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Characterization, categorization and classification of European protected geographic cheeses. A global perspective of cheese diversity (Turodiversity)

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ABSTRACT

Cheese is a basic element of the human diet and a cornerstone of the food economy. Furthermore, cheese has a key role in the gastronomic and cultural identity of the European Union (EU), in the protection/support of the social-economic systems as well as the sustainability of biodiversity in the regions related to cheesemaking. The aim of this review is to offer an overview of comprehensive and practical integrative picture of EU Protected Geographical (PG) cheese diversity considering fundamentally chemical, technological, microbiological and sensory characteristics to contribute to an overall characterization of the European map of cheese as well as to analyze the cheese diversity which could coin the term "turodiversity" that it is also intimately linked to territoriality, sustainability and biodiversity, as well as the preservation of product authenticity, broadening their social impact in the perspective of the common agricultural policy. This analysis suggests that Greece, Spain and Italy are the EU countries with the greatest turodiversity. Furthermore, we analyze the relationship between the protection and promotion of environmental and cultural heritage, the economic development of small local producers and the biodiversity promotion and the reduction of the carbon footprint related to EU PG cheesemaking. Considering the above-mentioned elements as part of a holistic and innovative strategy to consider turodiversity as an interdisciplinary application of knowledge and agri-food activity to improve human, animal and planetary health.

1. Introduction

After selecting dairy animals' domestication, ruminant milk and dairy products such as cheese have become fundamental foods throughout human history. Evidence of this is found in the human genome, where a strong signal of positive selection is observed on the mutation that maintains lactase activity into adult life (Irvin-Page et al., 2024).

Cheese is one of the oldest fermented food products that has a basic manufacturing technology that has experienced no important changes since it was developed several millennials ago. Archaeological evidence of cheese making based on organic matter found in ceramic stainers places the latest estimate of cheese-making origin in the Neolithic and likely became more common and important in the Copper, Bronze and Iron Age (7000 BC) in the Near East and Southeastern Europe (Evershed et al., 2008) and around 6000 BC in Northern Europe (Salque et al., 2013).

Cheese is a calcium paracaseinate reticulum strapping fat globules and a part of the soluble phase of milk (Guinee, 2003, pp. 1083–1174). The cheese yield depends on the milk's protein and fat contents as well as the ratio between the protein and fat fractions (Verdier-Metz et al., 2001).

Diverse farm-related elements such as cattle breed, genotype, feeding strategy, housing and milking systems are closely associated with milk quality characteristics and consequently the resulting cheese. Cheese elaboration has been also conditioned by the social, and fundamentally technical local conditions. Furthermore, cheese fermentation is deeply related to tradition and culture in rural landscape. The technological processes associated with the manufacturing environment shape the chemistry and microbiology of cheeses, which subsequently develop organoleptic characteristics that express and embody the identity of traditional and artisan cheeses (Fig. 1). Around the world there are over 1400 traditional cheese varieties, displaying an enormous diversity of appearances, textures, aromas and flavors. Alais (1984) suggested that

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Fig. 1. Overview of the main factors in the dairy value chain that influence the characteristics and the quality of cheese.

the quality and characteristics of milk, the technological processes that modify water:casein:fat ratio, and the effects of micro-organisms on components of milk are the main factors explaining cheese variety.

Considering the above comments, we must attend to Montanari (2006) suggestion that food is more than a source of nutrients, carries symbolic meanings too. Food is a key component of human identity and is one of the best ways to express and communicate that identity. Thus, cheese should be considered a cultural product and, consequently, is inherent to the socio-cultural and sustainability aspects of a territory.

Cheese production is currently about 25 million tons around the world, and the upward trend is set to continue, with an expected increase of 10 % between 2022 and 2031 (OECD/FAO, 2022). Around of 25 % of the human caloric diet is contributed by dairy products (milk, butter, cheese, cream and ice cream), although this consumption is low in Asian countries whereas is high in U.S.A. and Europe (OECD and FAO, 2019). Furthermore, Owolabi and Olayinka (2021) observed that according to the Food Fraud Database, dairy products have the highest fraud rate among foods, and cheese had the highest adulteration rate among dairy products. Thus, monitoring these high-consumption products is also more important.

The aim of this review is to offer an overview of comprehensive and practical integrative picture to better describe Protected Geographical (PG) cheese diversity within European Union (EU) considering fundamentally chemical, technological, microbiological and sensory characteristics to contribute to an overall characterization of the European map of cheese as well as to analyze the cheese diversity which could coin the term “turodiversity” that it is intimately linked to territoriality, sustainability and biodiversity.

2. Protected geographical status of cheese in european community

EU products almost 1000 different cheese varieties, including more of two hundred registered under PG status under EU and United Kingdom law through the Protected Designation of Origin (PDO), Protected Geographical Indication (PGI) or Traditional Specialty Guaranteed (TSG) regimes (European Commission, 2013). This normative protects regional foods and came into force in 1992 and applies in the EU and in Northern Ireland, and this protection program covers traditional cheese practices too (Donnelly, 2013). This legislation was inspired on existing national systems, such as the French AOC (Appellation d'Origine Contrôlée) and Italian DOC (Denominazione d'Origine Controllata) (European Commission, 2011). These EU designations are open for EU and non-EU products. Thus, UK cheese remained in this register after Brexit. Consequently, any PG cheese in the EU in 2020 is automatically protected in the UK as well.

PDO protects agricultural products and foodstuffs that are produced, processed and prepared in a specific geographical area, using recognized know-how. PGI protects agricultural products and foodstuffs closely linked to a geographical area; at least one of the stages of production, processing or preparation occurs in that area, while the raw material used in production can come from another area. Finally, TSG covers agricultural products and foodstuffs that are produced using traditional raw material or traditional production methods, or that have a traditional composition, with no restriction as to the product's geographical origin. EU producers are increasingly interested in using PG status to differentiate their products in international markets and thereby improve their competitiveness and profitability. On the other hand, consumers' growing interest in traditional products creates a demand for foods linked to their geographical origin and their traditional production method (Hajdukiewicz, 2014). Furthermore, there is a need to protect high quality agri-food products with PG status from possible commercial fraud. The economic value of the PDO and PGI cheese market was estimated at 7 billion euros in 2019, excluding fresh cheese and cream.

The principal objective of PG status products is to spread information about characteristic products relating to the specific factors of typicality that must be defined, verified and protected (Bertozzi, 1995). This recognition is a consequence of the actual EU agricultural policy that encourages the diversification and characterization of products in EU with the aim of achieving a better market equilibrium, reducing surplus, and stimulating an extensive agricultural production system. A strategy to improve environmental protection and to impair sociological problems with the heritage and cultural diversity of traditional agricultural products (Licitra et al., 2000).

The sustainability policies consider that the long-term development of any human activity must be structured solidly on economic, social and environmental factors. The economic relevance of PG products is enhancement in their value due to the recognition of these products as something traditional, artisan, and with overall quality. Thus, consumers preference by these kinds of products allows the predisposition to pay a higher price (Olsen et al., 2021). Moreover, PG products also contribute to the development of rural areas, the preservation of cultural heritage, and the promotion of the competitiveness of small local companies. All together contribute to the preservation and development of a

Table 1
Density of Protected Geographic Status (PDO/PGI/TSG) cheese in European Community.

	PG (PDO/PGI/TSG)	PG/Area Country	PG/Population	PG/milk production
Austria	6 (6/−/−)	71.60	0.659	1.87
Belgium	1 (1/−/−)	32.68	0.084	0.21
Bulgaria	1 (1/−/−)	9.02	0.156	1.45
Chekia	3 (-/3/-)	38.07	0.275	0.93
Denmark	4 (-/4/-)	93.24	0.677	0.70
France	58 (46/12/-)	90.84	0.846	2.40
Savoie	*6 (3/3/-)*	*576.92*	*5*	
Germany	7 (4/3/-)	19.58	0.083	0.21
Greece	21 (21/−/−)	159.57	2.019	21.43
Ireland	1 (1/−/−)	14.31	0.188	0.11
Italy	43 (41/2/-)	155.58	0.797	3.67
Lombardia	*10 (10/−/−)*	*419.39*	*0.980*	
Lituania	3 (-/3/-)	46.01	1.071	2.31
Netherland	7 (4/2/1)	187.67	0.391	0.50
Poland	5 (3/2/-)	16.03	0.137	0.39
Portugal	12 (11/1/-)	130.43	1.132	6.18
Rumania	2 (1/1/-)	8.38	0.105	1.67
Slovakia	6 (-/6/-)	122.45	1.111	7.5
Slovenia	4 (4/−/−)	197.04	1.904	8
Spain	27 (25/2/-)	53.37	0.555	3.10
Asturias	*5 (5/−/−)*	*469.92*	*4.950*	
Sweden	1 (-/1/-)	2.23	0.095	0.36
United Kingdon	17 (10/7/-)	69.78	0.251	
EU	233 (183/49/1)	50.70	0.511	

Area country (millions Km^2), population (millions of habitants), total milk production (millions of tonnes). The data were extracted from EUROSTAT (2024).

unique system that includes landscape, tradition and cultural values (Mattas et al., 2020). Finally, the ecological relevance of PG products such as cheeses is mainly linked to the valorization of the territory, the protection of indigenous cattle breeds and autochthonous microbiota biodiversity as well as local production reducing the carbon footprint of the final products.

According to DOOR database (2023), Southern European countries have the greatest number of PDO, PGI and TSG registrations and specifically cheese registrations. In this way, Italy and France stand out, having a long tradition of protecting and promoting nationally cheeses, followed by Spain, Portugal and Greece which strengthened their agricultural sectors and have recognized great appreciation for the protection and valorization of the territory and its agro-food culture. PDO is the main certification scheme in cheese production, followed by PGI and TSG, although the last named has a low number of registrations (see Table 1). According to these data, Slovenia, Netherland and Greece have the highest PG cheese density by area country. However, we must consider that French, Italian and Spanish are the more expanse European countries and particular regions such as Savoie, Lombardian and Asturias, respectively, presents three-fourfold higher cheese density that the corresponding country (Table 1) and the highest cheese density in EU geographical regions. Interestingly, Greece and Portugal have the highest number of PG cheese considering the total milk production of each respective country (Table 1).

PDO/PGI cheeses are distributed in the seven bio-geographical regions of EU (European Environment Agency) although they are majority concentrated in Atlantic, Continental and Mediterranean bio-geographical regions. Interestingly, there are great differences of PDO/PGI cheese density (number of PDO/PGI per area country/region) into a specific bio-geographical region. Per example, Spanish Atlantic bio-geographical sub-region presents high PG cheese density (12 PDO/PGI in 53 10^3 km^2) whereas Ireland Atlantic bio-geographical sub-region has a low PG cheese density (1 PDO/PGI in 85 10^3 Km^2). Thus, socio-cultural factors appear more important than bio-geographical conditions to develop a rich cheese culture and consequently a high cheese diversity (turodiversity). It should be mentioned that several EU countries do not have PG cheeses (Cyprus, Croatia, Estonia, Finland, Hungary, Latvia and Malta) and are therefore left out of this study.

The great diversity and complexity of EU PG cheese varieties do not help with the characterization and classification of cheeses. The specific traits of PDO/PGI cheeses are linked to milk differences which are related to animal species or breed, protein and fat contents and composition, chemical flavors originating from specific feeds, and renneting properties; and finally, the original microflora, as well as the technology of cheesemaking.

The fundamental cheesemaking factors include the milk type, the method of milk coagulation (acid versus rennet), the acidification characteristics (rate and time), and additional steps such as pressing and salting as well as cooking temperature conditions. Furthermore, it is important to consider the characteristics of the ripening conditions such as temperature, relative humidity, and the rates of O_2, CO_2, and NH_3 that finally condition the profile of cheese microbiota. Cheese ripening is a complex and dynamic biochemical process that produces primarily lactate metabolism, lipolysis and proteolysis, followed by secondary events, leading to the development of gross composition and volatile compounds, which makes a key contribution to texture and flavor of cheese, respectively (Luo et al., 2024).

3. Milk and turodiversity

The Roman polygraph Terentius Varro distinguished the cheeses made from goat's milk (capricus), sheep's milk (ovillus), and cow's milk (bubulus) in De re pecuaria, second book of his work De re rustica, on agricultural and livestock sciences. Now, we know that the quality and characteristics of cheese mainly depend on the quality and properties of the milk (Skeie, 2007), which in turn are linked to animal factors and to many on-farm factors such as grassland and farm conditions (Fig. 1). The literature has been reported cattle breed, genotype, lactation stage, parity, physiology-health and animal wellness are elements that influence quality and characteristics of the milk. In addition, several farm-related conditions that are closely related with milk quality characteristics are grassland factors including geographical and climatical conditions that influence pasture characteristics and consequently feed types and incorporate seasonality. Housing and farm management and milking system are additional pivotal elements of farm factors that influence milk characteristics.

According to Bertoni et al. (2001), the distinctive characteristics of PDO/PGI cheeses cannot be achieved under other farming conditions, through modifications of the raw milk, or by other processing strategies, because these must follow the specifications of the denomination. The link between raw milk quality and the quality of the final product is thus very strong for PDO/PGI cheeses, emphasizing the importance of knowledge concerning the procurement and characteristics of milk (Fig. 1).

3.1. Cattle breed and turodiversity

Cattle breed is one of the key factors influencing milk and cheese quality and diversity. Thus, some traits of cheese can be attributed to the species. Cow milk is the exclusive source of PDO/PGI cheesemaking in many countries such as Austria, Czechia, Denmark, Germany, Netherland or UK; and is the main source of French and Italian PDO/PGI cheeses (Fig. 2). Thus, most of the European PG cheeses (63 %) were prepared using cow milk. However, a great diversity of alternative milk source (goat, sheep, and mix milks) was used to cheesemaking in France and Italy, and specially in Greece, Portugal and Spain (Fig. 2) (Table 2). Table 2 also analyses the heterogeneity of milk source to produce PG cheese in EU countries. When cheeses were made using only one milk source for >60 % of PG cheeses, was assigned 0.2 as milk heterogeneity index; between 50 and 60 %, the index was 0.3; between 40 and 50 %

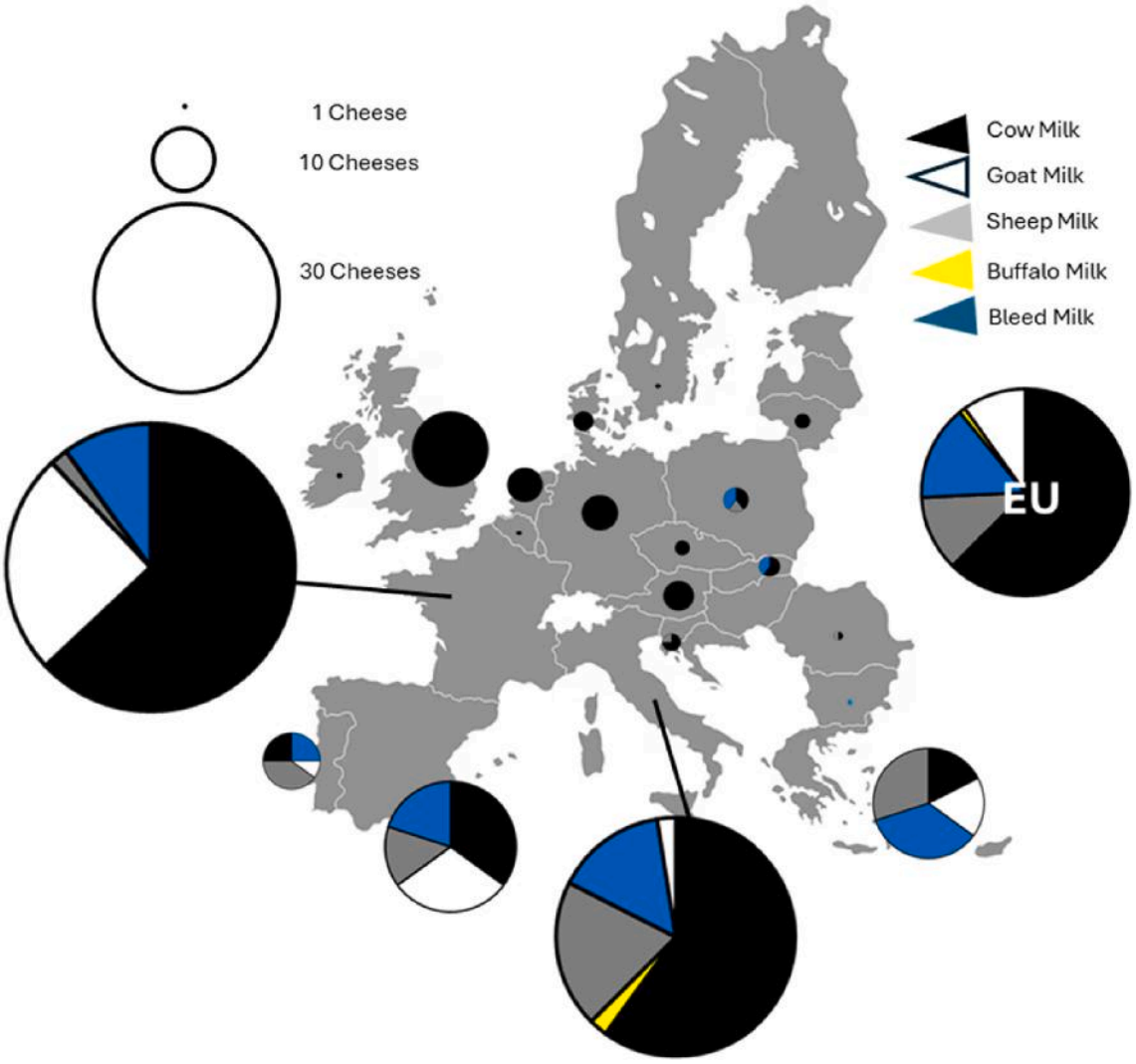

Fig. 2. Milk diversity map that represents the milk source used to the elaboration of the European PG cheeses. The data were extracted from the PDO/PGI denominations.

the index was 0.4; and for <30 % the index was 0.5. Considering these, PG cheeses of Greece, Portugal and Spain presented the higher milk heterogeneity index between EU PG cheese map (Table 2). Finally, the milk diversity index was calculated as the sum of sources of milk and the multiplied of sources of milk and milk heterogeneity index. Considering these, PG cheeses of Greece, Italy, Portugal and Spain presented the higher milk diversity index in the EU PG cheese map (Table 2).

With respect to breed, the differences are much less evident, but still important in obtaining some specific traits in the milk, and consequently in the cheese. A lot of original breeds have almost disappeared. Per example, traditional Parmigiano-Reggiano was elaborated using indigenous breeds (Reggiana and Modenese) until the end of the 1800s, when were substituted with Alpine Brown and Friesian. Nevertheless, there is renewed interest in them, because their milk has better rennet-coagulation properties which seem to be associated not only to a higher casein content, but also to differences in casein fractions (Bertoni et al., 2001). Thus, milk from specific indigenous breeds is often appreciated and used in France, Italy and Spain in the production of PDO/PGI cheeses (Table 3) resulting with a characteristic composition and organoleptic properties. Furthermore, it is important consider that the PDO/PGI cheese production contribute to protect these indigenous cattle breed that have specific characteristics adapted to the bio-geographical properties of the landscape. Thus, PDO Idiazabal and PDO Roncal cheeses elaboration have contributed to the conservation of the ancestral latxa sheep or PDO Queso Ibores are related to Retinta, Serrana and Verata goat survival. Table 3 shows the main cattle breed related to European PDO/PGI cheeses. From a perspective of sustainability which takes into consideration the social, economic and animal welfare aspects (Esposito et al., 2023), rearing these breeds help to preserve traditional productions of marginal territories, giving these breeding systems an added value. Considering the new EU Common Agricultural Policy Program, where ecosystem services will play a key role to protect and restore the forest heritage as well as to increase biodiversity (De Castro et al., 2012), indigenous breeds could be involved in this policy. Thus, among the possible breed interventions, aids for controlled grazing could be envisaged, being a tool that can have an effective help in the prevention of fires (Caballero et al., 2011) (www.ramatdefoc.org).

Recently, consumers and stakeholders involved in the milk production chain are interested in quality aspects that extend beyond the compositional traits of milk (Castellini & Graffigna, 2022). These aspects are driven by public concerns over the environmental impact and the ethical issues associated with animal welfare into the context of animal farming and milk production systems that could be integrated into the EU PG cheese system.

Table 2
Source of milk and types of cheese as main factors involved in the turodiversity of European PG of cheeses.

	Source of Milk (A)	Milk Heterogeneity Index (B)	Milk Diversity (C)	Types of Cheese (D)	Heterogeneity of Types (E)	Type Diversity (F)	Turodiversity
Austria	1	0.2	1.2	3	0.2	3.6	4.32
Belgium	1	0.2	1.2	1	0.1	1.1	1.32
Bulgaria	1	0.2	1.2	1	0.1	1.2	1.32
Chekia	1	0.2	1.2	2	0.2	2.4	2.88
Denmark	1	0.2	1.2	3	0.3	3.9	4.68
France	4	0.2	4.8	5	0.2	6	28.8
Germany	1	0.2	1.2	2	0.2	2.4	2.88
Greece	4	0.5	6	6	0.3	7,8	46.8
Ireland	1	0.2	1.2	1	0.1	1.2	1.32
Italy	5	0.2	6	6	0.3	7.6	45.6
Lituania	1	0.2	1.2	2	0.2	2.4	2.88
Netherland	1	0.2	1.2	3	0.4	4.2	5.04
Poland	3	0.4	4.2	4	0.4	5.6	23.52
Portugal	4	0.5	6	2	0.3	2.6	15.6
Rumania	2	0.3	2.6	2	0.3	2.6	6.76
Slovakia	2	0.2	2.4	3	0.2	2.6	6.24
Slovenia	2	0.2	2.4	2	0.2	2.4	5.76
Spain	4	0.5	6	6	0.3	7.6	45.6
Sweden	1	0.2	1.2	1	0.1	1.1	1.32
United Kingdon	1	0.2	1.2	4	0.2	4.8	5.76

Source of milk (A) correspond to the number of different milks used to make PG cheese of each EU country. Milk heterogeneity index (B) correspond to the distribution of milk used. When cheeses were made using only one milk source for >60 % of PG cheeses, was assigned 0.2 as milk heterogeneity index; between 50 and 60 %, the index was 0.3; between 40 and 50 % the index was 0.4; and for <30 % the index was 0.5. Milk diversity C = A + A x B. Type of cheese correspond to technological types using to cheese-making (D). Heterogeneity of types of cheese (E) correspond to the distribution of technologies used. When PDO/PGI cheeses were the same type of cheese, was assigned 0.1 as type heterogeneity index; when >60 % PDO/PGI cheeses correspond to a type, the index was 0.2; when 60-50 % PDO/PGI cheeses correspond to a type, the index was 0.3; and for <50 % the index was 0.4. Type diversity F = D + D x E. Turodiversity correspond to the multiplication of milk diversity and type diversity. The data were extracted from the PDO/PGI denominations.

Table 3
Main indigenous cattle breed involved in PDO/PGI cheesemaking.

PDO/PGI	Cattle	Indigenous breed
Afuega'l Pitu	Cow	Asturiana
Arzùa-Ulloa	Cow	Parda Alpina, Rubia Gallega
Beaufort	Cow	Abondance, Tarine
Bleu du Vercors-Sassenage	Cow	Abondance, Montbeliard
Bovški sir	Sheep	Bovec
Brousse du Rove	Goat	Rove
Caciocavallo	Cow	Podolica
Cantal	Cow	Saler
Canestrato Pugliese	Sheep	Gentil Puglia (Merina)
Comtè	Cow	Montbeliard, Simmental
Fiore Sardo	Sheep	Sarda
Fontina	Cow	Valdostana
Formaggella del Luinese	Goat	Camosciata, Saanen, Nigra de Verzasca
Idiazábal	Sheep	Carranzana, Latxa
Nostrano Valtrompia	Cow	Bruna
Queso Casín	Cow	Casina
Queso Ibores	Goat	Retinta, Serrana, Verata
Queso Majorero	Goat	Majorera
Queso Manchego	Sheep	Manchega
Queso Palmero	Goat	Palmero
Queso Tetilla	Cow	Parda alpina, Rubia gallega
Ragusano	Cow	Modicana
Roquefort	Sheep	Lacaune
Roncal	Sheep	Latxa
Single Gloucester	Cow	Gloucester
Spressa delle Giudicarie	Cow	Rendena, Bruna, Pía
Teviotdale Cheese	Cow	Jersey

3.2. Milk microbiota and turodiversity

The milk microbiota is highly dynamic and subject to variation between farms and times of collection (Skeie et al., 2019) and between housing and milking systems (Du et al., 2020). It is also influenced by the production environment and farm management practices (Doyle et al., 2017), and there are additional variations due to differences in the mammary microbiome of animals (Andrews et al., 2019). The microbiota profile in raw milk may influence the characteristics of milk, and consequently the organoleptic properties of cheese. Thus, the specific conditions for milk production should be considered when the milk is obtained to produce cheese with unique characteristics such as European PG cheeses. The characterization of these conditions would improve the current understanding of the relationship between farm and management factors and milk quality. As recently example, Santamarina-García and co-workers (2024) reports the role of the artisanal dairy environments in conditioning cheese microbiota and, consequently, quality and safety of PDO Idiazabal cheese. These results support the importance of the territoriality of each cheese produced in each micro-region. Thus, additional research that considers dairy landscapes within broader perspectives and develops multidimensional approaches to control the quality and properties of milk intended for European PG cheese elaboration is recommended.

Raw milk cheesemaking is strictly regulated in EU by PDO/PGI quality scheme that guarantees traceability. Nevertheless, the organoleptic characteristics of the cheeses under the same PDO/PGI denomination differ between manufactures as consequently, at least in part, of local microbiota, factors not considered by the PDO/PGI denominations. Furthermore, the evolution of microflora in cheeses with PG status is of particular interest because the biochemical processes induced by these organisms participate in cheesemaking and play a key role in the development of characteristic organoleptic properties during ripening as well as bio preservative shield against microbial pathogenic and spoilage populations.

4. Cheese technology and turodiversity

In De re rustica, Varro describes two kinds of rennet to make cheese, vegetable rennet (gallium flowers, fix latex, crocus seeds) and animal rennet. Furthermore, he preferred mineral salt to sea salt to salting cheese and distinguished between “fresh and soft cheese” and “aged and dry cheese”. But perhaps, the most complete historical description of the different steps and elements in cheesemaking is given by Lucius Junius Moderatus Columella from Gades (Cadiz) in his treatise on agriculture,

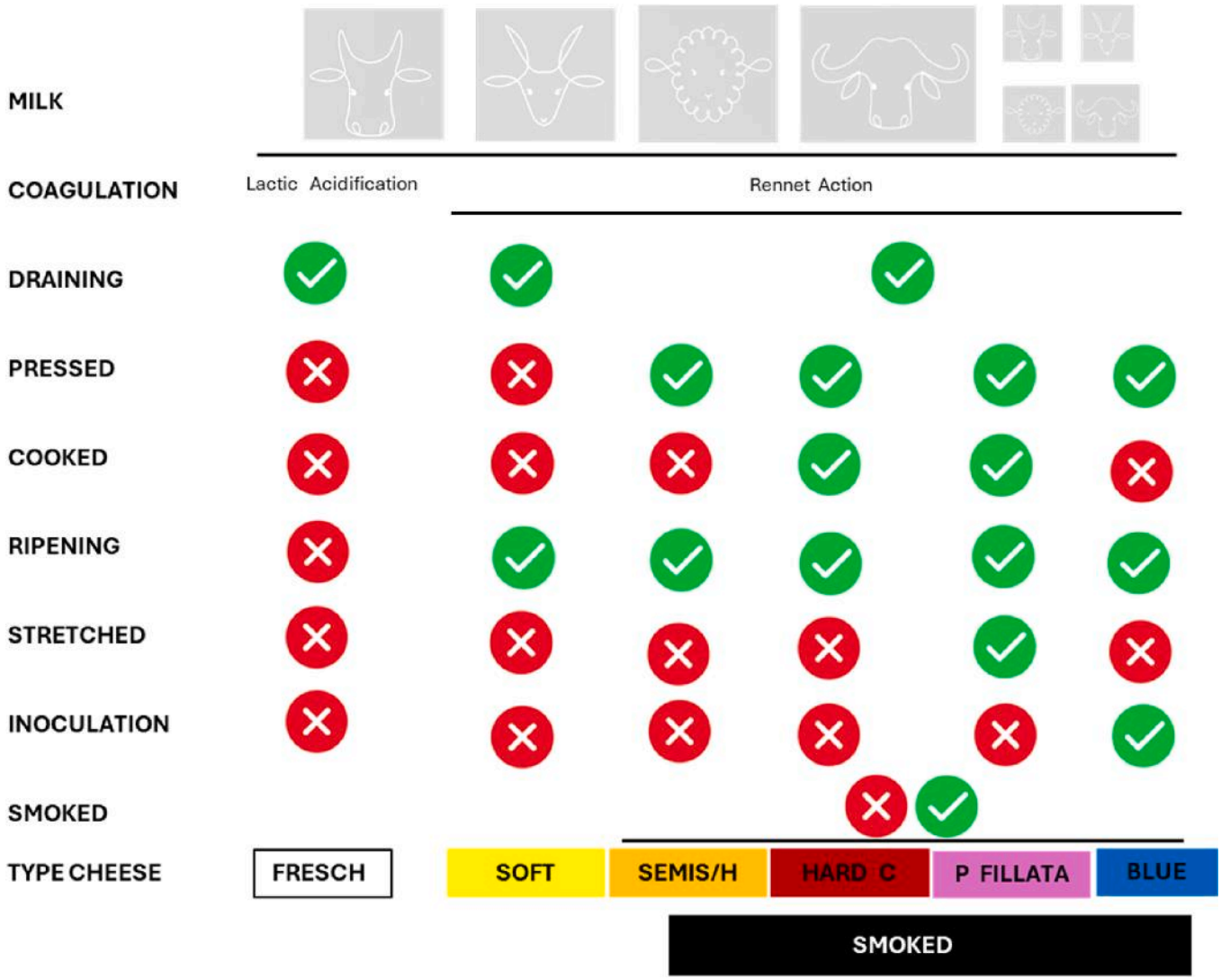

Fig. 3. Cheese classification considering milk source, conditions of coagulation, draining, pressed, cooked, ripening, stretched, inoculation and smoked.

entitled De Re Rustica. Milk coagulation and cheese manufacturing have experienced no major changes since it was described by Columella that finalize with an aging process, called maturation or ripening, that lead to a profound change in their physicochemical, biochemical, microbiological, and organoleptic characteristics (McSweeney, 2004).

Multiple cheese classification models exist but few studies have analyzed the interest of using a global approach for this characterization and classification. Most of the published literature addressing this classification mainly based on chemical and technological characteristics of each cheese as proposed by Lenoir et al. (1985). This classification considers that three main processing steps such as coagulation, draining and ripening define the type of cheesemaking technology and chemical characteristics of each cheese. Considering this, the cheeses can be classified as fresh cheese (lactic coagulation, no draining, no ripening), soft uncooked unpressed cheeses (rennet coagulation, slow draining, ripening), soft/semisoft and hard uncooked pressed cheeses (rennet coagulation, draining favored by cutting, stirring and pressing, ripening), and finally hard cooked cheeses (rennet coagulation, draining favored by cutting, stirring, heating, pressing, ripening).

More recent Sperat-Czar and Mietton classification (Sperat-Czar and Mietton, 2003) has included the pasta filata and blue cheeses as additional cheese types. Blue cheeses exhibit distinctive characteristics particularly due to the use of the well-known mold *Penicillium roqueforti* that have high enzymatic activities that induce a profound transformation of the cheese composition and its organoleptic properties (Gillot et al., 2017). In this way, it is commonly accepted that some cheese microbes have been selected for their specific traits and maintained through continuous passaging. For example, *Penicillium camemberti* found on Camembert cheese rind show genomic and phenotypic characteristics that distinguish them from their wild counterparts (Landis et al., 2021) or domesticated *Penicillium roqueforti* on blue cheeses (Ropars et al., 2017).

4.1. PG cheese classification

Considering the above-mentioned antecedents as well as Fox et al. (2017) proposal, cheeses have been classified in seven types: fresh, soft (unpressed), semisoft/hard (pressed), hard cooked, pasta fillata, blue and smoked (Fig. 3). Fig. 4 summarizes the European PG cheeses that have been ordered considering this classification, and I calculate a heterogeneity type factor. Furthermore, I analyzed the diversity of European PG cheese attended this classification. Thus, semi soft/hard cheeses were the more extended technology. As we can see in Fig. 5, most of the type of cheese are represented into the PG cheese of France, Greece, Italy and Spain. Hard cooked cheese is characteristic of central EU countries and fresh cheeses are representative of oriental EU zone.

Table 2 shows the types of cheese per country and the heterogeneity of types of cheese. When PDO/PGI cheeses were the same type of cheese

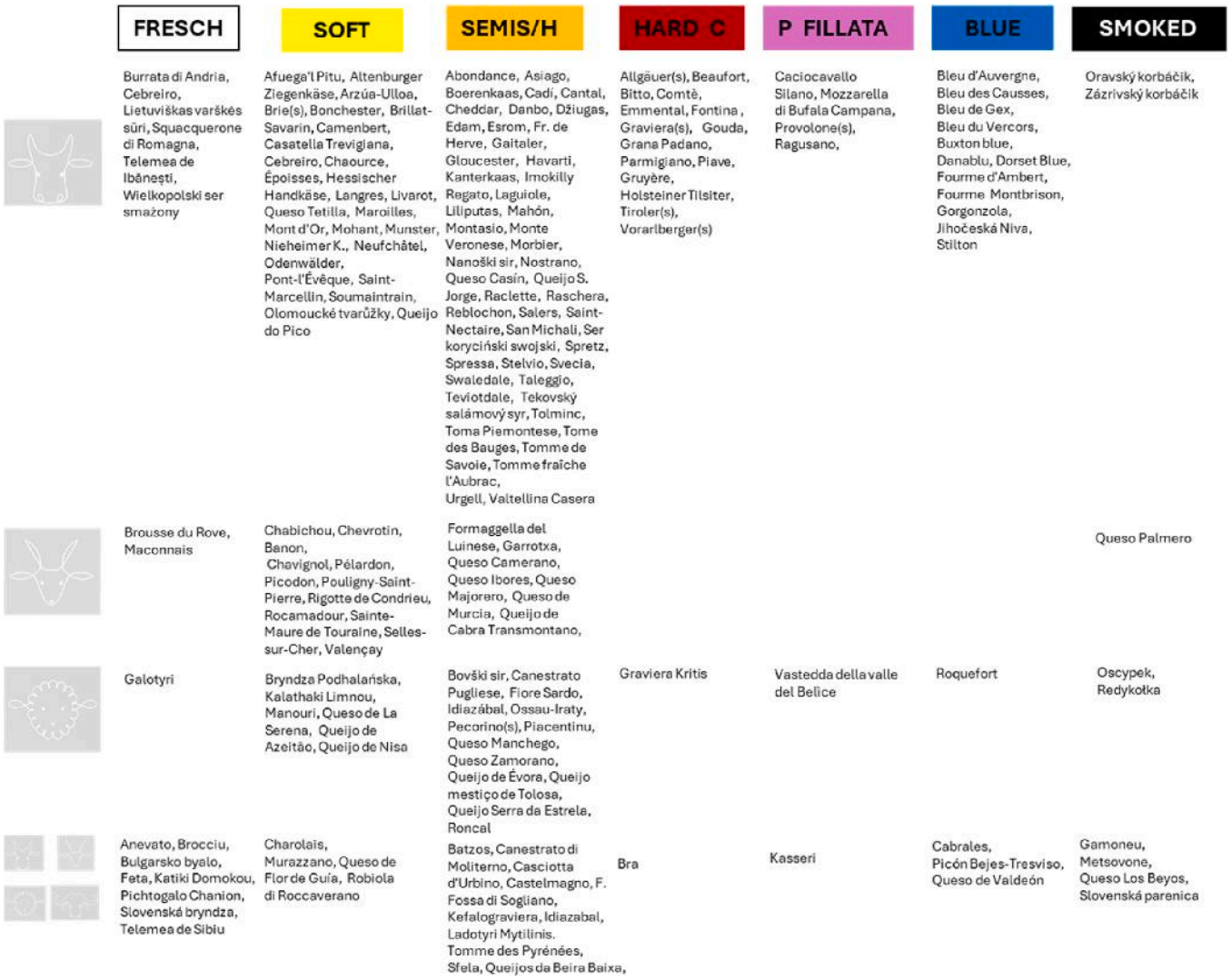

Fig. 4. European PDO and PGI cheeses ordered considering the milk source and the technology used in their elaboration. The data of PDO/PGI were extracted from DOOR data base and PDO/PGI denominations.

per country, was assigned 0.1 as type heterogeneity index; when >60 % PDO/PGI cheeses correspond to a type, the index was 0.2; when 60-50 % PDO/PGI cheeses correspond to a type, the index was 0.3; and for <50 % the index was 0.4. Considering these, PG cheeses of Netherland and Poland presented the higher type heterogeneity index between EU PG cheese map (Table 2). Finally, the type of diversity index was calculated as the sum of type of cheeses and the multiplied of type of cheeses and type heterogeneity index. Considering these, PG cheeses of Greece, Italy, and Spain presented the higher type diversity index between EU PG cheese map (Table 2). Finally, the turodiversity index was calculated by multiplying the milk diversity index and the type diversity index. Thus, PG cheeses of Greece, Italy, and Spain presented the higher turodiversity between EU PG cheese (Table 2).

Several Roman writers such as Cato the Elder, Columella, Pliny the Elder, and Varro described the cheesemaking process as well as the properties, and the culinary uses of cheese. Romans were considered major cheese consumers and used cheese in numerous recipes collected in famous cookbooks such as De re coquinaria (Marcus Gavius Apicius). Furthermore, cheese was a fundamental part of roman diet and was an element in the rations of legionnaires. Thus, cheesemaking was well known among the Romans, who spread the knowledge of fresh and aged cheeses elaborate from sheep, goats and cows' milk along the Empire. Considering that turodiversity index was highest in the Mediterranean countries such as Greece, Italy and Spain (Table 2), these facts could be consequence, at least in part, of Roman gastronomy tradition previously mentioned.

5. Sensorial characteristics of EU PG cheeses and turodiversity

Cheese is a complex organoleptic food. Texture, taste and flavor are the main attributes although external (size, shape, appearance of the cortex) and internal (color, homogeneity, presence of holes) aspects are also important, and all consequences of the methodology of cheesemaking.

5.1. *EU PG cheeses texture diversity*

Cheese is a soft solid material consisting of a network of water, proteins and lipids and its mechanical properties are related to network composition and interactions among these components. Thus, the perception of cheese texture can be described through hand evaluation terms (hand firmness, hand springiness or hand rate of recovery) and mouth evaluation terms (firmness, hardness, fracturability, degree of breakdown, cohesiveness, adhesiveness, or smoothness of mass) (Brown et al., 2003; Delahunty & Drake, 2004).

There are a great variety of textures between EU PG cheeses that

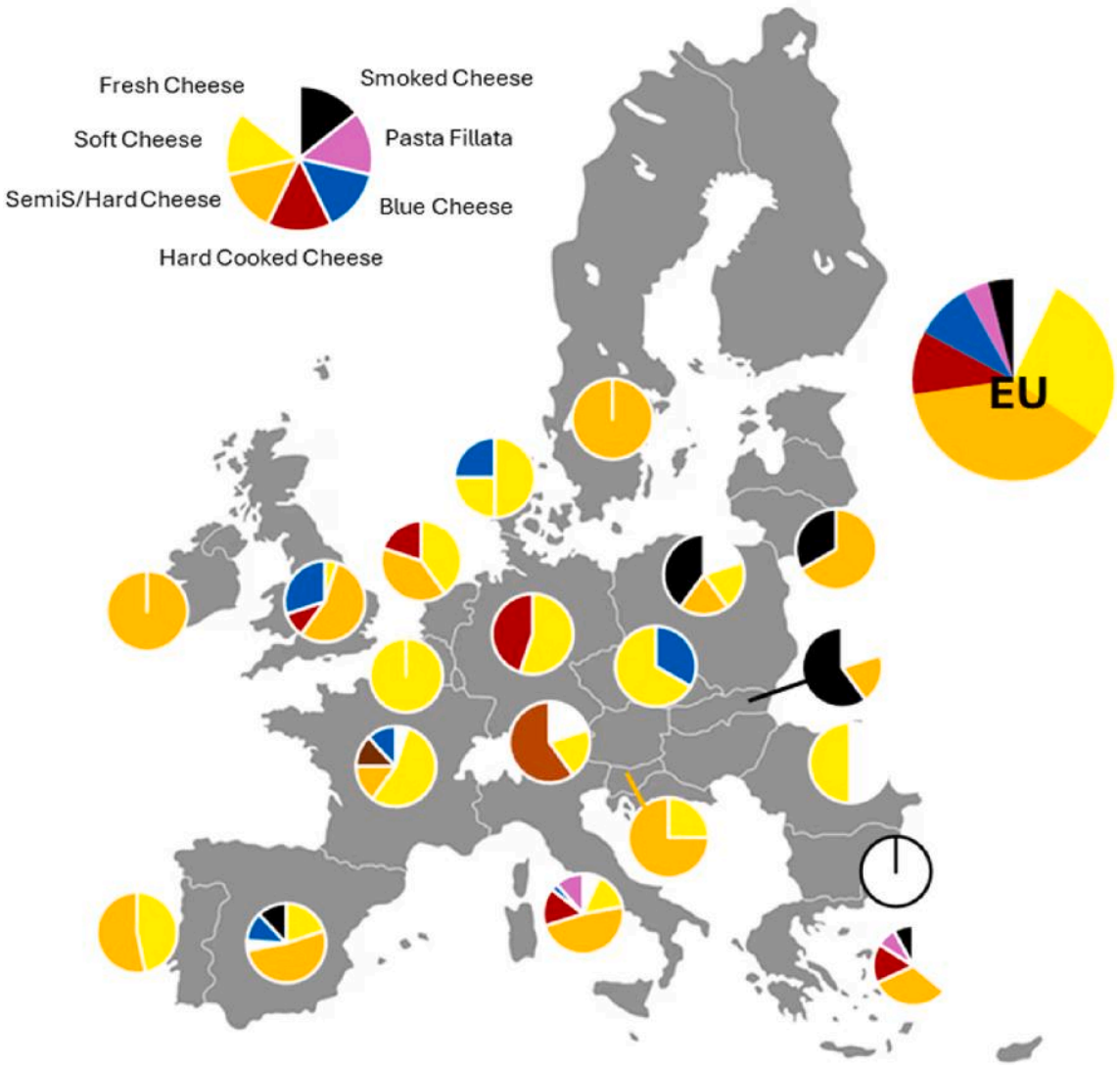

Fig. 5. Cheese technology diversity map represents the cheese technologies used to the elaboration of the European PG cheeses. The data were extracted from the PDO/PGI denominations.

have been considered to propose a cheese classification system based on this attribute. It is important consider that while in the Anglo-Saxon model, soft, semisoft and hard are used to describe cheeses considering its consistency, in the French model "soft cheese" is exclusively used for a cheese that does not involve pressing during its elaboration. This last criterion has been considered in the proposed classification here (Fig. 3). As we can see in Fig. 4, EU PDO/PGI cheeses present numerous examples to each characteristic texture such as soft cheese and semihard and hard cooked cheeses which are the majority.

5.2. EU PG cheeses taste and flavor diversity

Salty and sour are directly related to technological processes such as salting and coagulation, respectively. Sweet and umami tastes are related to the presence of monosaccharides and free amino acids produced as consequence of the biochemical changes during cheese maturation. Bitterness in cheese has been linked to $MgCl_2$ and $CaCl_2$ content, type of bacterial cultures and rennet applied that conditioned peptide release from casein breakdown with bitterness effects (Kuhfeld et al., 2024).

We can observe a great heterogeneity of taste between EU PDO/PGI cheeses, and several gustatory characteristics related to cheesemaking techniques. Thus, salty and sour are the main taste present in fresh cheese. Soft cheeses present additional tastes such as sweet, bitter and occasionally also umami. This last taste is more usually present in semihard and hard cheeses, and bitterness is a common taste of aged cheeses (Fig. 6).

Flavor is a major attribute affecting acceptability, palatability and consumer's preference for cheese, and the aroma and flavor are related to diverse volatile components, which individually do not reflect the overall odor. These compounds are developed as consequence of physicochemical, biochemical and microbiological processes mediated by enzymes and microorganisms and they are related to the basic steps of cheese manufacturing such as milk selection and treatment, curd making, whey draining, molding and pressing, and salting. Finally, ripening conditions (time, temperature, environment) also condition cheese flavor profile of each variety (Mc Sweeney & Sousa, 2000). During the above-mentioned processes numerous volatile compounds are formed through the metabolism of proteins, lipids, and carbohydrates to produce acids, alcohols, aldehydes, ketones, esters, lactones and sulfur compounds (Marilley & Casey, 2004; Yvon & Rijnen, 2001). Furans, terpenes, and hydrocarbons are also present in some types of cheese. Collectively, this array of compounds imparts characteristics flavors in a synergistic way to each type of cheese (Fig. 6). Consequently, turodiversity is manifested in an enormous rich diversity of flavors.

Recent advances in next generation sequencing methods that include

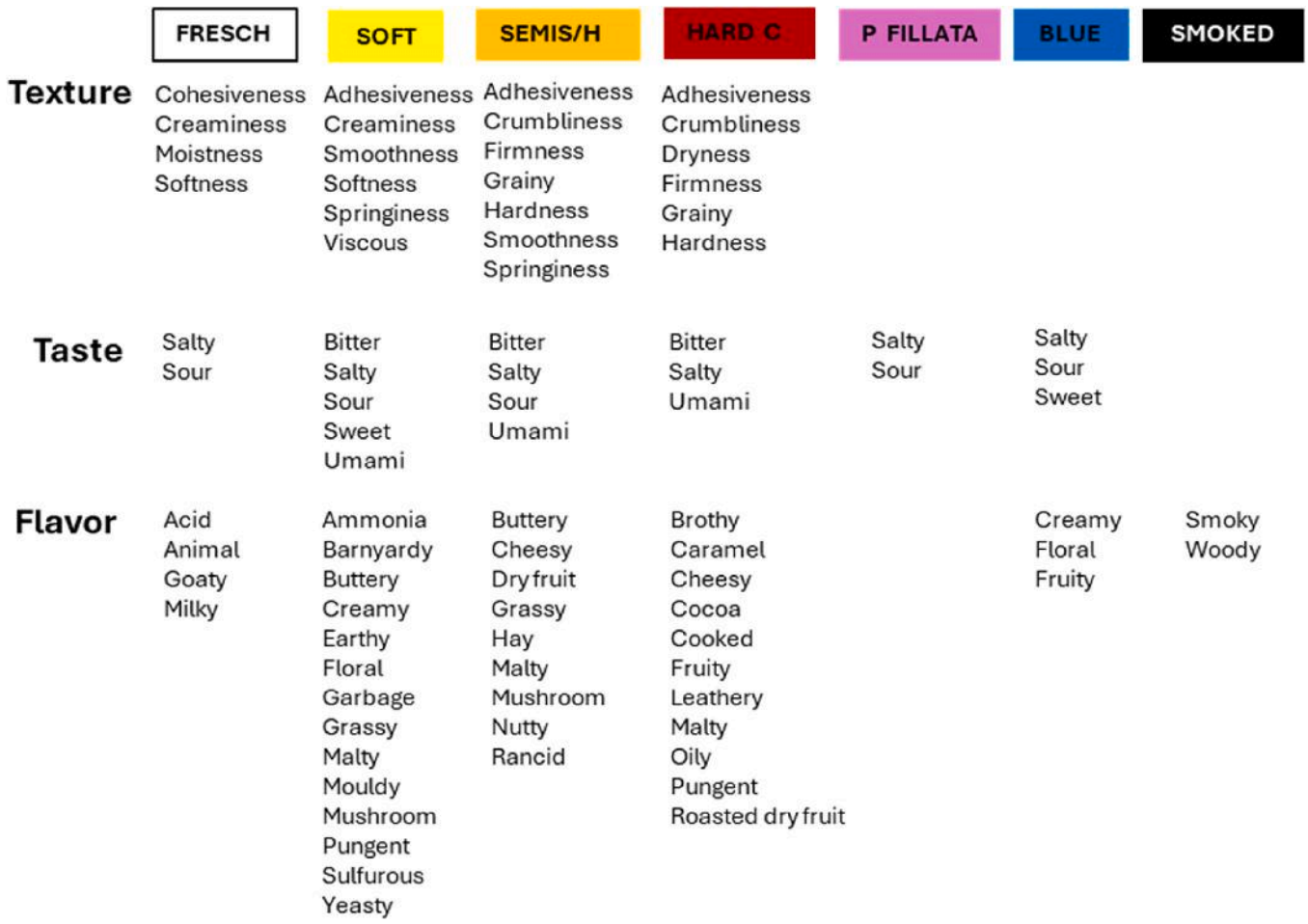

Fig. 6. Main sensory attributes of texture, taste and flavor of each type of cheese. The data were extracted from the PDO/PGI denominations.

meta-transciptomics, meta-proteomics and metabolomics together with sophisticated bioinformatics tools can provide deeper insights of cheese characteristics and potential functionally (Afshari et al., 2020). The application of these meta-omics technologies can lead to a better understanding of EU PG status cheeses and highlights opportunities by which the integration of outputs from diverse multi-omics analytical platforms (called "cheesomics") could be used to advance our knowledge of the cheesemaking and identify cheese quality and safety biomarkers as well as to characterize texture and flavor. Furthermore, cheesomics can contribute to discover and unravel the mechanisms by which cheese nutrients, metabolites and microbiota present potential health effects (Rizzoli & Biver, 2024) and offers an opportunity to discover novel bioactive compounds from the rich patrimony of EU PG status cheeses.

6. Turodiversity into protected geographical status of cheese in european community

Ecological factors such as climate, soil and human activities determine the phenotype of raw foods such as milk and may thereby affect the assembly of food fermentation microbiota. The concept of "terroir" refers to the set of unique characteristics that a specific geographic area brings to the agricultural products grown in this area. Although, originally coined to describe the link between local growing conditions and the sensory characteristics of wine (Brillante et al., 2020), this concept could be extended to other fermented foods such as cheese. However, the existence of a "terroir" among cheeses remains a controversial issue. Interestingly, the organoleptic qualities of the cheeses under the same PG denomination differ between producers. The role of bio-geographical factors on the characteristics of PG status milk and cheese could be related to coalescence with microbiomes in the environment of dairy ruminants (pastures, water), cheese dairies (brine, vats) and maturing cellars. These factors shape the environmental microbial exposome for milk and cheese that have an important impact on the composition and organoleptic characteristics of cheese that are not considered by the PG denominations, at least now.

In this respect, Irlinger and co-workers (2024) recently performed an exhaustive microbiota analysis of more than 2000 cheese samples from French PDO cheeses. They observed that microbiota profile was influenced by geographical factors and human practices and foster the link between PDOs and their "terroir". These findings, in agreement with Wolfe et al. (2014), highlighted the importance of considering the milk-cheese continuum in a microbial bio-geographical analysis of cheeses that also consider biochemistry. Magliulo and co-workers (2024) also performed the characterization of microbiome composition and the flavor profile of PDO buffalo mozzarella cheeses from the two main PDO areas (Caserta and Salerno), observed significant differences based on the geographical origin of cheeses. These findings also suggest that the microbiome of cheeses and its specific metabolic activity and volatile compounds involved in flavor mozzarellas are part of the "terroir" that shape mozzarella specific features, linking this traditional product with its area of elaboration. In this way, other studies have recently analyzed the cheese diversity under Roccaverano PDO cheese (Buzzanca et al., 2025), Portuguese Serra da Estrela PDO (Salamandane et al., 2024), Queijo da Beira Baixa PDO (Cardinali et al., 2022) and Queijo de Azeitão PDO (Cardinali et al., 2021).

Following the example of wines, there have also been some attempts to define the so-called 'cru', i.e. the small geographical area where the

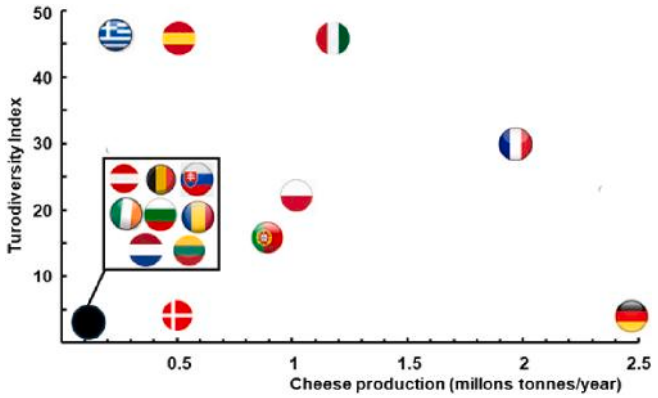

Fig. 7. Representation of the turodiversity index versus the total cheese production in each EU country that has EU PG cheeses. The cheese production data corresponds to the year 2024, according to Eurostat data.

PG cheeses have special traits mainly related to the forage base of the cattle diet (Coulon, 1997). Considering these, important cheese producers, such as Parmigiano-Reggiano in Italy and Comté in France, establish that the cows must be fed local forages (while the use of silages is prohibited) (Bertozzi, 1991); this statement would confirm a direct link between the bio-geographical factors and the final cheese characteristics, which is the basis of every factor of typicality (Bertozzi, 1995).

Together these findings highlighted the need to consider the production site-specific microbial metabolism to understand and guarantee the organoleptic features of the cheese recognized as PG status. Furthermore, these findings will support EU PG cheese sector stakeholders in their commitment to maintaining the turodiversity, considering the specifications for each PG in a vulnerable context considering the effects of climate change on livestock farming. On the other hand, a best knowledge of turodiversity opens new clues to the possibility of using microbial and volatile compounds patterns as a fingerprint of the local cheese production and developing novel systems to safeguard the traceability and quality of PG status cheeses and contributing to fraud detection.

7. Conclusions and perspectives

Along the review, we have seen that there are numerous aspects (milk diversity and diversity of cheesemaking technologies) that influence turodiversity, but more than bio-geographical or economic aspects, it is the cultural heritage that are most important and this is reflected in the fact that the country with the highest cheese production in the EU (23 %), Germany, has a very low turodiversity, while countries with a small production of cheese such as Greece and Spain (7 % of EU production both together), have a great deal of turodiversity (Fig. 7),

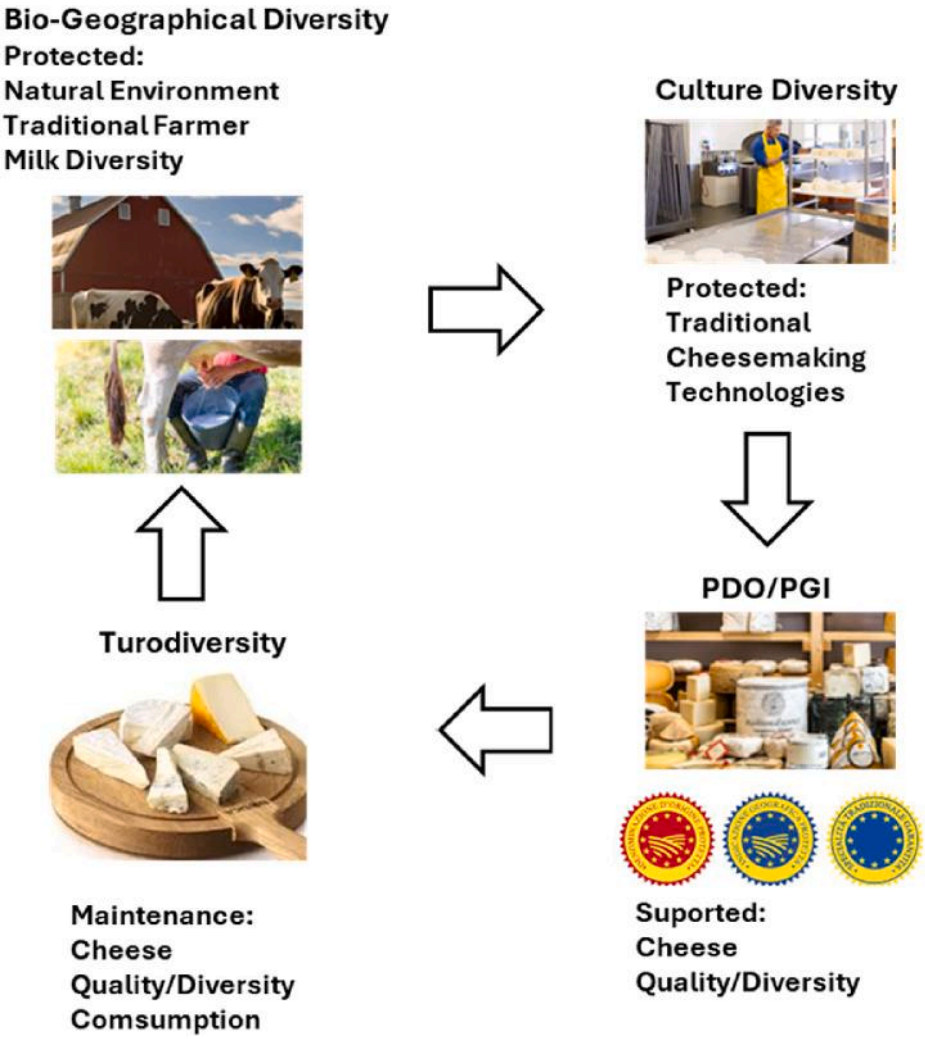

Fig. 8. Graphic representation of the virtuous cycle that related environmental conditions of semi-natural habitats, extensive farm systems and milk production, traditional cheesemaking systems, and supporting of cheese quality/diversity and PDO/PGI recognition.

probably consequence of their sophisticated gastronomic culture, at least in part.

Furthermore, turodiversity has an important role in supporting the maintaining and disseminating the traditions and culture of small territories and markets and consequently has a transcendental impact on the ecological and socio-economic resilience of rural regions as well as the global environment. In this way, there are recent initiatives to study the environmental impact (footprint) of high nature value farming systems and pivotal extensive ruminant food products such as milk and cheese (Torres-Miralles et al., 2025) to understand the potential role of these high nature value farming systems in transitioning toward a more sustainable food production and consumption.

PDO/PGI cheeses have specific traits, and they are made possible by milk characteristics and to the art and tradition of the cheesemakers. There is no doubt that today science and technology can help the PDO/PGI cheese production system, but this must be done without losing their particular and traditional characteristics. The multidisciplinary studies involving different omics sciences on cheese, called cheesomics, transform a discourse that could be seen as merely geographic, political, and subjective into a theme based on the chemical, biological and sensory characteristics of each cheese, a knowledge that helps to understand turodiversity to optimize cheesemaking process and to improve the overall quality of cheese.

In conclusion, we must consider the above-mentioned cheesemaking elements along the review as part of an innovative strategy to promote multi-sectorial and interdisciplinary application of knowledge and agri-food activities by working together to reach human, animal and planetary health (Fig. 8).

Finally, We have to consider as a limitation that this study and analysis has been carried out only considering the EU PG cheeses which is a part of the European cheeses, although it should be noted that it is a representative and well-characterized sample.

Furthermore, we can consider several new perspectives to integrate into the universe of EU PG cheeses. Milk produced in extensive organic systems is perceived by consumers as having a lower environmental impact than those obtained under intensive conditions. Interestingly, this is not always the case, and the environmental impact of traditional and organic systems cannot be supposed (Capper et al., 2009). An alternative strategy to evaluate the ecological footprint of milk products is the nutrient-focused life cycle assessment (nLCA) (Doran-Browne et al., 2015), recently endorsed by the FAO (McLaren et al., 2021). Thus, including nLCA information would allow an objective evaluation of the ecological footprint of the PDO/PGI cheeses and the transmission of more complete and appropriate information to consumers.

A wide accepted definition of animal welfare was proposed by the Farm Animal Welfare Council (2009) and the more recent concept emphasizes the importance of providing animals with opportunities for positive experiences, transcending the mere alleviation of suffering (Rault et al., 2020). Unfortunately, there is a lack of validated relationship between the indicators used and the real welfare state of the animals. These facts show the need for the development of reliable measures that can accurately analyze the true welfare conditions experienced by ruminants, including this recognition as additional PDO/PGI cheese quality standard driving the consumer's choice. These and other initiatives can contribute to improving turodiversity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

PDO, protected designation of origin; PG, protected geographical; PGI, protected geographical indication; TSG, traditional specialty guaranteed.

Data availability

No data was used for the research described in the article.

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