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Unlocking the potential of non-timber forest products: insights from the acorn and the pine nut value chains in Portugal

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Acorn (*Quercus* spp.) and pine nut (*Pinus pinea* L.) value chains in Portugal reflect contrasting development paths of non-timber forest products (NTFPs). Using a mixed-methods approach, combining stakeholder surveys, participatory workshops, and literature review, our study analyzes their structure, governance, and challenges. We map the network of actors and activities, highlighting key bottlenecks in both value chains. We found that the pine nut chain is industrialized and commercially consolidated but faces persistent issues such as yield variability, price volatility, and limited innovation. In contrast, the acorn chain remains largely artisanal, constrained by underdeveloped processing infrastructure and scalability barriers, but driven by cultural values and grassroots innovation. In terms of governance models, pine nuts operate within top-down, actor-driven systems, while acorns are shaped by bottom-up, community-led initiatives embedded in territorial identity. Our findings highlight that these NTFP value chains function within broader socio-ecological systems, shaped by land-use histories and cultural contexts. We suggest that for unlocking their full potential it is required adaptive governance, cross-sector collaboration, and investment in innovation. Supporting such integrated value chains could enhance rural livelihoods and a transition to a bio-based economy.

KEYWORDS

bioeconomy, rural development, adaptative governance, *Quercus* spp., *Pinus pinea*

1 Introduction

Non-timber forest products (NTFPs) include all biological materials other than timber that are harvested from both managed and degraded forests for human use (Muir et al., 2020; Shackleton et al., 2011). According to FAO (1999) they are biological products, other than wood, derived from forests, other wooded lands, and trees outside forests. In cases where NTFPs are cultivated, such as in plantations, they play a dual role in supporting local livelihoods and contributing to biodiversity conservation (Solomon, 2016; Zhou et al., 2023).

They provide diverse income opportunities for non-industrial forest owners and rural communities. The expansion of NTFP plantations has been driven, in part, by increasing off-farm employment, reflecting changing rural labor dynamics (Zhou et al., 2023). Additionally, integrating them into forest plantation management can enhance biodiversity and ecological resilience, mitigating the shortcomings of conventional plantations. However, as noted by Ingram et al. (2014a), to prevent resource degradation, harvesting must be conducted under a sustainable framework. Without appropriate

regulation, overexploitation may occur. Governance institutions, whether formal, international, customary, or market-based, must oversee and regulate NTFPs-based activities (Ingram et al., 2014b). Moreover, effective management practices, including policies that promote sustainable harvesting and community engagement, are influential for maximizing the potential of NTFP value chains (VC) (Bauhus, 2010; Chamberlain et al., 2019).

Amid calls for a transition to a bio-based economy, NTFP value chains are emerging as important drivers of rural economic development (Huber et al., 2023). In the Portuguese context, a wide range of NTFPs holds significant social and economic value. However, despite increasing concern for forest ecosystem health and livelihood diversification, there is still limited research on the value chain dynamics within the NTFP sector (Muir et al., 2020). Terms such as *"market"* and *"value chain"* are often used interchangeably to describe economic interactions (Gunasekaran et al., 2001), yet they refer to substantially different concepts. While *markets* capture transactional dynamics within a specific context and timeframe, *value chains* provide a broader analytical lens that traces how value is created, distributed, and governed across multiple stages, from production to consumption (Boscolo et al., 2025). In the case of acorns and pine nuts, adopting a value chain perspective is particularly relevant, as it allows us to integrate not only economic flows but also the socio-ecological and cultural factors that shape their production and use. The data gaps identified, underscore the need to involve value chain actors directly in data collection and validation, thereby improving the accuracy and reliability of value chain mapping. To address this challenge, we offer a holistic analysis of the acorn (*Quercus* spp.) and pine nut (*Pinus pinea L.*) value chains in Portugal, integrating socio-economic, and governance dimensions.

Social-ecological systems are complex adaptive systems where people and nature are closely interlinked (Reyers et al., 2018; Folke et al., 2016; Levin et al., 2013; Berkes et al., 1998). The social component refers to all human activities that include economy, technology, politics and culture. On the other hand, the ecological component refers to the biosphere, that is, to the part of the planet on which life develops (SARAS Institute, 2019). By integrating a socio-ecological approach perspective for mapping value chains, whether forest or agri-based, and treating the ecological and social components as more than resources for production, a holistic view is created, allowing for an integration of cultural and social aspects from different actors along the chain (Fabre et al., 2021; Belliggiano et al., 2024). This value chain analysis offers a structured approach to understanding the roles, relationships, and power dynamics among actors (FAO, 2007), as well as the economic, social, and environmental dimensions within VC. NTFPs VC are dynamic and diverse and can operate from local to national and global level (Boscolo et al., 2025; Ingram et al., 2018). As Escobedo Aguilar et al. (2018) note, mapping VC involves identifying key activities, such as production, transformation, commercialization, and consumption, and representing the flow of these activities across various actors, both direct and indirect. Direct actors include primary producers, harvesters, processors, traders, while indirect actors are the one providing support services like certification, therefore they could be service providers (Escobedo Aguilar et al., 2018). Products embody multiple layers of value, economic, social, cultural, and environmental (Ingram et al., 2018). Mapping the value chain also helps identify critical bottlenecks that limit competitiveness, offering opportunities for innovation and improvement (Escobedo Aguilar et al., 2018). It also serves as a tool to explore governance structures and identify strategic points for intervention and improvement (Boscolo et al., 2025; Humphrey and Schmitz, 2001).

While previous studies, such as Sacchelli et al. (2021), have conducted financial analyses of the acorn value chain, a comprehensive, end-to-end analysis has yet to be performed. The Mediterranean Forest Union UNAC has provided a foundational overview of the pine nut value chain in Portugal, offering an initial framework for understanding its dynamics within Mediterranean forest systems (Agri-ciência, 2014). However, the primary data collection, meaning the online survey and the participatory workshops conducted in this study allowed for a deeper analysis of the challenges and opportunities faced by actors and the governance model along the value chain. Our literature review further expanded our understanding of the adaptive governance mechanisms shaping these value chains, providing insights that go beyond the scope of previous reports and offering a more complete view of both value chains.

This study aims to map and analyze the acorn and pine nut value chains in Portugal using a socio-ecological systems lens. We argue that understanding these interconnections is key to highlight the potential of value chains to support sustainable forest and plantation management and uncover leverage points for landscape-level sustainability. Drawing on established value-chain methodologies (Kaplinsky and Morris, 2001; Escobedo Aguilar et al., 2018; Tallec and Bockel, 2005), and inspired by Sørensen et al. (2021) analysis of the cork value chain, we analyze the governance and socio-ecological relationships shaping acorn and pine nut value chains. The objective is to pinpoint practical challenges and opportunities, as well as potential leverage points for improving the sustainability and resilience of these two non-timber forest product value chains in Portugal.

2 Study area and socio-ecological context

The distribution of *Pinus pinea* (stone pine) and various *Quercus* species across Portugal provides essential ecological context and helps explain the seasonality and cultural practices linked to pine cone and acorn harvesting (Figures 1A,B). Several oak species are widespread throughout the country, including Cork oak (*Q. suber* L.), Holm oak (*Quercus rotundifolia* Lam.), Pyrenean oak (*Q. pyrenaica* Willd.), Portuguese oak (*Q. faginea* Lam.), English oak (*Q. robur* L.), collectively covering approximately 1.15 million hectares (ICNF, 2015). Figure 1A illustrates the distribution of major *Quercus* species, including Cork oak (*Q. suber*), Holm oak (*Q. rotundifolia*), and other oaks, and Figure 1B presents the distribution of *Pinus pinea* (stone pine) based on data from the 6th National Forest Inventory (NFI) from ICNF (2015).

Approximately 63% of this oak-dominated area forms part of traditional silvopastoral systems known as *montado*, especially prevalent in Alentejo, south of the Tagus River. The *montado* is a

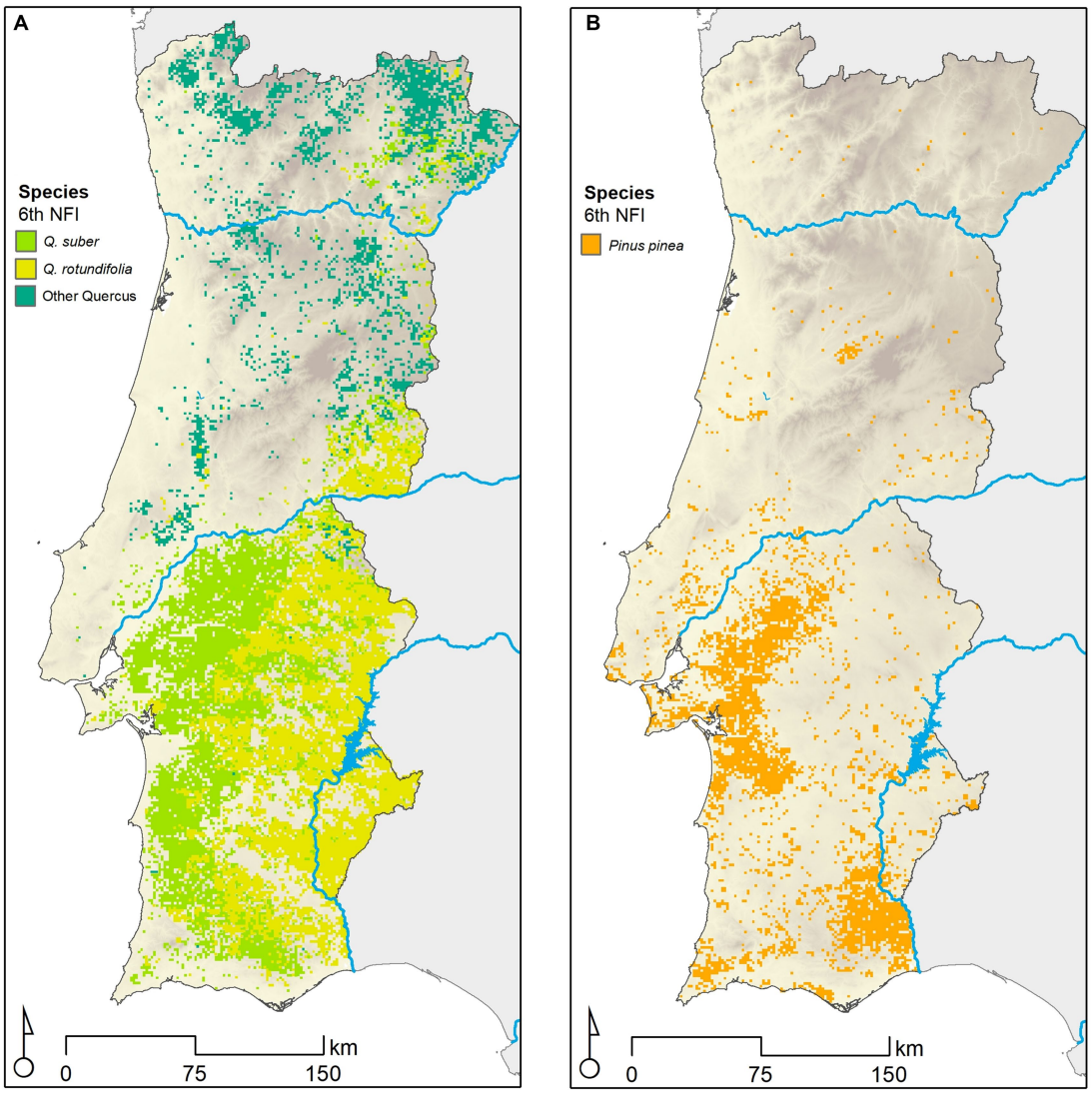


FIGURE 1
(A) Geographic distribution of Quercus species in Portugal, *Quercus suber* (light green), *Quercus rotundifolia* yellow), and other *Quercus* (dark green). **(B)** Geographic distribution of Pinus pinea (stone pine) in Portugal in orange.

cultural landscape shaped by centuries of human-environment interaction (Pinto-Correia et al., 2011; Pinto-Correia and Kristensen, 2013; UNESCO, 2017) and is dominated by Cork and Holm oaks. It plays a key role in rural development, biodiversity conservation, and the provision of diverse agroecological and socioeconomic benefits (Moreno et al., 2018; Pereira and Tomé, 2004). In contrast, the northern region of Trás-os-Montes is characterized by different *Quercus* species (Figure 1A), reflecting the ecological diversity across the country.

Pinus pinea is a valuable NTFP in Portugal (Correia et al., 2025; Mutke et al., 2024; Santos Silva, 2023). It is primarily concentrated in the coastal regions of Alentejo and Algarve, particularly within managed stands. Although stone pine accounts for just 6% of Portuguese forests, its area increased by 12% between 2005 and 2015 (ICNF, 2015) reaching 194,000 hectares. In Alentejo, stone pine stands are found both as pure plantations and interspersed within *montado* systems, particularly in the Sorraia and Sado river basins. These pine stands account for nearly all pine cone production, although they represent only 53% of the total *Pinus pinea* coverage in Portugal (ICNF, 2015).

Acorns, the seeds of oak trees, have long held cultural, nutritional, and economic significance in Portugal. Traditionally used in bread-making (Zocchi et al., 2022) and livestock feed, acorns were once a staple in both human and animal diets (Fonseca, 2020; López Bote et al., 2000; Mason, 1992). However, their use declined over recent decades, primarily due to associations with food scarcity and social stigma (Fonseca, 2020). Today, a revival is underway. Small-scale producers and local initiatives are reintroducing acorns into the food system, drawing on traditional knowledge to promote innovative, climate-resilient food products (Moreira, 2023).

Similarly, Mediterranean pine nuts—the edible seeds of *Pinus pinea*—are among the world's most valuable tree nuts, often called the "white gold of the forest" for their high market value. Pine nuts are harvested from both wild stands and plantations, with *Pinus pinea* forests spanning approximately 0.7 million hectares across the Mediterranean region (Mutke et al., 2012). In Portugal, pine nuts are a long-standing ingredient in traditional cuisine, commonly used in confectionery, rice dishes, and salads (DGDR, 2025).

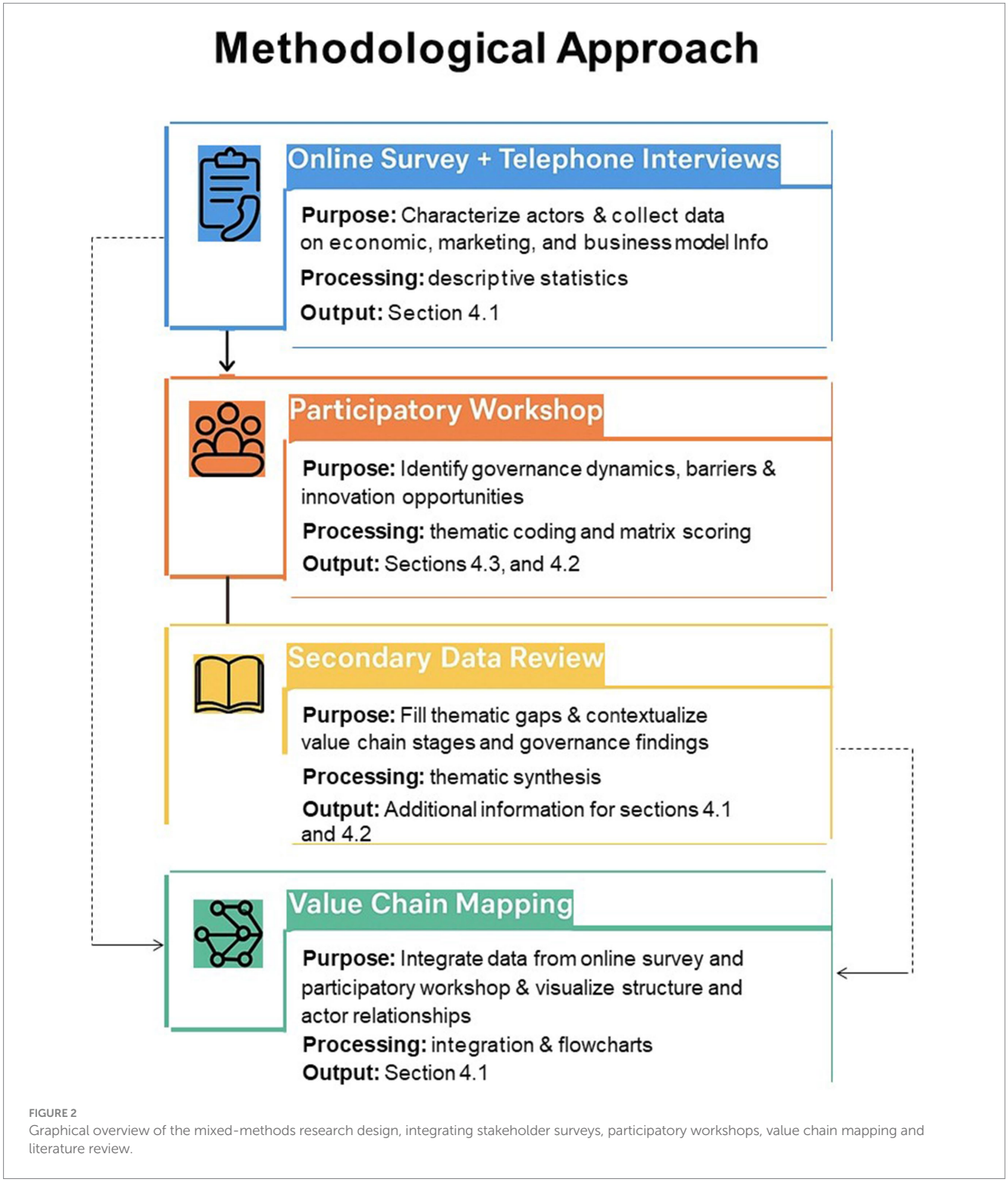


FIGURE 2
Graphical overview of the mixed-methods research design, integrating stakeholder surveys, participatory workshops, value chain mapping and literature review.

3 Methodology

The subsequent subsections provide a detailed explanation of each methodological step, while Figure 2 offers an overview of the overall approach.

3.1 Primary data collection

3.1.1 Online survey with key actors from the value chains

From January to September 2021, we conducted an online survey targeting key actors in the acorn (*Quercus* spp.) and pine nut (*Pinus pinea* L.) value chains in Portugal. The questionnaire included multiple-choice, short-answer, and checkbox questions (see annex 1). It gathered information on (i) economic factors (company profile, workforce size, main activities, product portfolio), (ii) marketing strategies (certifications, standards, promotional efforts), and (iii) business models (structural and operational characteristics).

Stakeholders were identified through online research and public databases, and the sample was expanded using snowball sampling, whereby respondents recommended additional relevant contacts. This approach was appropriate for the fragmented nature of the Portuguese NTFP sector, where many small producers and informal harvesters are not listed in institutional databases. Snowball sampling allowed us to reach otherwise hard-to-identify stakeholders and gather a more representative set of perspectives across the value chains.

Because of COVID-19 restrictions, data collection was conducted via phone interviews, and responses were subsequently entered into the online survey by the research team. Participants were contacted in advance to schedule interviews. Survey data was processed through descriptive statistical analysis and aggregated into an actor database, which informed the value chain mapping (Section 4.2)

3.1.2 Participatory workshop

In October 2021, we organized a participatory workshop to complement the survey findings and enable a deeper analysis of value chain activities, challenges, and innovation opportunities. The workshop had five main objectives: (i) present preliminary survey results, (ii) identify and prioritize barriers to market development, (iii) co-develop innovative solutions, (iv) explore suitable e-commerce platforms and ICT tools, and (v) strengthen stakeholder networking and collaboration.

Participants engaged in three structured exercises. First, they ranked pre-identified barriers on a 1–5 scale and added additional challenges. Second, they completed value chain-specific SWOT analyses, generating a shared understanding of strengths, weaknesses, opportunities, and threats for acorns and pine nuts. Third, they participated in a stakeholder/governance mapping exercise, where each actor was assessed using a multi-criteria framework considering (a) attitude toward business model innovation, (b) influence and connection, (c) willingness to actively engage, (d) power to implement change, (e) proximity to the consortium, and (f) communication responsiveness.

Workshop data were processed through thematic coding and matrix scoring to produce (i) a list of barriers, (ii) a synthesis of innovative solutions and explained (iii) consolidated SWOT diagrams, and (iv) actor power/influence maps. These outputs were triangulated with survey data and secondary literature and directly informed the Governance section (4.2) and Challenges and Opportunities for Growth section (4.3), highlighting leverage points for collaborative innovation, priority areas for capacity building, and opportunities for value-added transformation.

3.2 Secondary data collection

A literature review was conducted to complement and contextualize the primary data collected through interviews, and workshops. The review targeted thematic gaps that emerged during fieldwork, particularly those related to governance arrangements and value-chain stages that were under-represented in the stakeholder inputs. A systematic search was carried out across academic databases (Scopus, Google Scholar) and national and regional institutional repositories. Reports from UNAC, local cooperatives, and international organizations working on agroforestry and NTFPs were also included. The search strategy combined the keywords "value chain," "acorn," "pine nut," "governance," and "socio-ecological systems," and applied filters for publications between 2013 and 2023 focused on Portugal and the wider Mediterranean region.

The initial search returned 72 academic publications and 8 grey-literature documents. After screening titles, abstracts, and full texts using predefined inclusion criteria, addressing at least one of the following: (i) production and harvesting practices; (ii) cultural and territorial dimensions of resource use; (iii) governance structures and local participation; or (iv) sustainability strategies within value chains, 34 sources were retained for detailed analysis.

These selected publications were used in two ways. First, they supported the value-chain mapping, providing evidence on actors, processes, where primary data was not enough. Second, they strengthened the governance analysis by supplying comparative examples, typologies, and institutional insights that were not fully captured in interviews or workshop discussions. Consequently, references from the literature review appear throughout the results section, where they help contextualize and interpret the empirical findings.

3.3 Value chain mapping

Value chain mapping was done to integrate data from multiple sources and provide a comprehensive representation of the acorn and pine nut value chains. The process involved three main steps: (i) mapping and characterizing the core supply chain stages, (ii) identifying key actors and activities along each stage, and (iii) visualizing actor relationships and linkages.

Flowcharts were developed following the graphic guidelines of Tallec and Bockel (2005) and Escobedo Aguilar et al. (2018), combining information from surveys, participatory workshop discussions, and stakeholder references. This triangulation ensured that all relevant actors, direct and indirect, were represented, including those that are often under-documented. The resulting maps served as both analytical tools (to reveal bottlenecks, leverage points, and gaps) and communication tools (to visualize the structure and governance

TABLE 1 Target and number of validated responses obtained for the acorn and pine nut value chains, grouped by value chains segment.

Actors	Target	Producers	Wholesalers	Retailers	Ho. Re. Ca*	Total
		6 up to 10	2 up to 6	2 up to 8	2 up to 8	
Acorn	Identified	8	7	5	7	27
	Responses	5	6	4	5	20
Pine nut	Identified	8	8	5	8	29
	Responses	4	3	5	4	16

*Hotels, Restaurants and Catering (Ho. Re. Ca).

of the chains). These outputs directly informed section 4.1 of the results.

4 Results

A total of 36 validated responses were collected between January and September 2021: 20 pertaining to the acorn value chain and 16 to the pine nut value chain (Table 1). Although it was not feasible to define a parent population, Table 1 details the intended targets and the number of validated responses obtained for each value chain, disaggregated by segment.

Most respondents from the acorn value chain were small private companies (15). Other participants included cooperatives/consortiums (2), hybrid private-NGO structures (2), one NGO, and one individual producer. Most acorn enterprises operated with minimal staff: seven companies had only one full-time employee, while four employed two. Exceptions included one NGO with 11 employees, a cooperative with 30, and a hotel employing 50 staff. Seasonal employment was also limited, typically ranging from zero to two workers, with a few exceptions. The acorn sector surveyed reflected predominantly small-scale, local operations.

In contrast, the pine nut sector was primarily composed of private companies (14 out of 15), along with one public entity. Pine nut companies exhibited greater diversity in size: small firms dominated (1–5 employees), but some medium-sized enterprises (6–10 employees) and larger operations (37–108 employees) also were present but mainly for distribution and commercialization. With an average of around 26 full-time employees, pine nut enterprises exhibited a more specialized and structured profile than their acorn counterparts. Seasonal employment varied widely, from none to up to approximately 20 seasonal staff in the harvest season.

The participatory workshop engaged key actors from both value chains (Table 2). The acorn chain had the highest participation, with 21 attendees. Among these, producers were the most represented group, accounting for 10 participants, followed by 4 wholesalers, 4 retailers, and 3 actors from the Ho. Re. C*a.* sector. In contrast, participation from the pine nut chain was limited, reflecting existing power asymmetries and underscoring the need for cross-sector collaboration.

4.1 Value chains mapping

Figures 3, 4 illustrate the structure, key actors, and product and information flows of the acorn and pine nut value chains, respectively, as identified through primary data analysis. These visualizations reveal distinct differences between the two chains. The acorn value chain (Figure 3), still in an emerging phase, is relatively short and characterized by more direct relationships between actors, with producers often involved in multiple stages such as harvesting, initial processing, and small-scale distribution. However, not all small and medium enterprises (SMEs) engage in collection; many purchase acorns directly from farmers or harvesters. In contrast, the pine nut value chain (Figure 4) reflects a more consolidated and segmented structure, shaped by formalized harvesting rights, intermediary actors, and established processing facilities.

Table 3 summarizes key structural differences between the two value chains, helping to identify gaps, strengths, and potentially transferable practices.

4.1.1 Production/harvest

Acorns mature and fall between October and December, marking the Iberian pig *montanheira* season in southern Portugal and the acorn harvest period elsewhere in the country. Traditionally, acorns were not actively harvested by people but left on the ground as a vital food source for free-range livestock, particularly Iberian pigs (Hadjikoumis, 2012). Farmers continue to rely on the natural acorn drop to fatten their pigs. In this system, pigs act as de facto acorn harvesters, contributing to both economic value and the conservation of *montado* landscapes (Vizinho, 2023).

As shown in Table 3, harvesting is the most time-intensive activity in the acorn value chain. It is typically carried out by landowners or local gatherers. Collection methods, remain mostly manual (e.g., raking or picking) (Supplementary Figure 1), although there are efforts to introduce mechanization, such as vacuum or blower machines (as used for chestnuts) and handheld vibrators (similar to those used for olives). Overall, acorn collection remains small-scale and labor-intensive, often involving farmers and community members. Because acorns were historically abundant and considered "free" fodder, no formal or professionalized network of acorn harvesters emerged, unlike the specialized *pinhoeiros*[1] in the pine cone value chain.

Pine cones are harvested in winter, with mandatory collection dates set between December 1st and March 31st (Decreto-Lei no 528/99, 1999). This regulation helps prevent premature or illegal harvesting, which can reduce product quality and harm yields in the

1 Seasonal, specialized pine cone harvesters who climb stone pine trees using iron spikes or ladders and manually knock down cones using long poles.

TABLE 2 Actors involved in the participatory workshop.

Product	Producers	Wholesalers	Retailers	Ho. Re. Ca.	Total
Acorn	10	4	4	3	21
Pine nut	1	0	0	2	3

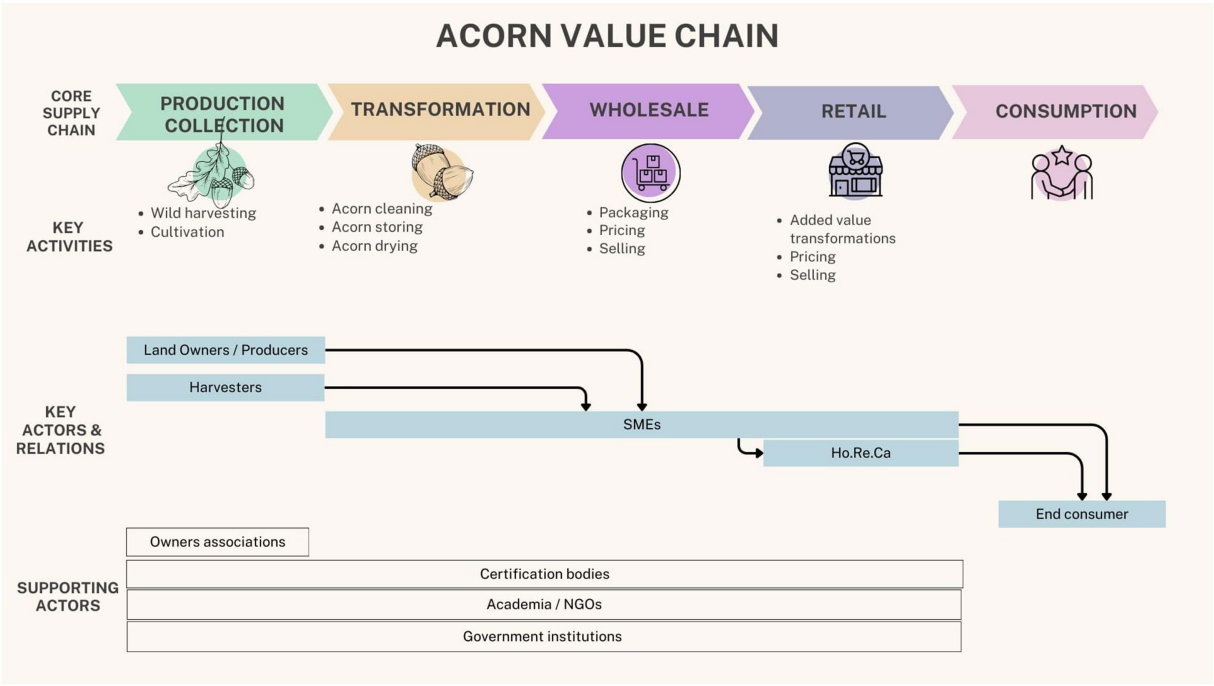


FIGURE 3
Acorn value chain map showing the main actors, core activities, and supporting actors.

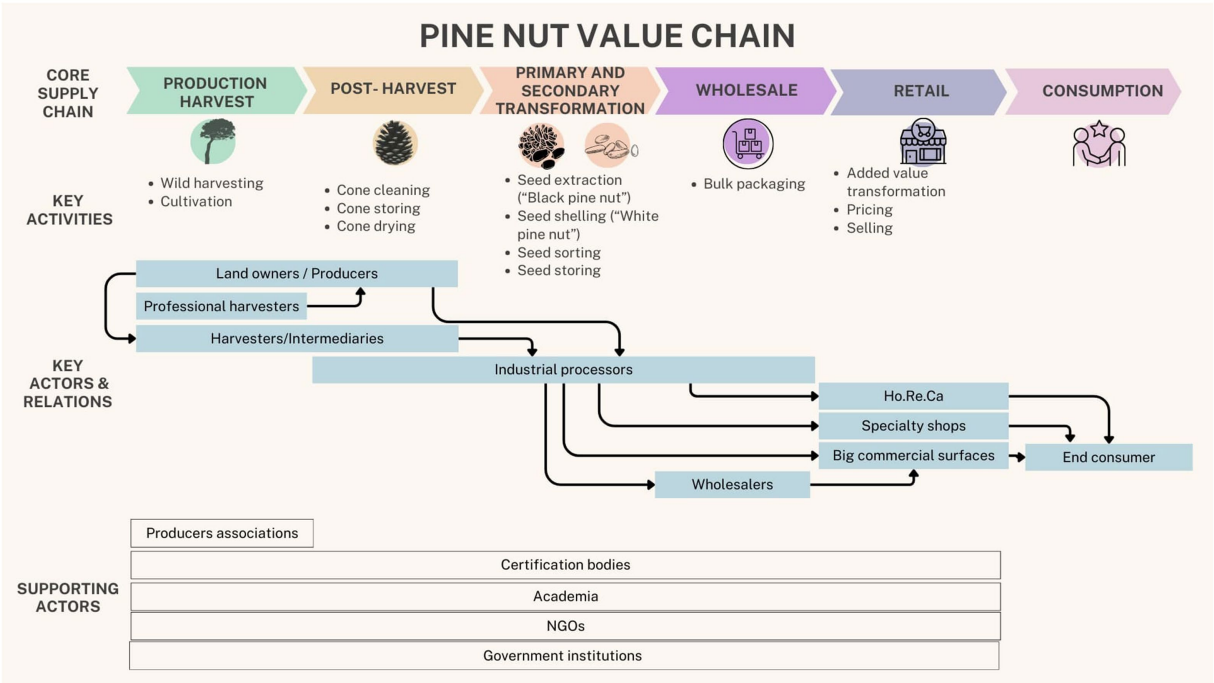


FIGURE 4
Pine nut value chain map detailing key actors, core operational stages, and supporting actors.

TABLE 3 Main differences between the acorn and pine nut value chains.

Criteria	Acorn	Pine Nut
Harvesting	- Manual harvesting	- Manual - Recent developments on machinery for harvesting
Efficiency in harvest and transformation	- High time allocation to harvest - Traditional transformation	- High time allocation to harvest - Industrialized primary and secondary transformation
Market dynamics	- Mainly private individuals involved - SMEs dominate the value chain	- Industrial processors and retailers dominate the value chain - Formalized market
Client segments	- B2C (Business to Consumer)	- B2B (Business to Business) or B2C (Business to Consumer).
Contracting	- Predominantly informal agreements	- Predominantly formal agreements
Packaging & sales formats	- Consumer-sized/small bulk; rare large bulk formats (in coherence with the predominance of B2C segment)	- Bulk packaging; rare individual packaging (in coherence with the predominance of B2B segment)
Certifications & branding	- *Montado* landscape could be certified for management; minimal branding and no wild labelling	- Some certifications (FSC, Organic); limited branding
Pricing & value-added products	- Lower pricing (€0.60–€1/kg fresh acorn, €2.5/kg dry acorn with shell, €5.5/kg dry acorn without shell) - Moderate value for transformed product €10–15/kg (flour) * at retail	- Higher pricing (€0.90–€1.40/kg pine cone, prices for the intermediate transformations are not available) - Higher value for white pine nut (€40-70/kg)* at wholesale - Higher value for white pine nut (€100–120/kg)* at retail
Market scope & revenue streams	- Local/Regional markets - Limited revenue (hundreds–few thousand euros)	- Broader markets (national to international) - Significant turnover (~€7 M) (source)
Social values	- Strong community ties, tradition, sustainability - Close cultural relationship to the landscape of origin	- Market-oriented, structured engagements, less explicit community focus - Still a relationship with the landscape of origin

*Prices from 2021.

following season. Harvesting is often done by specialized seasonal workers known as *pinhoeiros*, similarly to the acorn value chain, there is a high time allocation for harvesting (Table 3). To increase efficiency, mechanical tree shakers mounted on tractors are being gradually introduced to release the cones. The main producers are forest owners, particularly in the Alentejo region. Landowners rarely harvest cones themselves. Instead, they hire professional harvesters or sell harvesting rights to intermediaries, a practice known as selling "to sell on the tree".[2] While this approach reduces labor and risk for producers, it also shifts control and value capture to intermediaries.

4.1.2 Processing and added value

Raw acorns have limited culinary use without processing due to their bitterness (high tannin content) and hard texture (Stankov Jovanović et al., 2025a; Szabłowska and Tańska, 2024). Thus, processing of acorns focuses on making them palatable. As highlighted by workshop participants, the first processing step typically involves removing the acorn's hard shell and tannin-rich skin. Traditionally, as found in the literature, communities would peel, leach, or boil acorns to reduce bitterness and remove tannins, then dry and mill them into flour, or roast and grind them to create a coffee-like beverage base (Zocchi et al., 2022; Coelho et al., 2018). Today, most acorn processors, primarily small and medium enterprises (SMEs), still employ traditional methods.

As the acorn value chain is still emerging, only a few producers are currently involved in processing. For example, SMEs purchase acorns from multiple producers or harvesters and transform them through artisanal processes into a variety of products such as gluten-free acorn flour for baking (Beltrão Beltrão Martins et al., 2020; Martins et al., 2022), acorn-based coffee or infusions, and extracts like starch and polyphenols used as natural food ingredients (Stankov Jovanović et al., 2025b). As stated in the workshop, one Portuguese start-up established a pilot facility to process acorns from various oak species, enabling the aggregation of supply. This strategy helps overcome the ownership fragmentation characteristic of the *montado* acorn production segment.

After collection, pine cones must be processed to extract the edible kernels, known as "white pine nuts." Producers and intermediaries reported that cones are first dried or cured, traditionally through sun-drying or piling in dry, ventilated areas until the cones naturally open (Supplementary Figure 2). Alternatively, industrial processors use mechanical kilns to accelerate the process. The seeds, known as *pinhão com casca*[3] or informally as "black pine nuts," are then extracted from the cones.

Further processing is carried out by industrial processors who specialize in shelling the seeds. Specialized shelling machines crack the hard seed coat to release the edible kernel (*miolo de pinhão*,[4] or

2 A commercial arrangement where landowners sell the harvesting rights for pine cones directly to intermediaries, transferring the responsibility and risk of harvesting while receiving a fixed payment upfront.

3 The unshelled pine nut seed obtained after drying or curing pine cones, covered by a hard dark seed coat. It must be further processed to access the edible kernel.

4 The edible inner kernel of the pine nut, obtained after shelling the seed. It is the final high-value product sold for consumption.

"white pine nut"). This step is technically demanding, requiring precision to avoid kernel damage, and has historically posed a bottleneck in the value chain. Today, it is a highly mechanized process, enabling large-scale operations. After shelling, kernels may be graded by size/quality, and often undergo packaging (vacuum-sealed bags) for sale.

In the traditional model, producers sell cones to industrial processors, who manage all processing stages. However, there have been recent experiments with producers doing partial processing to capture more value under associative organizations. Overall, the main actors in processing are the industrial processors, who buy cones or "black pine nut" and produce "white pine nut." Processing adds most of the product's value, as the edible kernel commands significantly higher prices than raw cones.

4.1.3 Distribution and commercialization

The distribution of acorn products is in an early stage, evolving as the acorn value chain gains foothold. Traditionally, acorns lacked a formal distribution network for human consumption. They were mostly consumed on-farm by livestock or sold informally in local markets as snacks or animal feed. Today, with the emergence of new products, the acorn value chain is developing its distribution infrastructure from the ground up.

Some acorn-based products have begun to appear on retail shelves. Due to low volumes, distribution typically relies on direct-to-consumer channels, such as online sales, farmers' markets, and organic stores, and specialty retailers, rather than large commodity traders. Business-to-consumer (B2C) sales are the most common, with businesses selling directly to end-users. For example, a roasted acorn beverage (a coffee substitute) is sold under the brand "*Armazém da Bolota*." Similarly, acorn flour and whole processed acorns are sold through the online platforms of various SMEs. As an emerging value chain, acorn distribution is primarily led by SMEs, specialty retailers, and the Ho. Re. C*a.* sector (Hotels, Restaurants, and Catering) and specialty shops promoting these products, local farm shops, and a few forward-looking retailers tapping into the trend.

Another dimension of acorn commercialization is its indirect role in the livestock sector: acorns are still "commercialized" *in situ* by fattening free-range pigs, which are later sold as premium pork (*porco preto de montado or Iberian pig*). The Iberian pig sector holds significant economic value, as its products are prized for their exceptional quality and high levels of unsaturated fats. Studies show that Iberian pig production is a key factor in the economic sustainability *montado* farms (Gaspar et al., 2007, 2009). Acorns thus contribute to the economic value of the premium meat sector. However, this represents a form of internal, farm-level value addition rather than a formal market transaction involving acorns.

In the case of pine nuts, large intermediaries sometimes export pine cones or "black pine nut" directly to other countries for processing. Main actors in distribution include intermediaries and industrials who purchase cones from producers. The "white pine nuts" then enter well-established, global distribution channels. A substantial share of Portugal's pine nut production is exported (Centre for the Promotion of Imports, 2019).

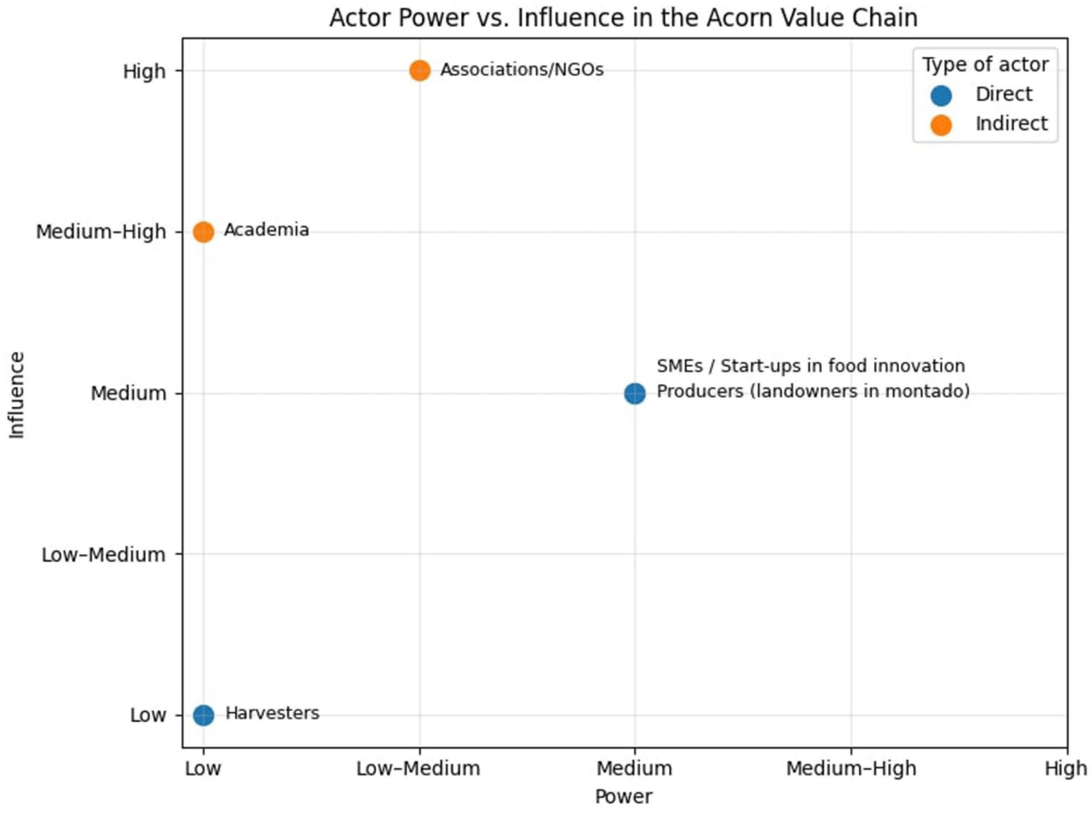


FIGURE 5
Actor power–influence matrix for the acorn value chain.

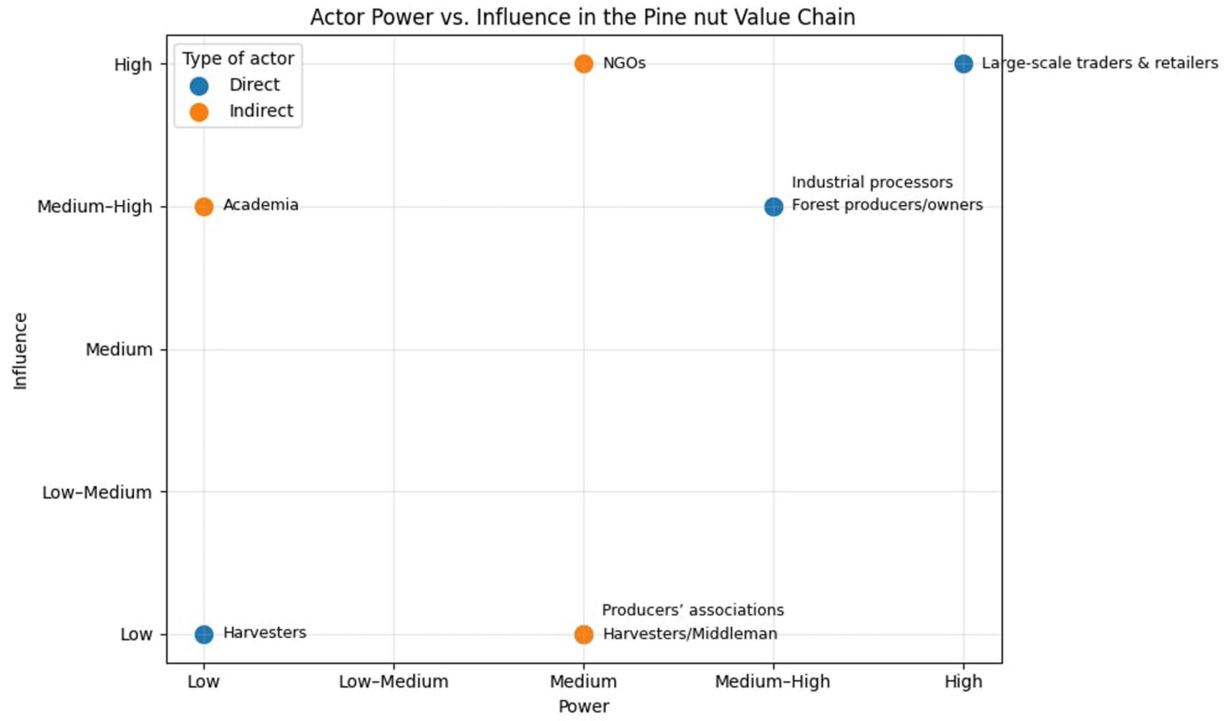


FIGURE 6
Actor power–influence matrix for the Pine nut value chain.

Processors or wholesalers typically manage bulk sales of kernels to foreign buyers or major domestic retailers; there is also a portion that is commercialized through specialty shops, and Ho. Re. Ca sector. The commercialization of pine nuts is relatively streamlined; the product is sold as a premium nut, either as an ingredient for the food industry as business to business (B2B) or as a packaged end-consumer product (B2C). Given their high price, pine nuts occupy a niche market that is highly sensitive to shifts in demand.

4.2 Governance

Drawing from workshop findings, we assessed each actor's power and influence within the overall governance of the value chains. Figures 5, 6 summarize these dynamics.

The analysis of the acorn value chain highlights the differentiated roles and degrees of influence among actors. Producers, particularly landowners in the *montado*, emerge as central players given their ecological stewardship and productive capacity, with their power strongly conditioned by land tenure and access to processing infrastructure, and enhanced when organized collectively. SMEs and start-ups contribute to innovation and the creation of new market niches, though their impact is constrained by limited capital and market reach. Harvesters, often operating informally, remain with low bargaining power and minimal influence over price-setting or decision-making. Indirect actors, such as associations and NGOs, are instrumental in shaping narratives around acorns as sustainable foods, promoting gastronomic and cultural valorization, yet they hold little financial or regulatory authority. Academia plays a similarly indirect role by driving innovation and informing policy debates, though with limited influence on production and commercialization processes.

The pine nut value chain is characterized by concentrated power in downstream actors, with large-scale traders and retailers exerting significant control over pricing and market access, thereby shaping governance outcomes. Forest producers and owners hold structural power as resource holders, which is reinforced when they act collectively through associations. Industrial processors occupy a central intermediary role, leveraging their processing capacity to link forest owners with retailers. Harvesters and middlemen are critical in mediating transactions between owners and processors, with some room to negotiate profit margins, yet their governance influence remains marginal. Individual harvesters, as in the acorn chain, often depend on owners and face precarious and hazardous working conditions. Among indirect actors, producers' associations provide essential organizational and technical support, while NGOs play a visible role in knowledge dissemination and policy advocacy, though their effectiveness is contingent on producer organization strength. Academia contributes primarily through research and innovation, with limited direct influence on production and commercialization dynamics.

In addition, we draw on the literature on adaptive governance in socio-ecological systems, particularly features such as the integration of multiple knowledge systems, including local, traditional, and scientific knowledge, as well as mechanisms for acquiring, integrating, and sharing this knowledge; variety (multiple problem frames and solutions); collaboration (networks, partnerships, shared power and responsibility, self-organization, and conflict resolution); and participation (engagement of scientists, resource users, civil society,

and policymakers to bring in a diversity of perspectives, preferences, interests, and values) (Folke et al., 2016; Munaretto et al., 2014).

According to each actor's power and influence, and the discussion during the workshop, we can conclude that the acorn value chain stands out as a bottom-up innovation, rooted in traditional knowledge and cultural identity. Current governance efforts focus on market creation, value chain sustainability, and knowledge integration, blending traditional practices with scientific and technological innovation. In contrast, the pine nut value chain is primarily driven by market forces and industrial actors. It is marked by partial hierarchies and fragmentation, with intermediaries and dominant retailers holding considerable influence. This structure often diminishes producers' bargaining power. Consequently, there is a pressing need to rebalance the chain by promoting collaboration and enhancing value retention among upstream actors, particularly producers, harvesters, and processors.

4.3 Challenges and opportunities for growth

Stakeholders identified several key barriers to the growth of the acorn value chain. These include certification and administrative hurdles, limited market reach and branding, inefficiencies in production and processing, and weak organizational coordination. Stakeholders proposed several innovative solutions:

1 Establishing a stakeholder network with support from local authorities, associations, and academic partners;
2 Launching nutritional marketing campaigns and promotional initiatives;
3 Raising awareness of the ecological value of NTFPs and promoting education around healthy, sustainable eating;
4 Investing in food technology innovation to integrate NTFPs into mainstream consumption, especially for specific dietary needs; and
5 Creating a dedicated support office to assist with certification processes.

Pine nut stakeholders identified key challenges hindering value chain growth, with theft of production emerging as a major concern. Additional challenges include yield variability caused by pests such as *Leptoglossus occidentalis* (Calama et al., 2020; Farinha et al., 2021; Pimpão et al., 2017; Mutke et al., 2024), a shortage of specialized labor, price volatility, and climate-related stressors such as intensified droughts. Another major concern is international competition (Evaristo, 2016; Mutke et al., 2012, 2024) and product misrepresentation, particularly from cheaper pine nuts derived from other species such as *Pinus armandii*, *Pinus koraiensis*, and *Pinus sibirica*.

To address these issues, stakeholders proposed several strategies:

1 Strengthening producer associations to improve collective bargaining and knowledge sharing;
2 Implementing resource-based interventions such as irrigation systems and phytosanitary treatments;
3 Adopting sustainable practices, including orchard establishment and tree regeneration;
4 Enhancing collaboration across the supply chain by fostering stronger connections between intermediaries, producers, and local stakeholders; and
5 Developing marketing strategies that emphasize the distinct qualities of Mediterranean pine nuts and their link to the landscapes where they are produced.

5 Discussion

Our comparative analysis of the acorn and pine nut value chains highlights the diverse pathways through which NTFP-based economies can evolve, blending innovation, cultural heritage, and sustainability. Despite their distinct challenges, both chains increasingly rely on innovation, multi-actor collaboration, and local value creation and retention for success. Whether navigating regulatory frameworks for novel foods, adopting context-sensitive mechanization, or valorizing traditional knowledge, innovation must be inclusive and grounded in place-based realities. Marketing and certification strategies that emphasize territorial identity and ecological value can help differentiate products and build consumer trust. Finally, adaptive governance models that empower upstream and marginalized actors are essential for achieving equitable value distribution and long-term viability. Unlocking the full potential of these NTFPs will require stronger collaborative frameworks, alignment with public policy, and investment in both social and technological infrastructure.

5.1 Innovation for acorn and pine nut value chain

5.1.1 Novel foods application

Our results show that actors in the acorn chain increasingly view food innovation as a critical entry point for market expansion. However, producers and SMEs face uncertainty regarding EU Novel Food procedures and limited technical capacity to navigate regulatory pathways. To date, the European Food Safety Authority (EFSA) has authorized only two oak species for human consumption: *Quercus robur* L., which is permitted for use in food supplements, and *Quercus rotundifolia* Lam., approved for general food applications.

Recent research by Maia et al. (2024) evaluated the valorization potential of *Q. rotundifolia* acorn kernel and shell, highlighting their promising nutritional and functional properties for innovative food uses. Other study is valuing the acorn cupule of different oak species in a circular economy context (Caeiro 2024). These findings suggest that traditional forest resources like acorns can support the development of novel, health-oriented products within sustainable food systems. However, according to the European Regulation on Novel Foods (EU 2015/2283), any species not consumed to a significant degree before May 15, 1997 requires formal authorization as a novel food. This regulation presents both a barrier and an incentive: while it limits immediate market access for underutilized species, it also provides a framework to evaluate and legitimize novel uses. As a result, many *Quercus* species, particularly those outside the *montado* region, remain largely untapped. Unlocking their potential could promote both dietary diversification and the revitalization of cultural food practices.

5.1.2 Mechanization

Survey and workshop participants reported low mechanization in both chains, particularly for acorn harvesting and early-stage pine cone processing. Mechanization in the pine nut chain, such as trunk shakers (Delard et al., 2023; UNAC, 2014) or artificial drying for drying (Neves et al., 2023; Mutke et al., 2024), has improved efficiency while maintaining tree health but harvest rely mostly in non-professional harvesters. In the acorn chain, manually intensive harvesting persists, and culturally embedded practices shape processing decisions. Beyond traditional leaching techniques used by processors, a lesser-known traditional practice is used by the Pomo people of California and communities in Sardinia involves mixing red clay with non-leached acorn meal for reducing bitterness, increase palatability, and decrease tannic acids (Johns and Duquette, 1991). At the industrial level, solvent-based methods such as extraction using ethanol-water solutions have demonstrated over 80% efficiency in tannin removal (Chao et al., 2017). Although this method has so far been used only for bioethanol production, it may offer a scalable, replicable solution for unlocking the potential of diverse acorn-based value chains.

Our findings support evidence that technical innovation in NTFPs is most successful when aligned with local ecological knowledge and cultural values (Kusters et al., 2022). Innovation in forest-based value chains is not only technical but social and cultural, requiring the co-production of knowledge across actor groups. Acorns and pine nuts are embedded in local traditions and landscapes, and recognizing their cultural significance is key to ensure that innovation does not come at the expense of identity and heritage. Strategic investments in research, innovation, and local infrastructure must prioritize both traditional knowledge systems and technological development.

5.2 Marketing, certification and labelling

Stakeholders in both value chains emphasized the importance of market differentiation strategies grounded in origin, identity, and ecological value. For pine nuts, our results confirm persistent competitive pressure from lower-cost imports and mislabelling, echoing earlier concerns (Evaristo, 2016). Despite this, Mediterranean pine nuts retain distinctive organoleptic and nutritional qualities (Evaristo, 2016; Evaristo et al., 2010; Mutke et al., 2012, 2024), which can be leveraged through marketing and labeling strategies that highlight geographic origin and product authenticity (Mutke et al., 2013).

In the acorn chain, stakeholders expressed strong interest in narrative-driven marketing and health-oriented positioning. This trend parallels broader developments in emerging wild-food markets. Evidence from the Balkans, for example, shows that pairing diversified acorn-based products with strategic storytelling can enhance consumer engagement and widen market reach (Rovira et al., 2023; Japelj et al., 2023). Health-oriented messages, including acorns' gluten-free properties and antioxidant content (Beltrão Martins et al., 2020; Xhakollari et al., 2019), also offer promising opportunities to reposition acorns beyond traditional or stigma-associated uses.

Territorial labelling emerges as a cross-cutting opportunity for both chains. Literature on landscape products (Sørensen et al., 2021) demonstrates that products rooted in specific socio-ecological systems could achieve stronger cultural recognition and market differentiation. Our findings support this: actors repeatedly identified provenance, montado identity, and Mediterranean forest landscapes as key assets for consumer engagement and value-added marketing.

Certification schemes can further reinforce these strategies. For pine nuts, Forest Stewardship Council (FSC) certification can strengthen the visibility and legitimacy of sustainable forest management practices. Developing a parallel certification approach for acorns—one that reflects their management systems, landscapes, and embedded traditional knowledge—could similarly enhance marketability and consumer awareness.

Ultimately, effective labelling, marketing, and certification of acorn and pine nut products must integrate nutritional, ecological, and cultural dimensions. Such approaches shape consumer perception while strengthening the resilience and visibility of national NTFPs. Both value chains illustrate how differentiated market strategies can drive sustainability transitions at the landscape scale, highlighting the socio-ecological embeddedness of food systems (Moreno et al., 2018; Stavi et al., 2022).

5.3 On adaptive governance and suggestions

In the acorn value chain, producers hold an intermediate but strategic position, largely due to their ecological stewardship and control over raw materials, a pattern also observed in other bioeconomy contexts (Araujo-Santos et al., 2025). Their influence, however, is limited by structural constraints such as land-tenure insecurity and insufficient processing infrastructure. Evidence from agri-food value chains shows that collective action can strengthen producers' bargaining power and governance influence (Olumeh and Mithöfer, 2024; Ibikoule et al., 2023; Reyes et al., 2018). Through cooperatives and associations, producers can improve market access and participation, an approach equally relevant for emerging bioeconomy sectors (Sudarić et al., 2019; Siegel et al., 2022). In contexts with weaker corporate concentration, these collective strategies become even more significant, enabling decentralized and participatory governance models (Rupp, 2024; Aza-Mengoa et al., 2025; Skondras et al., 2024).

SMEs and start-ups play a central role in product innovation and niche development (Ilie and Kelly, 2021), but their capacity to scale remains constrained by limited capital, infrastructure, and distribution networks (Han et al., 2023; Pellegrini et al., 2023). In contrast, harvesters, often informal actors, remain marginalized, highlighting governance gaps related to equitable participation and upstream value retention.

Indirect actors, including NGOs, associations, and academia, exert substantial influence despite lacking formal power (González Escobar et al., 2024; Szarka et al., 2023). NGOs and associations shape public narratives and enhance chain visibility, while academia contributes through research, innovation, and policy engagement (Trigkas and Karagouni, 2023). These actors act as catalysts for collective action (Szarka et al., 2023), facilitating knowledge integration and reinforcing the acorn chain's bottom-up dynamics by bridging traditional knowledge with institutional agendas (Kusters et al., 2022).

In contrast, the pine nut value chain operates within a formal, vertically structured system dominated by market forces and industrial actors. Large-scale traders and retailers hold substantial power, controlling downstream governance through pricing and market

access, reflecting imbalances also documented in Turkey's stone pine sector (Özden et al., 2022; Sülüsoglu, 2004). Forest producers and industrial processors possess medium to high influence, especially when acting collectively, yet their governance impact depends on coordination and organizational strength. Middlemen and informal harvesters, despite being essential for cone collection, remain largely excluded from decision-making, underscoring long-standing governance gaps related to labor and equity. As in the acorn chain, NGOs, academia, and producer associations play an influential supporting role in shaping narratives and advocating for policy change, although without formal power.

Addressing these governance challenges requires strengthening collaborative governance mechanisms (Ansell and Gash, 2008), improving equity and labor standards, and reinvesting value in forest landscapes (Wiersum et al., 2014; Baskent et al., 2024). UNAC's proposed model, where producers maintain control over harvesting and carry out initial processing collectively (Agri-ciência, 2014), provides a pathway to enhance upstream value capture.

In light of governance challenges across both chains, limited producer empowerment, fragmented coordination, and undervaluation of landscapes, cross-sector collaboration is urgently needed among government, producers, industry, research institutions, and civil society. We propose the following strategies:

1 Reinforce collective governance at the producer and harvester level, ensuring equitable participation and bargaining power.
2 Invest in enabling conditions for upstream value capture, including land tenure, infrastructure, and finance for SMEs.
3 Bridging roles for NGOs, academia, and associations, who already facilitate coordination and knowledge exchange but require institutional support to do so effectively.
4 Formalization and equity in labor governance, especially for harvesters in the pine nut chain.
5 Integration of territorial and landscape values into market strategies, governance structures, and policy frameworks.
6 Policy alignment, including the use of public procurement and rural development schemes to incentivize local processing and sustainable sourcing.

6 Conclusion

This study offers a comprehensive analysis of the acorn and pine nut value chains in Portugal, highlighting their contrasting stages of development, governance models, and pathways to promote innovation and collaboration. The acorn value chain, reflects a deep connection to cultural heritage, community-led innovation, and ecological restoration efforts, while contending with barriers related to market formalization, scalability, and infrastructure. In contrast, pine nut value chain, though structurally consolidated and market-oriented, faces persistent challenges such as price volatility, pest outbreaks, and climate-induced stressors.

Together, these case studies illustrate the complex, context-specific nature of NTFP systems and their critical role in rural development and bioeconomies. They underscore the need to understand value chains not as isolated economic processes, but as embedded within broader socio-ecological systems, shaped by historical land uses, cultural identities, governance dynamics, and ecological interdependencies. Recognizing and supporting this interconnectedness is key to designing effective interventions.

To unlock the full potential of these NTFPSs value chains, targeted policy support, adaptive governance, and inclusive stakeholder engagement are essential. Strategic investments in innovation, knowledge co-production, and horizontal and vertical linkages across the value chain can drive sustainable, culturally grounded development. Ultimately, reinforcing the cultural and territorial identities linked to NTFPSs, such as the acorn, can open pathways to differentiated markets that value provenance, tradition, and sustainability, while contributing to resilient territories and diversified livelihoods in Mediterranean forest regions.

Despite these contributions, this study has some limitations. The sample size was limited and may not fully reflect the diversity of actors and practices across Portugal. While participatory methods provided rich qualitative insights, they were not designed for statistical generalization. Moreover, informal and marginalized actors were underrepresented, despite their critical roles in both value chains.

Future research could address these gaps by expanding the sample size to better capture the diversity of actors and practices and by co-designing workshops and activities with stakeholders to strengthen participation. Involving a broader range of associations and actors may further enhance the process and its outcomes. For pine nuts, direct engagement with harvesters could provide valuable insights into traditional practices, working conditions, and their evolution under mechanization. Expanding the analysis to other Mediterranean contexts and conducting longitudinal studies would also enable stronger comparative insights and a deeper understanding of NTFP value chains over time.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

VM-A: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. JP: Conceptualization, Supervision, Writing – review & editing. DL: Formal analysis, Visualization, Writing – review & editing. DS: Data curation, Writing – review & editing. SM: Conceptualization, Supervision, Writing – review & editing. JB: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1628091/full#supplementary-material

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