)	
Viscous_TX	N (% of total)	11 (22.0)	18 (36.0)	16 (32.0)	5 (10.0)	9 (18.8)	23 (47.9)	11 (22.9)	5 (10.4)
	Mean (95% CI)	3.00 (2.40–3.60)	3.00 (2.39–3.61)	3.38 (2.73–4.02)	3.20 (1.84–4.56)	2.67 (1.90–3.44) ^{a}	2.70 (2.24–3.16) ^{a}	3.91 (3.44–4.38) ^{b}	3.20 (1.58–4.82) ^{ab}
Oily_TX	N (% of total)	11 (17.7)	27 (43.5)	20 (32.3)	4 (6.5)	13 (18.3)	27 (38.0)	23 (32.4)	8 (11.3)
	Mean (95% CI)	3.18 (2.24–4.12)	3.15 (2.65–3.65)	3.15 (2.69–3.61)	3.50 (0.74–6.26)	2.54 (1.73–3.34) ^{a}	3.33 (2.89–3.77) ^{ab}	3.61 (3.11–4.11) ^{b}	3.50 (2.41–4.59) ^{ab}

[*] _A = appearance, _O = odor, _T = taste, _TX = texture; $^{a, b}$ significance according to Fisher's LSD $\alpha = 0.05$

Table 3. RATA attribute assessment of plant-based cheese in two sessions on a 5-point scale, with different shares of 159 participants. Significant differences could be calculated for the attributes in **bold**.

		1st Session				2nd Session			
Attribute *		**Omnivore**	**Flexitarian**	**Vegetarian**	**Vegan**	**Omnivore**	**Flexitarian**	**Vegetarian**	**Vegan**
Yellow_A	N (% of total)	33 (20.9)	64 (40.5)	44 (27.8)	17 (10.8)	33 (20.8)	65 (40.9)	44 (27.7)	17 (10.7)
	Mean (95% CI)	4.85 (4.72–4.98)	4.89 (4.81–4.97)	4.77 (4.64–4.90)	4.94 (4.82–5.07)	4.79 (4.64 -4.94) ^{ab}	4.88 (4.79–4.96) ^{b}	4.77 (4.64–4.90) ^{ab}	4.65 (4.39–4.90) ^{a}
Glossy_A	N (% of total)	3 (18.8)	8 (50.0)	4 (25.0)	1 (6.3)	8 (32.0)	8 (32.0)	7 (28.0)	2 (8.0)
	Mean (95% CI)	3.67 (1.24–7.46)	3.38 (2.20–4.55)	3.50 (1.74–6.26)	3.00	2.13 (1.08–3.17)	2.75 (1.28–4.22)	3.14 (1.69–4.60)	4.50 (0.85–5.85)
Cheesy_O	N (% of total)	33 (21.6)	60 (39.2)	43 (28.1)	17 (11.1)	32 (21.2)	60 (39.7)	42 (27.8)	17 (11.3)
	Mean (95% CI)	4.27 (3.86–4.68) ^{a}	4.67 (4.46–4.88) ^{b}	4.51 (4.27–4.76) ^{ab}	4.59 (4.33–4.85) ^{ab}	4.28 (3.96–4.60) ^{ab}	4.62 (4.45–4.78) ^{b}	4.52 (4.31–4.73) ^{ab}	4.12 (3.52–4.72) ^{a}
Nutty_O	N (% of total)	15 (22.4)	26 (38.8)	17 (25.4)	9 (13.4)	16 (21.9)	25 (34.2)	24 (32.9)	8 (11.0)
	Mean (95% CI)	3.27 (2.50–4.03)	3.35 (2.88–3.82)	3.53 (3.04–4.01)	3.22 (2.08–4.36)	2.56 (1.89–3.24) ^{a}	3.60 (3.14–4.06) ^{b}	3.71 (3.27–4.15) ^{b}	3.50 (2.73–4.27) ^{ab}
Sour_O	N (% of total)	21 (23.1)	40 (44.0)	24 (26.4)	6 (6.6)	21 (20.8)	40 (39.6)	30 (29.7)	10 (9.9)
	Mean (95% CI)	3.43 (2.94–3.92)	3.40 (3.03–3.77)	3.25 (2.78–3.72)	3.83 (2.80–4.87)	3.19 (2.62–3.76)	3.58 (3.22–3.93)	3.17 (2.65–3.69)	3.20 (2.26–4.14)
Brothy_O	N (% of total)	23 (18.3)	50 (39.7)	38 (30.2)	15 (11.9)	21 (17.1)	46 (37.4)	41 (33.3)	15 (12.2)
	Mean (95% CI)	3.52 (3.02–4.02) ^{a}	3.76 (3.46–4.06) ^{ab}	3.84 (3.53–4.15) ^{ab}	4.27 (3.88–4.66) ^{b}	3.86 (3.37–4.34)	3.89 (3.51–4.27)	4.05 (3.78–4.32)	4.33 (4.06–4.60)
Cereal_O	N (% of total)	7 (25.9)	11 (40.7)	8 (29.6)	1 (3.7)	9 (26.5)	13 (38.2)	8 (23.5)	4 (11.8)
	Mean (95% CI)	3.86 (3.03–4.69)	2.73 (1.87–3.58)	3.63 (2.74–4.51)	4.00	1.89 (0.91–2.86)	2.46 (1.62–3.30)	2.88 (1.83–3.92)	2.75 (0.36–5.14)
Cheesy_T	N (% of total)	27 (19.4)	58 (41.7)	38 (27.3)	16 (11.5)	29 (19.7)	61 (41.5)	41 (27.9)	16 (10.9)
	Mean (95% CI)	4.26 (3.94–4.58)	4.33 (4.13–4.52)	4.18 (3.94–4.42)	4.25 (3.94–4.56)	4.00 (3.66–4.34)	4.33 (4.13–4.53)	4.24 (3.95–4.53)	3.94 (3.37–4.50)
Milky_T	N (% of total)	17 (21.5)	30 (38.0)	25 (31.6)	7 (8.9)	20 (22.2)	32 (35.6)	34 (37.8)	4 (4.4)
	Mean (95% CI)	3.65 (3.29–4.01)	3.60 (3.25–3.95)	3.60 (3.14–4.06)	3.43 (2.38–4.48)	3.10 (2.53–3.67) ^{a}	3.66 (3.36–3.95) ^{b}	3.56 (3.30–3.82) ^{ab}	3.75 (1.75–5.75) ^{ab}
Salty_T	N (% of total)	27 (18.9)	59 (41.3)	44 (30.8)	13 (9.1)	26 (17.9)	60 (41.4)	42 (29.0)	17 (11.7)
	Mean (95% CI)	4.07 (3.64–4.51)	3.93 (3.65–4.21)	4.05 (3.72–4.37)	4.00 (3.51–4.49)	4.12 (3.73–4.50)	4.08 (3.83–4.33)	3.93 (3.59–4.27)	3.88 (3.41–4.36)
Sweet_T	N (% of total)	6 (20.7)	13 (44.8)	9 (31.0)	1 (3.4)	10 (34.5)	11 (37.9)	6 (20.7)	2 (6.9)
	Mean (95% CI)	3.67 (2.81–4.52)	2.62 (1.74–3.49)	3.11 (1.99–4.23)	4.00	2.80 (1.86–3.74)	2.73 (1.99–3.47)	3.50 (2.62–4.38)	3.00 (1.71–5.17)
Umami_T	N (% of total)	26 (17.8)	60 (41.1)	43 (29.5)	17 (11.6)	25 (17.5)	60 (42.0)	41 (28.7)	17 (11.9)
	Mean (95% CI)	3.96 (3.56–4.37) ^{a}	4.12 (3.93–4.30) ^{ab}	4.26 (4.01–4.50) ^{ab}	4.47 (4.15–4.79) ^{b}	3.84 (3.45–4.23) ^{a}	4.08 (3.85–4.31) ^{ab}	4.37 (4.17–4.56) ^{b}	4.29 (3.79–4.80) ^{ab}
Creamy_TX	N (% of total)	30 (20.4)	63 (42.9)	37 (25.2)	17 (11.6)	27 (18.8)	61 (42.4)	40 (27.8)	16 (11.1)
	Mean (95% CI)	4.07 (3.70–4.43)	4.05 (3.78–4.31)	4.14 (3.82–4.45)	4.00 (3.55–4.45)	3.70 (3.25–4.15)	3.98 (3.73–4.24)	4.15 (3.91–4.39)	3.81 (3.16–4.46)
Juicy_TX	N (% of total)	23 (20.0)	48 (41.7)	29 (25.2)	15 (13.0)	22 (19.5)	49 (43.4)	30 (26.5)	12 (10.6)
	Mean (95% CI)	3.65 (3.17–4.13)	3.79 (3.47–4.11)	3.93 (3.59–4.27)	4.20 (3.89–4.51)	3.55 (3.00–4.09)	3.67 (3.31–4.03)	3.83 (3.51–4.16)	3.83 (3.38–4.29)
Sticky_TX	N (% of total)	14 (35.9)	16 (41.0)	7 (17.9)	2 (5.1)	14 (30.4)	19 (41.3)	9 (19.6)	4 (8.7)
	Mean (95% CI)	2.86 (2.05–3.67)	3.25 (2.54–3.96)	3.29 (2.13–4.45)	2.50 (1.56–3.15)	2.36 (1.55–3.16)	3.05 (2.49–3.62)	2.89 (1.99–3.79)	3.00 (1.16–4.84)

[*] _A = appearance, _O = odor, _T = taste, _TX = texture; $^{a, b}$ significance according to Fisher's LSD $\alpha = 0.05$.

Table 4. RATA attribute evaluation of plant-based salami in two sessions on a 5-point scale, with different shares of 159 participants. Significant differences could be calculated for the attributes in **bold**, without the vegan nutrition style.

		1st Session			2nd Session		
Attribute *		**Omnivore**	**Flexitarian**	**Vegetarian**	**Omnivore**	**Flexitarian**	**Vegetarian**
Red_A	N (% of total)	33 (23.6)	64 (45.7)	43 (30.7)	32 (23.0)	64 (46.0)	43 (30.9)
	Mean (95% CI)	4.36 (3.99–4.74)	4.50 (4.29–4.71)	4.53 (4.33–4.74)	4.28 (3.86–4.70)	4.42 (4.20–4.64)	4.65 (4.49–4.81)
Glossy_A	N (% of total)	13 (21.7)	29 (48.3)	18 (30.0)	13 (21.7)	26 (43.3)	21 (35.0)
	Mean (95% CI)	3.15 (2.27–4.04)	3.72 (3.37–4.07)	3.44 (2.87–4.02)	3.15 (2.24–4.07)	3.23 (2.81–3.65)	3.14 (2.64–3.65)
Brothy_O	N (% of total)	29 (21.6)	63 (47.0)	42 (31.3)	30 (22.1)	63 (46.3)	43 (31.6)
	Mean (95% CI)	4.52 (4.20–4.83)	4.65 (4.50–4.80)	4.67 (4.48–4.86)	4.40 (4.05–4.75)	4.59 (4.41–4.76)	4.53 (4.34–4.73)
Meaty_O	N (% of total)	32 (23.5)	62 (45.6)	42 (30.9)	30 (22.7)	61 (46.2)	41 (31.1)
	Mean (95% CI)	4.28 (3.94–4.63)	4.53 (4.31–4.75)	4.62 (4.42–4.81)	4.07 (3.66–4.47)	4.26 (4.03–4.49)	4.46 (4.25–4.68)
Cereal_O	N (% of total)	6 (27.3)	8 (36.4)	8 (36.4)	6 (33.3)	8 (44.4)	4 (22.2)
	Mean (95% CI)	2.17 (0.94–3.39)	3.00 (1.66–4.34)	2.88 (1.36–4.39)	2.67 (1.09–4.25)	1.88 (1.34–2.41)	3.25 (0.86–5.64)
Paprika_O	N (% of total)	17 (21.5)	36 (45.6)	26 (32.9)	19 (24.4)	35 (44.9)	24 (30.8)
	Mean (95% CI)	2.88 (2.16–3.61)	3.19 (2.75–3.64)	3.15 (2.72–3.59)	3.47 (2.91–4.04)	3.57 (3.24–3.91)	3.38 (2.85–3.90)
Meaty_T	N (% of total)	25 (21.4)	56 (47.9)	36 (30.8)	25 (20.5)	57 (46.7)	40 (32.8)
	Mean (95% CI)	3.44 (2.92–3.96) [a]	3.89 (3.60–4.18) [ab]	4.22 (3.94–4.50) [b]	3.84 (3.40–4.28)	3.86 (3.59–4.13)	4.13 (3.83–4.42)
Cereal_T	N (% of total)	9 (25.7)	16 (45.7)	10 (28.6)	9 (31.0)	13 (44.8)	7 (24.1)
	Mean (95% CI)	3.22 (2.22–4.22)	2.75 (2.04–3.46)	2.80 (1.69–3.91)	2.78 (1.94–3.62)	2.69 (1.90–3.49)	3.29 (2.01–4.56)
Pepper_T	N (% of total)	23 (19.8)	55 (47.4)	38 (32.8)	22 (18.3)	56 (46.7)	42 (35.0)
	Mean (95% CI)	3.83 (3.36–4.29)	3.87 (3.58–4.16)	4.08 (3.79–4.37)	3.41 (2.89–3.93)	3.91 (3.67–4.15)	3.88 (3.53–4.23)
Salty_T	N (% of total)	27 (20.8)	61 (36.9)	42 (32.3)	26 (20.3)	61 (47.7)	41 (32.0)
	Mean (95% CI)	3.96 (3.58–4.35)	3.95 (3.71–4.19)	4.21 (3.96–4.47)	3.92 (3.50–4.35)	4.15 (3.94–4.35)	4.12 (3.88–4.37)
Sweet_T	N (% of total)	8 (28.6)	12 (42.9)	8 (28.6)	7 (26.9)	15 (57.7)	4 (15.4)
	Mean (95% CI)	3.13 (2.08–4.17)	2.83 (1.90–3.77)	2.75 (1.35–4.15)	3.71 (3.02–4.41) [b]	2.53 (1.78–3.28) [a]	2.50 (0.45–4.55) [ab]
Umami_T	N (% of total)	25 (19.7)	61 (48.0)	41 (32.3)	27 (21.4)	57 (45.2)	42 (33.3)
	Mean (95% CI)	4.16 (3.70–4.62)	4.28 (4.02–4.54)	4.29 (4.05–4.54)	4.22 (3.87–4.57)	4.21 (3.97–4.45)	4.21 (3.98–4.45)
Firm_TX	N (% of total)	16 (17.6)	44 (48.4)	31 (34.1)	20 (20.0)	49 (49.0)	31 (31.0)
	Mean (95% CI)	3.56 (2.89–4.24)	3.34 (3.00–3.68)	3.58 (3.24–3.92)	3.65 (3.02–4.28)	3.29 (2.94–3.63)	3.39 (2.95–3.83)
Juicy_TX	N (% of total)	23 (21.5)	51 (47.7)	33 (30.8)	22 (20.8)	49 (46.2)	35 (33.0)
	Mean (95% CI)	3.52 (3.09–3.95)	3.63 (3.31–3.95)	3.48 (3.14–3.83)	3.55 (3.06–4.03)	3.43 (3.11–3.74)	3.57 (3.22–3.93)
Gummy_TX	N (% of total)	22 (26.5)	37 (44.6)	24 (28.9)	20 (28.2)	29 (40.8)	22 (31.0)
	Mean (95% CI)	3.68 (3.16–4.20)	3.19 (2.79–3.59)	3.17 (2.55–3.79)	3.05 (2.43–3.67)	3.28 (2.78–3.77)	3.18 (2.59–3.77)

[*] _A = appearance, _O = odor, _T = taste, _TX = texture; [a, b] significance according to Fisher's LSD $\alpha = 0.05$.

Table 5. Attribute overall liking for the plant-based alternative products in two sessions. Mean values of the 9-point hedonic scale with 95% confidence intervals and significance variances.

Nutrition Style	Attribute "Likes Very Much" and "Likes Extremely"	N	Oat Drink Mean (95% CI) and Significance		Cheese Mean (95% CI) and Significance		Salami Mean (95% CI) and Significance	
			1st	2nd	1st	2nd	1st	2nd
Omnivore		36	6.48 (5.92–7.05) [a]	6.45 (5.91–7.00) [a]	6.58 (5.90–7.25) [a]	6.73 (6.14–7.31) [a]	5.24 (4.42–6.06) [a]	5.52 (4.70–6.33) [ns]
	% within nutrition style		33.3	27.2	42.4	27.3	18.2	21.2
Flexitarian		62	7.05 (6.71–7.39) [a]	7.11 (6.73–7.48) [ab]	6.97 (6.58–7.35) [a]	6.88 (6.42–7.33) [a]	6.40 (5.93–6.87) [a]	6.26 (5.77–6.75) [ns]
	% within nutrition style		41.5	47.7	44.6	46.1	30.8	26.2
Vegetarian		44	7.27 (6.96–7.59) [a]	7.02 (6.62–7.42) [ab]	6.70 (6.10–7.31) [a]	6.70 (6.06–7.35) [a]	6.27 (5.68–6.86) [b]	6.32 (5.78–6.86) [ns]
	% within nutrition style		52.3	40.9	45.4	47.7	31.8	22.7
Vegan		17	8.06 (7.77–8.34) [b]	7.82 (7.37–8.28) [b]	8.18 (7.85–8.50) [b]	8.06 (7.72–8.40) [b]		
	% within nutrition style		88.2	76.4	88.2	82.3		

[a, b] Significance according to Fisher's LSD α = 0.05, [ns] not significance.

3.3 Characterization of Plant-Based Product Consumption by Participants

Table 6 displays the frequency of consumption of plant-based alternative products. Regarding PBMAs, only 3.8% of participants reported never consuming such products. On average, they were consumed predominantly on a monthly basis (i.e., more than once a month but less than once a week). PBCAs were more likely to be consumed occasionally. A total of 49.1% of participants reported consuming them less than once a month or less than once a week, and 28.3% had tried these products once. PBMiAs were most frequently used along with the plant-based products in this study. They were consumed daily by about 13.8% of the participants, while 44% reported consuming them at least once a week.

There were significant differences in the consumption of plant-based alternative products between dietary styles (Table 6). Omnivore participants infrequently (i.e., less than once a month) or never ate PBMAs at a rate of 66.7%, PBCAs at 87.9%, and PBMiAs at 84.8%. Vegetarians and vegans had a significantly higher intake of alternative products compared to omnivores; vegans had a significantly higher intake than flexitarians and vegetarians. A total of 47.1% of vegans used PBMAs daily, and 58.8% consumed PBMiAs five times a week or more.

PBMAs with 95% (Figure 1C) and PBMiAs with 91% (Figure 1A) were the most known product groups among the respondents, so they could indicate from which raw materials these products are made. Soy, cereals, and legumes were the most mentioned sources for PBMAs, followed by nuts, seeds, and wheat (gluten). For PBMiAs, soy, oats, and almonds were the main raw material sources of products purchased and consumed by participants, at over 80%. Rice followed in fourth place with 55.2%, the product group with the lowest allergenic potential for consumers. For PBCAs, over 30.6% of consumers did not know the source of the raw materials used in the products. At about 56%, almonds were the raw materials most frequently present in the products. Figure 1B shows again that PBCAs currently still have the lowest level of awareness among consumers in the large market of plant-based alternative products.

Table 6. Frequency of consumption (%) of PBMAs (plant-based meat alternatives), PBCAs (plant-based cheese alternatives), and PBMiAs (plant-based milk alternatives) of all participants and by diet.

		All n = 159	**Omnivore** *n* = 36	**Flexitarian** *n* = 62	**Vegetarian** *n* = 44	**Vegan** *n* = 17	***p*-Value**
PBMAs	never	3.8	6.1	6.2	0.0	0.0	
	<1x per month	31.4	60.6	33.8	13.6	11.8	<0.001 [1]
	>1x per month, <1x per week	27.0	21.2	27.7	34.1	17.6	
	1–2x per week	14.5	12.1	15.4	18.2	5.9	
	3–4x per week	9.4	0.0	7.7	18.2	11.8	
	≥5x per week	5.0	0.0	4.6	9.1	5.9	
	daily	8.8	0.0	4.6	6.8	47.1	<0.001 [1]
PBMAs [3]	Mean (SD)	3.45 (1.63)	2.39 (0.79) [a]	3.17 (1.49) [a]	3.95 (1.47) [b]	5.24 (1.99) [c]	<0.001 [2]
PBCAs	never	22.0	51.5	24.6	4.5	0.0	<0.001 [1]
	<1x per month	49.1	36.4	55.4	59.1	23.5	0.025 [1]
	>1x per month, <1x per week	12.6	9.1	9.2	18.2	17.6	
	1–2x per week	7.5	3.0	4.6	4.5	35.3	<0.001 [1]
	3–4x per week	4.4	0.0	4.6	4.5	11.8	
	≥5x per week	1.3	0.0	0.0	2.3	5.9	
	daily	3.1	0.0	1.5	6.8	5.9	
PBCAs [3]	Mean (SD)	2.40 (1.37)	1.64 (0.78) [a]	2.15 (1.15) [ab]	2.80 (1.52) [b]	3.76 (1.44) [c]	<0.001 [2]
PBMiAs	never	8.8	21.2	10.8	0.0	0.0	0.006 [1]
	<1x per month	29.6	42.4	30.8	27.3	5.9	

	>1x per month, <1x per week	17.6	12.1	21.5	20.5	5.9	
	1–2x per week	10.1	12.1	9.2	9.1	11.8	
	3–4x per week	11.3	6.1	6.2	20.5	17.6	
	≥5x per week	8.8	3.0	7.7	9.1	23.5	
	daily	13.8	3.0	13.8	13.6	35.3	0.020 [1]
PBMiAs [3]	Mean (SD)	3.67 (1.94)	2.61 (1.52) [a]	3.48 (1.95) [ab]	4.05 (1.78) [b]	5.53 (1.55) [c]	<0.001 [2]

[a,b] Values with the same superscript letter indicate statistically significant differences between nutritional styles based on the Kruskal–Wallis rank test, and when differences existed, they were determined using the Bonferroni correction two-sample test, $p < 0.05$. [1] Pearson chi-square. [2] Kruskal–Wallis rank test. [3] Measured on a 7-point scale from "never" (1) to "daily" (7).

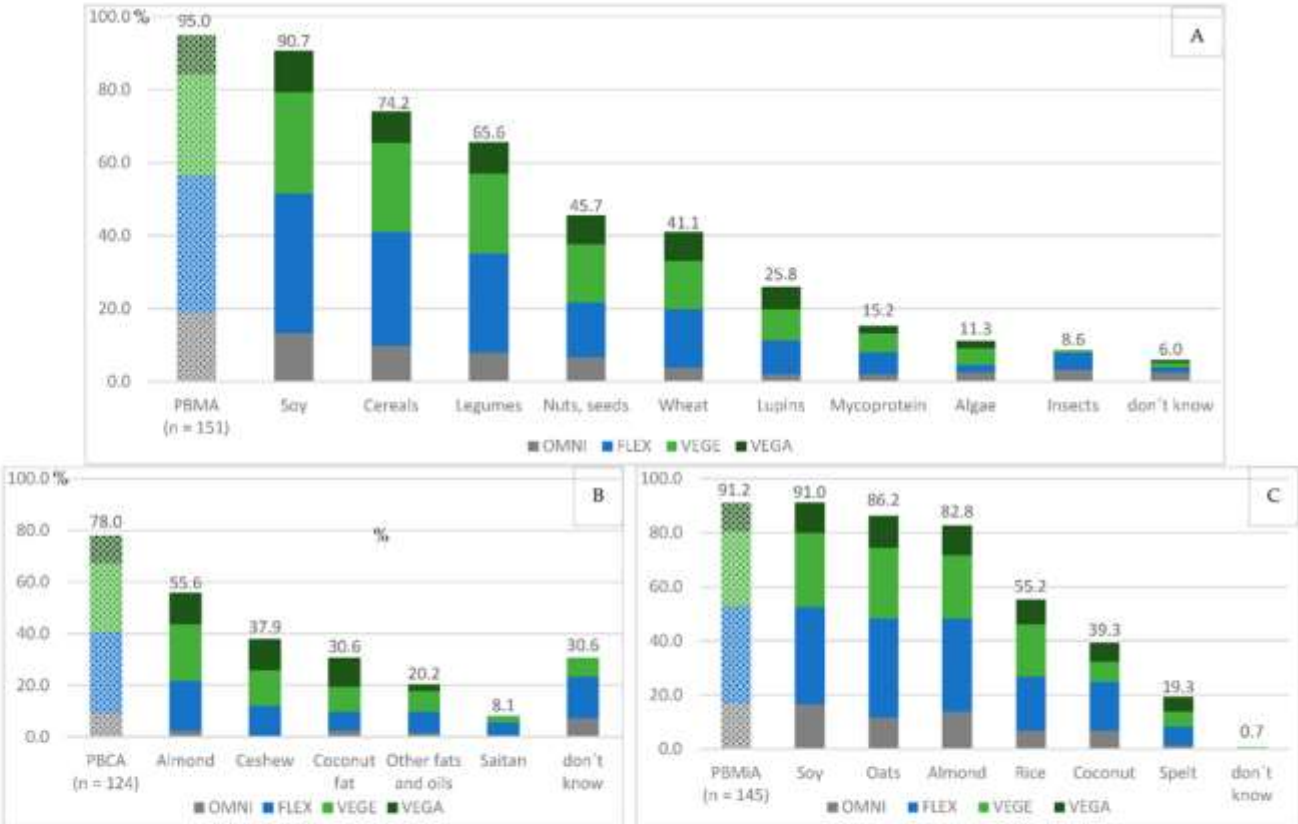

Figure 1. Percentage representation of the basis of the different plant-based alternative products, (A) = PBMA (plant-based meat alternative), (B) = PBCA (plant-based cheese alternative), (C) = PBMiA (plant-based milk alternative); patterned bars represent the total value related to the response of the participants, blank bars relate to the food or raw material basis of the products, with multiple mentions resulting in different percentages. Abbreviations of the nutrition styles: OMNI = om-nivore, FLEX = flexitarian, VEGE = vegetarian, VEGA = vegan.

3.4 Motives for Consuming Plant-Based Alternative Products

Table 7 shows that overall, for PBMAs, the strongest motives for consumption were animal welfare, followed by the environment and health. This was followed by the curiosity of the participants to try new foods and the interest aroused by design and advertising (see Appendix A Table A1 for items). Sensory appeal and convenience were rated rather neutrally overall, with an average scale score of around 3.0, while the social environment was not really decisive for consumption. There were significant differences between the dietary styles with regard to animal welfare, the environment, and social environment. Overall, vegans and, to some extent, vegetarians, had a significantly greater agreement with the motivation items than omnivores. For vegans in particular, animal welfare was a strong motive.

With regard to PBCAs, animal welfare and the environment were also strong motives for consumption (Table 8). However, the product lifestyle was also rated with a higher agreement here. Health and sensory characteristics were rated rather neutrally, while the social environment received little approval as a motive. However, there were significant differences regarding the latter as well as with regard to animal welfare and the environment. Vegans showed significantly higher agreement than those with meat-based eating styles and, in part, also vegetarians.

Additionally, with regard to PBMiAs, the strongest motives for consumption were animal welfare and the environment (Table 9). However, sensory properties also moderately motivated consumption as well as the product design, curiosity, and advertising for PBMiAs. Health slightly motivated the consumption, while the social environment was less decisive for consumption. Differences between the dietary styles occurred in relation to animal welfare, the environment, health, and the social environment, whereby vegans and vegetarians showed a higher approval than omnivores and flexitarians.

Table 7. Motives for purchasing PBMAs [1] by diet measured on a 5-point-scale (1 "totally disagree", 5 "totally agree").

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	***p*-Value**
Animal Welfare	148	4.41 (1.00)	30	4.00 (1.26)^{a}	57	4.37 (0.94)^{ab}	44	4.50 (0.95)^{ab}	17	5.00 (-)^{b}	0.008
Environment	145	3.78 (1.18)	28	2.93 (1.33)^{a}	56	3.91 (0.98)^{b}	44	4.02 (1.07)^{b}	17	4.12 (1.22)^{b}	<0.001
Health	149	3.63 (1.00)	30	3.33 (1.03)	58	3.72 (1.01)	44	3.66 (0.99)	17	3.76 (0.97)	0.325
Product Lifestyle	149	3.46 (0.92)	30	3.43 (0.90)	58	3.34 (0.98)	44	3.52 (0.79)	17	3.71 (1.05)	0.506
Convenience	145	3.05 (1.19)	28	2.39 (1.31)^{a}	58	3.07 (1.30)^{ab}	44	3.25 (0.97)^{b}	17	3.18 (0.88)^{ab}	0.020
Sensory appeal	147	3.01 (1.20)	28	2.43 (1.29)^{a}	56	3.04 (1.18)^{ab}	44	3.25 (1.10)^{b}	17	3.59 (0.94)^{b}	0.005
Social setting	146	2.35 (1.54)	30	2.03 (1.63)	57	2.26 (1.43)	42	2.33 (1.48)	17	3.24 (1.68)	0.068

[1] plant-based meat alternative, ^{a,b} different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$). Deviation in N due to the answer option "I don't know".

Table 8. Motives for purchasing PBCAs [1] by diet measured on a 5-point-scale (1 "totally disagree", 5 "totally agree").

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	***p*-value**
Animal Welfare	122	4.30 (1.13)	16	3.69 (1.66)^{a}	47	4.06 (1.13)^{a}	42	4.52 (0.92)^{ab}	17	5.00 (-)^{b}	0.001
Environment	122	4.11 (1.10)	16	3.56 (1.59)	47	4.21 (1.00)	42	4.12 (0.99)	17	4.29 (0.99)	0.181
Product Lifestyle	122	3.39 (0.91)	16	3.56 (0.98)	47	3.28 (0.93)	42	3.31 (0.84)	17	3.71 (1.05)	0.304
Health	121	3.01 (0.95)	15	2.80 (1.21)^{ab}	47	2.79 (0.83)^{a}	42	3.12 (0.86)^{ab}	17	3.53 (1.07)^{b}	0.029
Sensory appeal	122	2.97 (1.27)	16	2.31 (1.08)^{a}	47	2.89 (1.37)^{a}	42	2.90 (1.14)^{a}	17	3.94 (0.90)^{b}	0.002
Social setting	122	1.67 (1.26)	16	1.56 (1.37)^{a}	47	1.49 (1.08)^{a}	42	1.50 (1.02)^{a}	17	2.71 (1.69)^{b}	0.003

[1] plant-based cheese alternative, ^{a,b} different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$). Deviation in N due to the answer option "I don't know".

Table 9. Motives for purchasing PBMiAs [1] by diet measured on a 5-point-scale (1 "totally disagree", 5 "totally agree").

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	**N**	**Mean (SD)**	***p*-Value**
Animal Welfare	143	4.31 (1.08)	26	4.00 (1.36)^{a}	56	4.13 (1.13)^{a}	44	4.50 (0.90)^{ab}	17	4.94 (0.24)^{b}	0.010
Environment	143	4.18 (1.11)	26	3.50 (1.53)^{a}	56	4.05 (1.03)^{ab}	44	4.57 (0.73)^{b}	17	4.65 (0.79)^{b}	<0.001
Sensory appeal	143	3.66 (0.29)	26	3.35 (1.47)	56	3.71 (1.32)	44	3.52 (1.19)	17	4.35 (1.00)	0.070
Product Lifestyle	143	3.64 (0.92)	26	3.73 (1.00)	56	3.50 (0.98)	44	3.77 (0.83)	17	3.65 (1.11)	0.488
Health	143	3.36 (1.15)	26	3.00 (1.30)^{a}	57	2.98 (1.13)^{a}	43	3.77 (0.92)^{b}	17	4.12 (0.86)^{b}	<0.001
Social setting	143	2.08 (1.50)	26	2.23 (1.77)^{ab}	56	1.80 (1.27)^{a}	44	1.95 (1.28)^{ab}	17	3.06 (1.92)^{b}	0.019

[1] plant-based milk alternative, ^{a,b} different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$). Deviation in N due to the answer option "I don't know".

3.5 Objective Knowledge on Plant-Based Alternative Products

Tables 10–12 show the participants' objective knowledge of the sustainability aspects of plant-based alternatives. Since some of the participants answered "I do not know," the number of responses differed from the total sample.

Participants' overall agreement with statements about the sustainability benefits of PBMAs ranged from a value of 2.22 to 4.25. The highest level of agreement, with a value of 4.05, was related to the consistency of PBMAs, suggesting that participants viewed such products as less of a fad and more of a permanent product in the marketplace. The majority of respondents could also identify PBMAs as ultra-processed foods. There was also a higher level of agreement on environmental aspects, indicating that participants were aware that PBMAs are more environmentally friendly due to lower CO_2 emissions than meat and meat products. Moderate agreement was found for health aspects, indicating limited knowledge among participants about health-promoting properties of PBMAs. There was low agreement on additives, to the extent that respondents did not know that organic PBMAs have fewer additives than conventionally produced PBMAs and, moreover, rated this statement as rather inaccurate. Significant differences between dietary styles occurred, particularly in relation to consistency and the environment, with vegans and vegetarians more likely to agree with these sustainability aspects than omnivores. There were also differences with respect to additives, with vegans still moderately agreeing with this characteristic (Table 10).

With regard to PBCAs, the aspect of consistency also received the highest level of agreement, meaning that participants did not rate such products as a fad, but as a product that will persist on the market. There was also agreement in terms of the degree of processing and additives, which means that respondents were largely aware of the intense processing of PBCAs as well as the supplementation of additives. Moderate knowledge was found in relation to the health aspects, with an overall score of 3.51. With regard to the health aspects, there was significantly greater agreement shown by vegetarians. No significant differences were found for additives based on the post hoc test (Table 11).

Participants' overall agreement with statements about the sustainability benefits of PBMiAs tended to be in the upper range of agreement, with values ranging from 3.56 to 4.57. Again, most of the knowledge was related to PBMiAs' consistency. A greater agreement, but with fewer respondents having knowledge, was found regarding the taxation of PBMiAs and cow milk. Overall, only about a third of respondents knew that plant-based milk is subject to the 19% tax rate while cows' milk is tax-deferred as a staple food. The majority of respondents could identify PBMiAs as the more environmentally friendly food compared to cow milk. Moderate knowledge existed regarding health aspects. Significant differences between dietary styles occurred regarding the environment, with vegans agreeing significantly more with these sustainability aspects than omnivores (Table 12).

Table 10. Mean scores and standard deviation of the objective knowledge about sustainability characteris-tics of PBMAs [1] by participants' diets.

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	*p*-Value
Consistency	151	4.25 (0.87)	30	3.83 (1.09)[a]	60	4.22 (0.85)[ab]	44	4.41 (0.76)[b]	17	4.71 (0.47)[b]	0.004
UPF	142	4.05 (0.88)	30	4.00 (1.08)	54	4.07 (0.82)	41	4.02 (0.82)	17	4.12 (0.86)	0.966
Environment	145	3.89 (1.04)	25	3.28 (1.14)[a]	59	3.90 (1.05)[ab]	44	4.07 (0.87)[b]	17	4.29 (0.92)[b]	0.005
Additives	111	2.22 (1.11)	23	1.87 (1.06)[a]	45	2.24 (1.21)[ab]	33	2.15 (0.83)[ab]	10	3.10 (1.20)[b]	0.030

[1] plant-based meat alternative, [a,b] different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$); UPF = ultra-processed food. Deviation in N due to the answer option "I don't know".

Table 11. Mean scores and standard deviation of the objective knowledge about sustainability characteristics of PBCAs [1] by participants' diets.

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	*p*-value
Consistency	121	4.33 (0.82)	15	4.00 (1.25)	48	4.21 (0.71)	42	4.45 (0.80)	16	4.69 (0.48)	0.057
UPF	113	4.11 (0.90)	15	4.13 (1.25)	44	4.18 (0.79)	38	4.00 (0.84)	16	4.13 (1.03)	0.839
Additives	103	4.11 (0.78)	16	4.31 (1.01)	41	4.15 (0.65)	33	3.82 (0.73)	13	4.46 (0.78)	0.035
Health	124	3.51 (1.16)	16	3.63 (1.18)[ab]	49	3.57 (1.17)[ab]	42	3.15 (1.22)[a]	17	4.07 (0.58)[b]	0.038

[1] plant-based cheese alternative, [a,b] different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$); UPF = ultra-processed food. Deviation in N due to the answer option "I don't know".

Table 12. Mean scores and standard deviation of the objective knowledge about sustainability characteristics of PBMiAs [1] by participants' diets.

	Total		Omnivore		Flexitarian		Vegetarian		Vegan		
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	*p*-value
Consistency	142	4.57 (0.74)	25	4.32 (0.99)	57	4.56 (0.68)	44	4.61 (0.72)	16	4.88 (0.34)	0.123
VAT	49	4.27 (1.08)	4	3.25 (1.71)	19	4.42 (0.84)	17	4.35(1.00)	9	4.22 (1.30)	0.256
Environment	133	4.20 (0.91)	22	3.75 (1.11)[a]	52	4.14 (0.83)[ab]	43	4.31 (0.90)[ab]	16	4.72 (0.58)[b]	0.008
Health	104	3.56 (1.05)	13	3.42 (1.41)	45	3.60 (1.04)	33	3.42 (0.98)	13	3.92 (0.89)	0.502

[1] plant-based milk alternative, [a,b] different subscripts indicate that the mean scores were different between the diet groups (Bonferroni test, $p < 0.05$); VAT = value-added tax. Deviation in N due to the answer option "I don't know".

4. Discussion

4.1 Sensory Perception of Consumers

Centered sensory and consumer research can play a crucial role in enabling the optimization of sensory attributes for plant-based alternative products. Various research projects have combined qualitative and quantitative consumer studies with subsequent behavioral analyses and interviews. In this study, for example, the interviews were used as a treatment where the participants had to deal intensively with the topic of sustainable protein sources. With a high proportion of young adults as target consumers, this study showed that commercial PBCAs and PBMiAs tended to elicit higher general preferences than PBMAs.

In the study by Verbeke [64], insect-based products were able to achieve significantly higher levels of preference when consumers were informed about the products. They explained it by suggesting that young adults might be more open to trying food products prepared with insects and willing to compromise on taste when they are informed about other product benefits [51]. At this point, the initial question about consumer acceptance can be answered. The overall sensory evaluation for the plant-based products tasted here was higher after consumers were informed and treated with the questionnaire, which could not be confirmed. However, significant differences in the evaluation between the nutritional styles can be seen here. Thus, the omnivorous consumers surveyed rated the alternative products lower than vegetarians and vegans, while flexitarians rated them high at a similar rate to vegetarians (Table 5). This reflects the findings of Elzerman et al. [65], who found that meat alternative users gave higher ratings than non-users. In Table 6, it is shown that the vegetarians and vegans that were surveyed were medium-to-high users of plant-based products.

Given the low overall sensory evaluation of meat alternatives in this study, it appears that the poor sensory quality of the product may be a primary reason for the low acceptance. Since the sensory quality is an important factor in food choices, manufacturers of plant-based alternatives consider sensory attributes when developing food products. This is especially the case if they want to position their product as a meat alternative, as similarity to meat and sensory quality are crucial for consumer acceptance [47].

According to van Trijp and van Kleef [66], several factors led to the increase in acceptance of new products, such as perceived meaningfulness (usefulness to target users) and novelty (uniqueness) and the required change in existing behavior patterns. A new product should be new enough to arouse curiosity, but familiar enough not to create fear and neophobia. Product familiarity might also have played a role in the difference in evaluation. Repeated positive experiences could have led to higher acceptance by users of alternative products. This was also shown by Hoek et al. [67], who reported a pure exposure effect after repeated consumption of meat alternative products (two times per week for 10 weeks). This suggests that the more reluctant consumers' opinion may shift toward a more positive perspective on plant-based meat products after repeated exposure to these products. Schouteten et al. [68] describe that emotions are mainly sensory-driven, as information alone has limited influence on emotional characterization. Therefore, for the market success of products with sustainable plant protein sources, it is important that potential consumers trying the product associate positive emotions with the product, replacing the expected negative emotions present before consumption. Although good taste leads to improved acceptance, familiarity plays an important role in the adoption of novel food products and should not be neglected [69].

One of the interesting findings in the present data was that the mean RATA score was very frequently above 2.5 for all dietary styles and was thus close to the scale anchor "very applicable." This can most likely be attributed to a boundary effect. Since values higher than 5 are impossible, very consistently high values are required to reach an average score of 2.5 or higher, a consistency that is rarely observed in consumer data, according to Vidal et al. [70]. Even when an attribute is clearly present, some consumers may not select it or may assign a lower score to avoid the extreme intensity anchor on the RATA scale [70]. New insights into consumers' ability to make detailed sensory product characterizations of plant-based oat drinks, sliced cheese, and salami style products support the results of this study. Ares et al. [41] showed that consumers performed similarly in RATA questions as trained panelists in descriptive analysis for appearance and basic taste attributes. However, consumers found it difficult to identify differences between samples in terms of complex sensory attributes or attributes related to specific flavors [41]. This may also be true for individual attributes in the results in Tables 2–4 shown here, such as astringency and umami. With brief training, it may be possible to improve consumers' ability to describe and discriminate between complex/similar samples.

What is particularly noticeable in the RATA data on the plant-based oat milk is that vegans were the only ones in both tasting rounds who did not perceive the product as bitter or sour, and only one person found it astringent (Table 2). It has long been known that consumers have an innate preference for sweetness and an aversion to bitter-tasting foods [71]. In a recent study by Pagliarini et al. [72], a large population sample size was used to confirm the finding that the perception of sour and bitter tastes is related to eating behavior and age. Van Bussel et al.'s [73] results show that participants who eat healthier and more sustainable diets consume fewer foods from the umami, salty, fatty, and bitter taste groups than participants who eat less healthy and sustainable diets. When comparing dietary styles, this is related to lower consumption of meat products and coffee and higher consumption of fruits, vegetables, grain products, and tea [73]. Therefore, they recommend that taste profiles should be considered when suggesting healthy and sustainable menus and meals.

A larger, cross-national sample would allow further investigation into how Western consumers perceive the consumption of plant-based alternative products. In addition, the consumer tastings in this study only took place in a laboratory setting. This must be considered when interpreting the results, as the context could influence the emotional and sensory profiles of foods [74]. Therefore, future research should investigate how people evaluate this type of food in other contextual situations, such as in a restaurant, food exhibition, or supermarket.

4.2 Consumers' PBAP Consumption Behavior

The results of this study reveal that the frequency of PBAP consumption varies along with the examined products.

PBMiAs were found to be the most consumed products among those studied, with an average consumption of about one or two times per week. In fact, the market and demand for PBMiAs has grown significantly in recent years [75]. There are currently over 50 brands offering PBMiAs to German consumers, and the fact that almost all major German food retailers have entered the plant-based milk category indicates that the market for plant-based milk is already developed. According to a recent survey, 93% of German consumers already buy plant-based milk alternatives, which is higher than any of the other plant-based product categories [76]. Oat milk has recently become the most popular PBMiA ahead of soy milk [77] and is predicted to be the fastest-growing alternative in the coming years [78]. The results show that a slight majority of respondents indicated a preference for soy as a plant-based alternative milk product, albeit this was closely followed by oat milk.

PBMAs were consumed by respondents of this study more occasionally, with an average eating frequency of two to three times per month. In line with this finding, a recent consumer survey in Germany on the consumption of meat alternatives found a share of 19.3% of consumers reported consuming meat substitutes, and most of these (62.2%) were occasional users with a consumption frequency of once a month or less [20]. The use of these products in the daily diet of consumers in Germany remains low for now, as in other European countries [47,79–81], and a shift in consumer dietary habits to replace meat with a plant-based alternative is progressing slowly. Nevertheless, increasing concerns about the sustainability of meat production and the rise of vegetarian and vegan lifestyles have increased the demand and market for meat alternatives [10,67]. Experts predict an annual growth rate of 20% to 30% worldwide [82], and the supply in restaurants and canteens is also likely to increase. At this point, further accompanying scientific surveys are crucial to give a more accurate prediction of consumer acceptance of PBAPs in the community food supply.

Among the studied alternative products, PBCAs are the least consumed, although this result was not unexpected. Within the plant-based product market, PBCAs is a product group that has yet to gain traction and interest among a broad consumer base. Although sales of PBCAs continue to grow, such products are still in the early stages of development compared to other plant-based alternatives (i.e., milk and meat) [57,83], and consumers in supermarkets have limited options to choose from [28].

In terms of the consumption behavior of respondents following different dietary styles, the analysis indicated that PBAPs were strongly represented in vegan and vegetarian diets. On the other hand, flexitarians described lower consumption, as did omnivores. This is consistent with other studies that have found no increased consumption of meat alternatives among frequent meat eaters and moderate meat eaters who are willing to substitute meat [84,85]. Consumers who avoid meat and meat products are instead more likely to consume PBAPs, as shown by Haas et al. [86] and Ohlau et al. [87]. In this context, there is also the likelihood that the higher consumption within plant-based dietary styles correlates with sociodemographic characteristics of the sample. A higher proportion of the sample consisted of women, and the group of vegetarians and vegans was younger in age than the meat eaters. Previous studies showed that predominantly women follow a plant-based diet [86,87], and some studies showed a higher prevalence of plant-based eaters among younger age groups [88,89]. In addition, women and younger individuals were found to be more likely to consume meat substitutes [79,87].

4.3 Related Motives for PBAP Consumption

The reported reasons for consuming PBAPs revealed that animal welfare followed by environmental concerns were the main reasons given for consumption. Animal welfare is often cited as the primary motivation for consumers reducing or avoiding the consumption of animal products [84,90,91]. Fresán et al. [92] also found that it is the main motivation for continuing the diet. Environmental concerns are also commonly named as an important reason for consumer demand for alternative proteins [47,91,94]. However, Sanchez-Sabate and Sabaté [94] indicated in their review that only a small minority of consumers are willing to stop or significantly reduce meat consumption for environmental reasons or have already changed their meat intake for ecological concerns. Nevertheless, motives can differ in the strength of their influence according to dietary behavior [95]. For example, Hoek et al. [47] found that higher interest in ecological well-being is a driver of more frequent consumption of meat alternatives. Consistently, the results of the present study show that the stated sustainability-specific motivations for consuming PBAPs increased along with the strictness of the plant-based diet, such that vegans and to some extent vegetarians showed greater agreement than omnivores and to some extent flexitarians. Previous studies suggest that people who completely avoid eating animal products tend to be more ethically motivated than people who partially avoid eating animal products; this is true for vegans more so than vegetarians [96-100], and flexitarians more closely resemble traditional meat consumers than vegetarians and vegans in terms of their motivations related to animals and the environment [90,101-103]. A major reason that prevents meat eaters and flexitarians from eating a plant-based diet or PBAPs is their preference for the taste of meat [104,105].

Overall, the sensory appeal as a motive was found to be negligible to not applicable in this study. This agrees with studies that revealed that consumers perceive PBMAs as less sensory-attractive [20,47,80,106].

In terms of health, the present results show rather indifferent ratings as a consumption motive. While it seems to be somewhat more important for PBMAs, it is less crucial for the consumption of PBCAs and PBMiAs. Although numerous studies describe health concerns as one of the most important reasons for switching to a plant-based diet [92,102,107–110], it is possible that consumers may not rate PBAPs as healthy themselves. As the health assessment database for PBAPs grows, concerns are generally raised about the level of processing of plant-based substitutes [27,111] and about their partial nutrient deficiencies compared to their animal counterparts [112]. It stands to reason that while consumers may see a health benefit in a plant-based diet, they are cautious in transferring such an assessment to substitute products.

4.4 Consumers' Objective Knowledge of Sustainability Characteristics of PBAPs

Although the assessment of PBAPs' sustainability attributes is still in its infancy and needs to be expanded and verified, the analysis of participants' objective knowledge in this study was helpful in gaining better insight into consumer perceptions of PBAPs. One intriguing finding was that respondents, regardless of the product, possessed higher agreement that PBAPs are not a fad but will be in the marketplace in the long term. In fact, market forecasts predict a significant growth of such products in the coming years [113]. Consumers' assessment of this is critical, as it can play an important role in long-term acceptance and integration into dietary habits.

Additionally, the higher compliance to PBMAs and PBCAs as compared to ultra-processed foods was striking. Indeed, there is a current debate concerning the degree of processing of plant-based alternative products [111]. Like conventionally processed meats, some PBAPs, such as meat imitations, are highly processed and, for example, high in sodium, saturated fat, and often added sugars [29,114]. In a similar respect, studies have found that consumers perceive PBAPs as more artificial and less natural [20,115]. It is expected that the processing of PBAPs may well represent a barrier to their consumption. Additional measurement of this correlation could be useful to ultimately better predict consumer perceptions and attitudes toward PBAPs as ultra-processed foods.

The respondents had a better knowledge of the environmental benefits of PBMAs than they did for PBMiAs, which nevertheless indicates that respondents' perceptions of the environmental friendliness of such products generally do not match the objective assessment based on environmental measurements. This further suggests that participants are not aware that plant-based alternatives are generally more environmentally friendly than meat- and animal-derived products. This result supports previous findings from Siegrist and Hartman [79] and Hartmann et al. [115] that consumers are unable to assess the environmental friendliness of products sufficiently. Hartmann et al. [115], who examined in detail whether consumers' knowledge of the environmental friendliness of different products was consistent with life cycle assessment (LCA) data, concluded that the environmental friendliness of animal products was greatly overestimated, while meat substitutes were perceived as far less environmentally friendly than they are. Efforts should be made, for example, in the form of an environmental label, to inform and educate consumers about the environmental impact of individual products, not only PBAPs but also meat and meat products.

Respondents seemed to have lacked knowledge of certain health aspects of PBCAs and PBMiAs. For example, there was only modest agreement among respondents that, for example, with respect to cheese substitutes, such products have no lactose and no cholesterol due to the absence of animal ingredients. Overall, since the PBAP segment is still relatively new and continuously growing, it can be assumed that consumers have not (yet) gained sufficient knowledge about these products. In addition, Bucher et al. [116] found that consumers tended to neglect the number of single nutrients, such as saturated fat, protein, and sodium, in their ratings, which further leads to assuming that consumers are more likely to make general statements about health ratings rather than evaluate specific characteristics.

Lastly, it should be noted that knowledge levels partially significantly varied along with the different dietary groups, with vegans and vegetarians showing higher knowledge levels than omnivores. For example, with regard to the environmental friendliness compared to the respective animal product or the fact that organically produced PBMAs contain fewer additives than conventional PBMAs, vegans and partial vegetarians were in agreement. Thus, plant-oriented consumers may be more interested in the properties of such foods and more likely to seek knowledge than meat eaters, who consume less of such products. A study by Hartmann et al. [117] found that people with a pro-ecological orientation have more knowledge about the environmental impact of food. Similarly, Michel et al. [20] reported in their study that non-meat eaters perceive meat alternatives to be better in terms of environmental friendliness than meat eaters, although only the perception was examined here. In general, respondents’ knowledge regarding the current sustainability aspects of PBAPs seems to be still insufficient. Studies indicate that relevant knowledge is a prerequisite to enable consumers to make environmentally friendly choices [30,117]. However, with a wide and rapidly growing range of products, there is a lot of information in the media about the valuation of PBAPs, causing a risk of consumer confusion and misinformation. For both science and consumers, the alternative product segment is still young, and more scientific evaluations need to be generated as well as general educational efforts to provide consumers with helpful and accurate information.

5. Limitations

The sample used was not representative of the German population due to convenience sampling during recruitment. Because of the high proportion of students, the sample consisted mainly of younger people. Furthermore, the public announcement of the sensory tasting of substitute products primarily addressed individuals with vegetarian and vegan diets. Yet, using a random sample is not unusual in sensory research. Additionally, the sample size was sufficient for the method of valid sensory testing and provided interesting findings. In terms of consumer research (i.e., consumption behavior, motivation, and knowledge), however, the treatment group might have been small. Nevertheless, this study fulfilled the standard criteria in light of sensory science, making valuable connections to the field of consumer research.

With regard to the sensory test, only three products, one from each product segment, were included in this study for practical reasons. Although market-leading products were selected, studies on a wider variety of food categories are needed to generalize the conclusions of the current study.

Further, the CATA and RATA assessments were conducted using attributes pre-sampled by a trained sensory panel. Thus, the vocabulary may have been too subject-specific for the lay consumers. It might be interesting to perform a profiling of the products with a consumer panel to gain a deeper insight into the sensory perception of the consumers towards PBAPs.

The questionnaire used to assess the respondents’ objective knowledge was designed to test laypersons’ factual knowledge of the properties of certain plant-based substitutes. We focused on sustainability aspects such as the environmental friendliness of PBMAs versus meat or degree of processing of PBMAs and PBCAs. In doing so, care was taken to use very specific information since the product range and thus the formulations of the individual products are very diverse, and general statements about generic properties, such as environmental friendliness, are difficult to make. For example, instead of stating “plant-based milk alternatives are more environmentally friendly than cows' milk,” it stated “more land area is required to produce one liter of cows' milk than to produce one liter of oat milk.” However, such a query might be too specific to the consumer and provide only limited results about consumer knowledge, even if it does offer interesting insights into consumer perceptions of detailed characteristics.

6. Conclusions

The variety of novel protein alternatives on the market is increasing, and there are many new product innovations potentially prompting consumers to change their nutrition habits. PBAPs may replace and complement meat- and animal-derived products in the human diet, potentially reducing the environmental impact of food consumption. However, there is a shared negative perception of plant-based dishes' taste; in particular, plant-based protein products that mimic meat and animal products are associated with a reputation of negative sensory characteristics.

This sensory study showed that all PBAPs tested achieved good acceptance on average. In terms of the products used, PBMiAs and PBCAs were rated slightly better than PBMAs. However, particularly noticeable were the differences in ratings between dietary styles. Vegetarians and vegans gave a significantly higher rating to the products than omnivores and, to some extent, flexitarians.

Therefore, meat alternative products are of particular importance to meat-eating consumers because they offer a way to reduce meat consumption. If they do not like the taste, they are less likely to try these products again, despite the knowledge that switching to a more sustainable, plant-based diet has positive environmental and health impacts. Omnivores and flexitarians, who regularly consume animal-based products, have a different sensory comparison and relationship to plant-based products than vegetarians and vegans. They are the target group of these PBAPs and therefore of particular importance for further sensory research projects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods11152339/s1. Table S1: Sensory Attributes Survey.

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Appendix A

Table A1. Constructs of motivation with associated questionnaire items and sources.

Construct	Scale/Items	Source
Animal welfare	I think animal welfare is important	[6]
Environment	It's better for the environment	[6]
Sensory appeal	I like the sensory aspects such as taste and mouthfeel	[50]
	I would like a plant-based alternative source of protein	[50]
Health	It contributes to a healthy diet for me	[48]
	It's healthier, not frequently eating meat	[6]
Product lifestyle	I am interested in the advertising and the product design	[49]
	I am curious about new foods	[49,51]
Social setting	Others in the household don't want to eat animal-based products	[6]
Convenience	It is easy to prepare	[48,51]

Appendix B

Table A2. Questionnaire items for knowledge of the respective products and sources.

Product	Scale/Items	Source
PBMA	Plant-based meat alternatives are a source of vegetable protein	[26]
	Plant-based meat alternatives have a better fatty acid profile than meat and meat products	[26]
	Plant-based meat alternatives have lower CO_2 emissions compared to meat and meat products	[52,53]
	Organically produced meat substitutes have fewer additives than conventionally produced meat substitutes	[26]
	Plant-based meat alternatives have equivalent amounts of salt as meat and meat products	[26]
	Plant-based meat alternatives are ultra-processed foods	[54,82,118]
	Plant-based meat alternatives are a fad and will be gone in a few years	
PBCA	Plant-based cheese alternatives are free from lactose	[57,58]
	Plant-based cheese alternatives are free of cholesterol	
	Plant-based cheese alternatives are reduced in saturated fatty acids	[58]
	Plant-based cheese alternatives have a reduced salt content	[58]
	Plant-based cheese alternatives can be fortified with important vitamins and minerals	[58]
	Plant-based cheese alternatives are ultra-processed foods	[111]
	Plant-based cheese alternatives are a fad and will be gone in a few years	[118,119,120]
PBMiA	Plant-based milk alternatives have lower calorie content compared to whole cows' milk	[59]
	Plant-based milk alternatives have a better fatty acid profile compared to cows' milk	[59]
	More land area is required to produce one liter of cows' milk compared to plant-based milk alternatives.	[60]
	Plant-based milk alternatives produce fewer CO_2 emissions.	[60]
	Cows' milk falls under the reduced VAT rate of 7%, while plant-based milk alternatives are subject to the regular rate of 19%.	[121]
	Plant-based milk alternatives are a fad and will disappear in a few years	[78,121]

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Chapter 5

General discussion

5.1. Introduction

The present work was conducted within the framework of the Sustainable Nutrition Styles (short title: Nachhaltige Ernährungsstile, NES) project. The aim of the project was, first, to compare the different dietary styles from a comprehensive sustainability perspective, including human health, and second to capture the sustainable implementation of a plant-based diet depending on the motivation of the individuals and their experiences, such as sensory preferences. The variety of plant-based products available to consumers has been continuously expanding for several years and includes an increasing number of meat, cheese, and dairy alternative products. It is well known that consumption of animal-based products is one of the Big Five drivers of climate change (Wynes and Nicholas, 2017), and a dietary style low in whole grains, fruits, and vegetables is associated with significant health risks (Afshin et al., 2019). Therefore, plant-based alternative products could be the key to reducing the consumption of animal products and supporting a long-term plant-based dietary style. The research in the work package on which this dissertation was based focused on plant-based alternative products. In more detail, this examined not only the interrelationships of sensory quality assessment and the possibilities to include instrumental sensory analysis but also ingredients, and nutritional value, especially micronutrients, and finally, it explored consumer behavior with a focus on motivation, knowledge, and sensory evaluation of alternative products. Research objectives were defined (see Chapter 1, Section 1.6), and the study can be divided into three main themes (see Chapter 1, Figure 4).

1. Nutritional characteristics of plant-based alternative products, the composition of macro-and micronutrients of these products.
2. Product variety for plant-based alternative products and the different possibilities to determine sensory quality parameters.
3. Consumer acceptance of sensory quality, levels of motivation, and consumers' knowledge of novel plant-based products.

5.2. Key findings

The main findings of the present study are summarized based on the results of the three main topics discussed below. First, a market analysis was conducted to gain a general overview of which novel plant-based meat and cheese alternative products are on the market and where significant growth in the different food product groups was found in two years (Chapter 2). Since micronutrients have many important functions in the human metabolism and deficiencies can occur even with a Western diet, the main focus was on minerals and vitamins (Chapters 2 and 3). For example, the daily requirement for iron can be relatively well covered by meat alternatives (Chapter 2) and the requirement for calcium and vitamin B_{12} by milk alternatives (Chapter 3), although the products usually have to be fortified with these nutrients. The sensory quality of plant-based alternatives was determined using a sensory panel as well as instrumental analysis, here using the example of non-dairy milk drinks. Positive correlations between the panel and the e-tongue were obtained for the basic tastes "sweet," "sour," and "salty." The results of the volatile compounds analysis compared with the sensory data show that instrumental methods are also suitable for novel products. Finally, the consumer questionnaire and sensory tasting focused on the evaluation of overall liking of plant-based alternative products and the participant's level of knowledge about these products. It was noticeable that meat-eating participants evaluated the sensory aspects and responded to the survey questions differently to vegetarians and vegans (Chapter 4). The main motivations of the respondents were always animal welfare in the first place and the environment in the second position.

5.3. General discussion

5.3.1. Aspects of health evaluation and nutrient value

Understanding the dietary effects and profiles of plant-based alternative products is important as more people adopt flexible, vegetarian, or vegan diets. In addition, there appears to be a "health halo effect" (Sundar and Kardes, 2015) that may lead to novel plant-based products being perceived as healthier, which may not be warranted. Studies were able to show that product composition is critical, as some plant-based meat products have higher sodium content (Crimarco et al., 2020; Harnack et al., 2021) than animal-based ones. The market analysis results also found significantly higher salt levels for some meat alternatives compared to animal-based products. However, the percentages increased for the meat products with a higher degree of processing, for example, significantly lower values could be analyzed for the vegetable sausage and salami (Chapter 2).

Coconut oil is a popular ingredient used by the food industry for the production of plant-based meat but also cheese products. Santo et al. (2020) found that the saturated fat content of meat alternatives containing coconut oil was lower than beef, but the fat intake was comparable to or higher than that of poultry and pork. Also, Bohrer (2019) found that most meat alternative products evaluated contained coconut oil and corn oil with short-chain and medium-chain saturated fatty acids. Further research is needed to determine whether the intake of vegetable short- and medium-chain saturated fatty acids in processed foods has positive or negative health effects. A recent review demonstrated that coconut oil has a negative impact on lipid parameters associated with cardio-metabolic health (Jayawardena et al., 2021).

Plant-based alternative products may contain similar macronutrient profiles as animal products, but the replacement does not necessarily reflect a healthy dietary pattern (Hu et al., 2019). Thus, they state that even plant-based burgers served with a wheat bun, sauces, a few vegetables, low nutrient side dishes such as fries, and soft drinks in fast food restaurants do not bring any nutritional health benefits. Further research is needed to study if plant-based alternative products eventually lead to healthier dietary behaviors than the consumption of animal products. It has been demonstrated in several studies (Afshin et al., 2019; Maretzke et al., 2020; Steinbach et al., 2021) that diets rich in whole plant foods such as legumes, whole grains, vegetables, and nuts have been associated with a lower risk of diet-related diseases, and NCDs. That a diet rich in plant components is associated with a more diverse gut microbiome than omnivorous diets was demonstrated by Tomova et al. (2019). An imbalance of the gut microbiota has been linked to numerous gastrointestinal diseases but also to systemic diseases such as type 2 diabetes, cancer, Alzheimer's disease, and many more (Tomova et al., 2019). It is unclear if or how plant-based alternative products impact the gut microbiome and health outcomes, as beneficial effects are mainly due to whole plant ingredients and properties (Hu et al., 2019; Tomova et al., 2019).

Currently, there are few studies on the micronutrients of plant-based alternatives. In the literature review for Chapters 1, 2, and 3, the lack of comparison of additional elements, such as vitamins and minerals, was frequently addressed as a limitation. The study by Harnack et al. (2021) looked at the vitamin and mineral content of plant-based ground beef alternatives and compared them to the U.S. Food and Drug Administration reference values and recommended daily nutrient levels. The result was that the mean percentage daily value was 10% or higher for folate, niacin, iron, phosphorus, sodium, manganese, and copper, and most products contained less zinc and vitamin B_{12} than ground beef (Harnack et al., 2021). However, it should be noted here that the data were obtained from databases and were not analyzed independently. Results from Chapter 2 can make a valuable contribution at this point since the data on the four alternative products investigated are based on independent analyses. The iron, copper, magnesium, phosphorus, and calcium requirements were significantly better covered by the meat alternatives than by the animal products (Chapter 2, Table 7). In the case of vitamins, the fat-soluble vitamins E and K and the water-soluble vitamins B_2, B_6, folate, and biotin stand out in particular and cover the requirements very well (Chapter 2, Table 8).

Milk is an essential source of many vitamins and minerals, especially vitamin B_2, B_{12}, pantothenic acid, and calcium, with important functions for the maintenance of the human metabolism (Mäkinen et al., 2016). The Codex Alimentarius Commission (1994) has indicated that a food substitute that is intended to replace another food that has been identified as an important source of energy or essential nutrients for human nutrition is strongly recommended to have nutritional equivalence. The studies of Clegg et al. (2021) and Paul et al. (2020) have focused extensively on the nutritional composition of plant-based dairy products. The corresponding micronutrient content of a product will depend on the natural raw material source. For example, products made from soy will have different mineral levels than those made from oats, and an almond drink will have a different vitamin value than rice drinks. Clegg et al. (2021) found the highest content of vitamin B_2 in coconut alternatives, followed by cow's milk, beverages based on whole cereals, legumes, nuts, and seeds, which had slightly lower contents. Cow's milk had a much higher content of vitamin B_{12} compared to all alternative products. No differences were found in calcium content, as most non-dairy milk beverages fortify this. The results from the plant-based milk alternative study (Chapter 3, Table 3) also showed significant differences in the products depending on the raw material source. The soy products were able to achieve similar micronutrient values to cow's milk. Again, it depends on whether the food manufacturer fortifies or not, as in the example of calcium in the oat drink, which is strikingly lower.

However, where products are not fortified, consumers need to know their requirements for these important nutrients and make informed decisions when choosing plant-based alternative products. Otherwise, removing dairy products from the diet could lead to deficiencies in these nutrients. It should also be emphasized that non-dairy milk beverages labeled as "organic" may not contain fortification under European organic regulations. When milk alternative products are fortified with minerals and vitamins, they can obtain levels similar to cow's milk that contains them naturally.

According to the NOVA criteria, most novel alternative products can be classified as ultra-processed foods (Bohrer, 2019; Monteiro et al., 2019; Santo et al., 2020). Their negative health properties were described in detail in Chapter 1.4. In the online market analyses in 2019 and 2021, it was also found that most products contain additives such as flavors, colorants, binders, and thickeners and are composed of protein concentrates or isolates from high-tech processing with other ingredients in a new food matrix (Chapter 2).

5.3.2. Sensory profiles of plant-based alternative products

In this study, the nutritional quality of plant-based dairy alternatives was investigated, but the main focus was on evaluating the sensory quality of these products (Chapter 3). The characterization of novel products is often made by descriptive sensory analysis, as was done for meat, cheese, and milk alternatives in the present study. Sensory attributes are identified by an expert panel that are trained on the foods to be assessed, and a sample characterization follows (Lawless and Heymann, 2010). Descriptive sensory analyses are among the most widely used methods in the sensory development of products due to their detailed, accurate, and repeatable results (Meilgaard et al., 2006). However, since these methods are associated with a high cost as well as time factor (Ares et al., 2013), more rapid methods have been developed over recent years that are easy to use, can be performed with consumers, and are comparatively less expensive (Valentin et al., 2012). The main difference between the CATA and RATA methods is that the respondents completing the questionnaire not only tick the product descriptive attributes but also rate them according to their intensity using a scale (Ares et al., 2014). Ares et al. (2014) also showed that the results between trained and untrained testers are merging and making sensory product perception by consumers possible. Hence, it was included in the study for this reason (Chapter 4).

An important finding regarding the almond oat and soy-based drinks was described in Chapter 3. Due to the production on an organic basis or using a conventional method with the addition of flavorings and hydrocolloids, the samples differed considerably in the intensity of selected attributes. A previous paper by Pangborn et al. (1978) suggested that this was due to the stabilizer gellan in beverages, which is present in conventional products. With the help of hydrocolloids, a decrease in saltiness in tomato juice, acidity in orange juice, and bitterness in coffee was shown (Pangborn et al., 1978). These findings are consistent with the results described in Chapter 3 (Figure 1), where higher bitterness associated with mouthfeel astringency, acidity, and saltiness were found for organically produced products.

Consumer demand for plant-based milk alternatives is increasing as the food market for these products has grown continuously in recent years (Tangyu et al., 2019). While many modern non-dairy milk products have improved sensory quality, some consumers associated them with a negative "beany," "rancid," "earthy" off-taste attributes, and "chalky" mouthfeel (Mäkinen et al., 2016; Tangyu et al., 2019; Vaikma et al., 2021). Volatile compounds such as n-hexanal and n-hexanol, derived from the oxidation of vegetable lipids, are mainly responsible for this type of off-flavor (Drewnowski and Gomez-Carneros, 2000), whereas large insoluble particles are responsible for the impaired mouthfeel (Mäkinen et al., 2016). In the present study, these and other odor-active compounds were also detected in the plant-based milk alternatives studied (Chapter 3, Table 5). The study of Tangyu et al. (2019) indicates the high potential of fermentation to help improve the sensory profiles, nutritional properties, texture, and microbial safety of plant-based milk alternatives. In particular, mixed-culture fermentation with two or more microbial species will continue to be the focus of intense scientific attention in the coming period.

Generally, the taste is the most important food purchase criterion, and information about good and/or familiar taste is most likely to increase willingness to try a novel food (Magnusson et al., 2001). Plant-based beverages are often used as an alternative to milk. Thus, cow's milk was used as a reference in the assessment of the nutritional profile of macro- and micronutrients. The results underlined that there is significant variability in nutritional claims, depending mainly on the plant-based ingredient used and whether the product is fortified or not. Therefore, plant-based beverages cannot be easily considered as dairy alternatives. To improve consumer knowledge about the nutritional quality of plant-based alternative drinks and all other products, information must be easy to read and understand, including on food packaging. Moreover, such information can increase the willingness to try new foods.

5.3.3. Increased consumer acceptance through positive product characteristics

Recently, there have been systematic reviews of emerging trends, such as the acceptance of novel alternative protein products (Aschemann-Witzel et al., 2021; McClements et al., 2019; Onwezen et al., 2021). However, the impact of consumer motivational reasons for choosing certain foods as well as their knowledge on topics such as ingredient and nutritional labeling, environmental impacts, and other product-specific aspects of these novel products is still largely unexplored (Tonsor et al., 2021). The production of animal products in response to market demand will continue, assuming that not all consumers become vegetarian or vegan, i.e., many people do not voluntarily adopt vegetarian or vegan diets (Leahy et al., 2010), and that numerous people will continue to consume animal foods because it is considered as "natural, normal, necessary, beautiful" (Hopwood et al., 2021).

The studies described in Chapter 4 and the discussion on participants' objective knowledge can contribute to filling this research gap to gain better insight into consumers' perception of plant-based alternative products. It was noticeable that a majority of the participants answered "I don't know" to the knowledge questions. In particular, there appears to be a lack of knowledge among consumers in the area of health and nutritional value. Therefore, novel products may present an additional challenge in terms of their evaluation. Previous studies with well-known foods such as cheese, meat, chocolate, and pasta were able to establish correlations between respondents' perceived health and nutritional profile (Bucher et al., 2015; Lazzarini et al., 2016). For environmental aspects, the data also show that participants are not aware that plant-based alternatives are generally more environmentally friendly than animal products, especially meat. Hartmann et al. (2022), who compared consumer knowledge of the environmental friendliness of various food products with LCA data, demonstrated that the ecological benefits of animal products are highly overestimated, while meat alternatives are perceived to be far less environmentally friendly than they are. The vast majority of respondents were able to identify meat and cheese alternatives as ultra-processed foods, and indeed there is critical debate about the degree of processing of plant-based alternative products (Wickramasinghe et al., 2021). There was a high level of consumer agreement related to the permanence of plant-based alternative products suggesting that participants view such products less as a fad and more as a permanent product in the marketplace. This was also found by data from a study with younger Canadians (Korzinski, 2019), for whom plant-based protein alternatives were not perceived as a food trend or phenomenon but rather as a product category that will persist in the marketplace. Market prognoses also predict the significant growth of such products in the coming years (Geijer and Gammoudy, 2020). The level of knowledge varies with the different dietary groups, sometimes considerably, with vegans and vegetarians having a higher level of knowledge than omnivores, for example, regarding environmental friendliness. In their study, Michel et al. (2021) reported that non-meat eaters perceive meat alternatives as more environmentally friendly than meat-eaters, although only perceptions were investigated here. The respondents' knowledge about the sustainability aspects of alternative products is generally still insufficient.

However, given the wide and rapidly growing range of products, there is much information in the media on the evaluation of novel plant-based products, which may lead to confusion and misinformation among consumers. In order to maintain a higher purchase probability among consumers, trust must be established. When consumers have positive product experiences, such as experiencing good sensory product qualities, trust in novel plant-based products is increased (Elzerman et al., 2015). The positive evaluation of plant-based products regarding overall liking showed that these products generally appeal to consumers (Chapter 4). Since the alternative products segment is relatively new, more scientific ratings need to be performed to provide consumers with helpful and accurate information. For example, the Nutri-Score could be helpful for a fast assessment of the health value, an ECO-Score for a simple assessment of the ecological aspects, and a NOVA classification to identify the degree of processing for the consumer quickly in a shopping context.

5.4 Conclusion

Many forecasts indicate that the market for plant-based alternative products will continue to grow and that further product research will improve the products in terms of their formulation and nutritional composition. The present study compared the coverage of individual nutrient requirements in modern plant-based meat, cheese, and milk alternatives with that of animal products. A key point was the description of the sensory qualities and the characteristic properties based on the main raw materials of the plant-based products. The high current consumption of animal products, especially meat, in the Western diet is a risk factor for diet-related diseases and a driver of adverse environmental effects. When choosing plant-based alternatives, consumers must keep in mind that numerous products are highly processed foods that could have adverse effects on human health. Therefore, a recommendation would be to consume these foods in moderate amounts. To create tasty dishes, though, with fewer animal-based products or their highly processed plant-based alternatives, consumers may require to develop new cooking skills so that these can be interpreted as their own cooking culture. Based on current scientific knowledge, this study has demonstrated that a plant-based diet is beneficial from an ecological view and animal welfare perspective.

In summary, a comprehensive health-related overview of vitamins, minerals, and macronutrients was carried out for the first time for representative plant-based products on the German market. Further, the sensory results shown here may be useful for quality evaluation and product development of plant-based alternatives in the future. In particular, the results of this study can be used by consumers to make informed decisions based on currently available claims for modern plant-based products. How the world eats in the future shows how the world will be in the future.

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Summary

One of the greatest challenges of the 21st century is to meet the food needs of a growing world population without exceeding the planetary boundaries. The consumption and production of food products of animal-based origin are an essential part of this puzzle, as they provide important and high-quality nutrients on the one hand and are one of the Big Five drivers of climate change on the other. Meat consumption in developed countries such as Germany is higher than recommended, and the increased intake of processed meat products, in particular, is associated with negative health impacts in these countries. In recent years, a new generation of plant-based alternative products has entered the market, which are designed to imitate animal-based products in terms of sensory and nutritional composition. These products are primarily aimed at consumers who want to reduce the amount of animal-based foods they consume in their daily lives. The marketing of these products particularly serves the niche market of flexitarians.

The dissertation presented uses the example of plant-based meat, cheese, and milk alternatives to show how a change to a sustainable diet is possible. The environmental impact and resource consumption of plant-based products are lower, and the nutritional content and sensory qualities of these products are the focus of this study. The aim was to determine the characterization of the sensory quality of these plant-based alternative products. In addition, the question of nutritionally relevant ingredients in the commercially available products was to be investigated.

At first, an online market analysis of the nutritional composition of plant-based meat and cheese products and animal-based products was conducted. The aim of this study was to fill the research gap regarding the comparison of nutrient composition, especially micronutrients, of processed plant-based meat and cheese products compared to the animal-based products they resemble. The results show that plant-based meat products demonstrate better Nutri-Score values than the animal-based comparators, while the cheese alternatives generally score lower than the respective dairy products. Meat alternative products provide high-quality plant protein, and the contents are in some cases comparable to meat products. In six of twelve meat product groups, plant-based products have significantly higher salt contents than meat products. The salt content in the five cheese product groups is quite high in both plant-based and animal-based products. The results of the micronutrient assessment show that the relationship to the reference values for recommended daily intake is reasonable. In this way, deficiencies and surpluses of vitamins and minerals could be made clear. The daily requirement of copper, iron, magnesium, and zinc can be better covered by the plant-based products analyzed here than animal-based products, which is shown by the reference values. On the other hand, the vitamin requirements of B_1, B_3, B_{12}, A, and D are not sufficiently covered by plant-based products. The example of cheese alternatives shows that these can cover the requirement just as well if vitamins and minerals are added to the products. In particular, the high sodium content, the high degree of processing, and a large number of ingredients and additives used in the production of these foods are increasingly criticized. Therefore, these modern plant-based alternative products cannot be considered per se as a "healthy" alternative to animal-based products. However, the products have to be evaluated individually due to the considerable heterogeneity.

In the second step, plant-based milk alternatives (based on almond, oat, and soy) were also analyzed for micronutrients and compared with cow's milk, and their sensory quality was evaluated. Cow's milk is a good source of vitamins B_2 and B_{12} as well as of zinc and especially calcium. It is also clear that if plant-based products are fortified with these micronutrients, they can have the same micronutrient content as cow's milk. Based on descriptive analysis by a trained sensory panel, five products of each of the three different raw material bases could be evaluated. The data from the instrumental sensory analysis showed positive correlations with the panel results. Thus, these methods could also be used to analyze and evaluate plant-based alternative products. The nutritional profiles of the individual products differ, sometimes widely, within the product group with the same raw material source and in comparison to cow's milk. Plant-based products are naturally lower in protein, minerals, and vitamins than cow's milk. As a result, these modern plant-based beverages are not nutritionally comparable or equivalent to cow's milk. Because of the wide range of products on the market, consumers should consider nutritional values and ingredients when selecting a product.

Based on the results from the first and second studies, a sensory consumer test combined with a questionnaire on plant-based alternative products was conducted. 159 participants divided according to their nutrition style were served three products in two tasting rounds. Interestingly, the vegans did not perceive the attributes of bitter, sour, and astringent for the oat drink. This could be related to higher consumption of vegetables and fruits and their products. Altogether the acceptance of the products was evaluated quite positively. Although omnivores always evaluated the products lower than vegans, the oat drink achieved the best overall liking. The main motivations for consuming plant-based alternatives for all three products were animal welfare and the environment. A larger gap was revealed with the knowledge questions, for example, concerning health aspects. As these products are still relatively new on the market, it is currently difficult for consumers to obtain essential information from independent sources.

In summary, plant-based alternative products are suitable for reducing the consumption of animal-based products and can therefore be used by consumers as a support tool. Due to the variety of products in the different product categories and the heterogeneity, the products have to be evaluated individually according to their nutritional and sensory qualities. Therefore, the need for information on sustainable plant-based alternative products is high so that consumers are familiar with and well informed about the different products.

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Declaration

1. I hereby declare that this work has not been made available in the same or in a similar form for the purpose of meeting examination requirements.

I further declare that I have not applied for a doctorate at any other university.

2. I hereby declare that this dissertation was written independently and without unauthorized assistance.

Goettingen, 27 June 2022

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Marcel Pointke