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REVIEW PAPER

Innovation of argan (*Argania spinosa (L.) Skeels*) products and byproducts for sustainable development of rural communities in Morocco. A systematic literature review

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Abstract
Argan tree is endemic of Moroccan arid regions, providing socioeconomic and cultural benefits since ancient times. This study identifies the emerging threats for the argan forest, and the opportunities related to the innovative uses of argan products and byproducts. Argan forest is facing pressure from overgrazing, demand for argan oil and nuts, and land degradation, despite its recognition as a UNESCO Biosphere Reserve and the inclusion in the FAO Globally Important Agricultural Heritage Systems (GIAHS) Programme. Innovative use and recycling of the waste deriving from argan nuts processing, offer promising opportunities to support a local bio-economy. Argan press cake can be used to integrate livestock feeding, to extract sudan dyes or to produce bioplastics. Argan nut shells can be used to produce environment-friendly and low-cost purifying materials and biochar, or as a source of bioenergy. Argan pulp can be used for bioethanol production or to obtain natural insect repellent. Despite these promising opportunities, the socio-economic impact of innovative uses is still limited. Local population is not sufficiently involved in management and development strategies. To support the sustainable development of local communities, it is necessary to promote a participative approach as well as training and product differentiation among argan women cooperatives.

Keywords Argan · Argan forest · Agricultural heritage · Sustainable development · Circular economy · Morocco

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Introduction

The argan tree (*Argania spinosa* (L.) Skeels), endemic of Middle and Southwestern Morocco and Western Algeria, is highly adaptive to arid and semi-arid environments (Bouzoubaâ and El Mousadik 2003). The tree has an important economic and cultural role especially for the rural population of Southern Morocco. It is a multipurpose tree, whose products and by-products have been used by local communities since ancient times. Around the mid-1550s, Alhassan Alwazan (Leo Africanus) in his description of Africa, reported that in the southern Moroccan region there were a lot of trees that "produce a fruit as large as the olives [...]. In the local language, this fruit is called: argan", and that it was commonly used "to make an oil [...] which is used for cooking and for lighting" (Leo Africanus 1896). At that time, the distribution range of the argan forest must have been much wider than today, considering that it has been significantly reduced in the last century. During Saadi sultanate (1510–1659), the extension of argan forest was impacted by the spread of sugarcane cultivation, especially in the Souss region (Tiouite, Assads, Oulad berhil) (El fachtali, 1973). More recently, during World War I, about 150,000-200,000 ha disappeared due to intense exploitation of argan wood and to replacement of argan forest with cultivated land. In 1924, the Moroccan Forest Service tried to limit the argan wood exploitation for charcoal production or other uses, suggesting the use of different species, but with little success (Morton and Voss 1987). During World War II, local wood demand again increased, but from the end of the war different initiatives have been undertaken to protect and restore the argan forest. In the mid-80s, the so-called "argan oil project" was launched, corresponding to a series of initiatives at various levels for the promotion and valorization of argan oil. The aims of the project included the shifting from family-scale to industrial-scale argan oil production, the establishment of the chemical composition of high-quality argan oil and its certification to avoid adulteration, the improvement of argan oil preservation, and the promotion of argan oil on international markets as a niche product (Charrouf and Guillaume 2018). The overall aim was to protect the natural argan natural forest and to contribute to the sustainable development of rural areas providing job opportunities and more incomes to local communities.

In about 20 years, argan oil became the most expensive vegetal oil on the market, highly appreciated and wanted by the cosmetic sector, whose benefits for human health have been largely assessed (El Abbassi et al. 2014; Cherki et al. 2006). In 2022, the argan market accounted for 299.45 USD million and is expected to grow by 11.4 USD million by 2030 (AA.VV., 2022). The argan forest was declared a Biosphere Reserve by UNESCO in 1998 (Aboutayeb 2014), while in 2014 the "Argan, practices and know-how concerning the argan tree" were included in the UNESCO List of the Intangible Cultural Heritage of Humanity, increasing the international interest around the argan forest and the argan oil. In 2010, the Moroccan state created the National Agency for the Development of Oases and Argan Forest (ANDZOA), whose aim is to promote initiatives for the sustainable development within the oasis and argan forest systems and to promote integrated rural development of Arganeraie Biosphere Reserve (ABR). The ANDZOA strategy includes the restoration of the argan ecosystem, supervising projects for the promotion, marketing, and labeling of argan products, and encouraging scientific research for argan forest protection (Msanda et al. 2021).

Despite the market (and marketing) success of argan oil, with a general positive and significant impact on rural communities' livelihood and wellbeing, a deep evaluation of trade-off of production/conservation is needed to sustain the gain and overcome weaknesses. In particular, after about 40 years since the inception of the "argan oil project", there is the need to assess the current situation of the argan sector and the related opportunities for sustainable rural development. The aim of this research is to contribute to filling this knowledge gap, by identifying the main current threats for the argan forest as well as the main opportunities related to the valorization and to innovative uses of argan tree by-products, with particular attention on its role for the sustainable development of rural communities and for circular bio-economy.

Study area, data and methodology

Geographical setting of argan forest

The Moroccan Argan forest is mainly located in central and western Morocco, along the Atlantic coast and in the Atlasic foothills, in the provinces of Essaouira, Agadir Ida Outanan, Taroudant, Chtouka Ait Baha, and Tiznit (Fig. 1). This region covers approximately 2.5 million hectares known as Argan Biosphere Reserve (ABR). In addition, there are some isolated natural populations in the further northeastern (Díaz Barradas et al. 2010). The ABR corresponds to the southern slope of the High Atlas Mountains and to the coastal lowlands, with an average elevation of 200 m a.s.l. The ecological and functional connection between the high mountains and coastal area is assured by dry valleys.

The climate of the ABR is generally characterized by aridity and shows a high variability depending on the altitude and elevation gradient, which greatly affect precipitation quantity, duration and intensity (Abahous et al. 2018). In general, precipitation decreases from High Atlas in the north to Anti Atlas in the south and from west to east. The High-Atlas Moun-

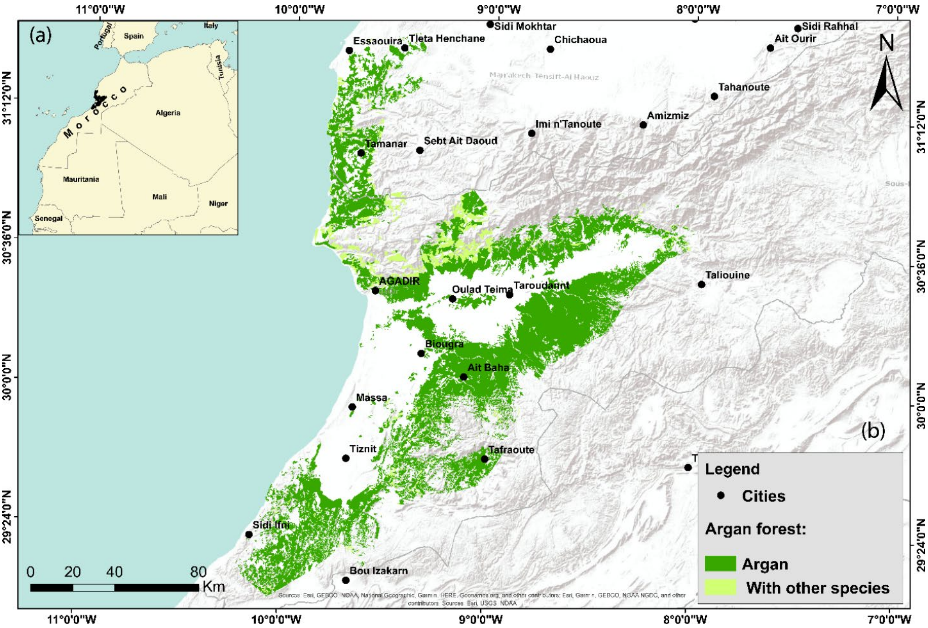

Fig. 1 Spatial distribution of argan forest in Morocco

tains receive the highest amount of precipitation with an annual average rainfall exceeding 600 mm, while in coastal plains and in the Anti Atlas Mountains precipitation is reduced to less than 200 mm/year. The Argan tree is well-adapted to this dry climate and to the immature and poor soils, especially in mountainous areas (Ain-Lhout et al. 2016). The soils are generally red fersialiric such as regosols, leptosols and fluvisols covering Paleozoic, Mesozoic and Cenozoic formations of the High Atlas Mountains and Precambrian and Paleozoic of the Anti-Atlas Mountains (Díaz Barradas et al. 2010; Jones et al. 2013).

Data and methods

This systematic review follows a methodology proposed by Pullin and Stewart (Pullin and Stewart 2006). This approach has been developed to validate systematic reviews providing more efficient and less biased data, to be used by scientists, stakeholders and decision makers. An internal protocol, based on six steps, has been developed and strictly followed to minimize bias and to increase repeatability:

I. Establishing the “Specific research question”;
II. Choosing the database;
III. Defining the time interval;
IV. Establishing the keywords to be used in the search phase;
V. Selecting the relevant publications;
VI. Extracting and analyzing the data.

Data collection

The research question refers to the importance of the argan tree as a multipurpose tree for local rural communities, identifying the main vulnerabilities for the argan forest and the main opportunities related to innovative use of argan products and by-products, to be investigated through a systematic literature review. The choice of the database was made by applying a test on the two most complete databases of scientific publications, Scopus and Web of Science (WOS). The test was performed with the same keywords, and resulted in a higher number of papers found in the Scopus database. No time interval was set, since it was necessary to broaden the search field as much as possible, while both publications published in English and French were considered in this study. In fact, although most relevant studies are commonly published in English-language international journals, since argan trees are endemic of Morocco, we factored studies published in French so as to include journals with a national dissemination.

The search in Scopus database was carried out in March 2023 using only two keywords within title, paper keywords and abstracts: “argana” and “*Argania spinosa*”. The use of only two generic keywords made it possible to include a higher number of published papers. Editorials, commentaries, conference proceedings and book chapters were excluded in the research, while review papers have been included. Only already published papers have been considered. The following is the final search string that has been used: (TITLE-ABS-KEY (argan) OR TITLE-ABS-KEY (argania AND spinosa)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND

(LIMIT-TO (LANGUAGE, “English”) OR LIMIT-TO (LANGUAGE, “French”)) AND (LIMIT-TO (SRCTYPE, “j”)).

Bibliometric analysis

The ultimate purpose of bibliometric analysis and mapping is to evaluate the scientific literature in the relevant field (Andrés 2009). Bibliometric analysis uses metadata of published work such as citation numbers, keywords, titles, collaborations, and institutions retrieved from different databases. In this study, the objective is to map and highlight main trends in the Argan forest literature. Bibliometrix, an open-source tool package of R software for executing a comprehensive science mapping analysis of scientific literature (Aria and Cuccurullo 2017), has been used to assess the argan forest literature trends.

Selection of relevant publications

From the list of papers downloaded in the previous phase through the Scopus database, it was necessary to perform a selection of the relevant ones, applying a double-steps filtering. The first one has been based on the title and the abstract, to exclude the papers that were not related to the aim of this study. Therefore, all the papers focusing solely on argan biology, argan oil chemical composition, health or cosmetic benefits of argan-derived molecules or products, were not considered in this study. The second filtering was instead based on reading the whole text, to perform an additional and even more accurate control of whether or not they fell within the scope of this review.

Extraction and analysis of the information

Finally, all the selected papers were carefully full-text reviewed, reporting on the database spreadsheet the threats, the main innovative use of argan products and byproducts, as well as previous experiences for the sustainable development of argan-based communities.

Results and discussion

The results of the search phase

The search in Scopus database returned 794 potentially relevant papers. After the first filtering phase (titles and abstracts analysis), the number of potentially relevant papers has been narrowed down to 334 papers; most of the papers excluded in this phase were considered out of scope, i.e. the ones focusing only on health benefits of argan oil or on its chemical composition. The second filtering (whole texts analysis) left out an additional 42 papers: 38 out of scope, 1 no full text available online, 3 duplicates (i.e. same exact study published in two different journals). Therefore, the final number of relevant publications resulted to be equal to 292 papers (Fig. 2). The complete list is reported in Annex 1.

The bibliometric analysis allowed us to identify the main trends in argan research. The most relevant source of information was the “Journal of Materials and Environmental Science” with 11 documents included in the filtered database, followed by “Acta Botanica

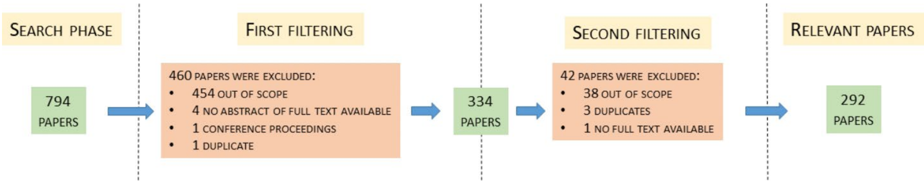

Fig. 2 The different steps performed in the search phase returned 292 relevant papers

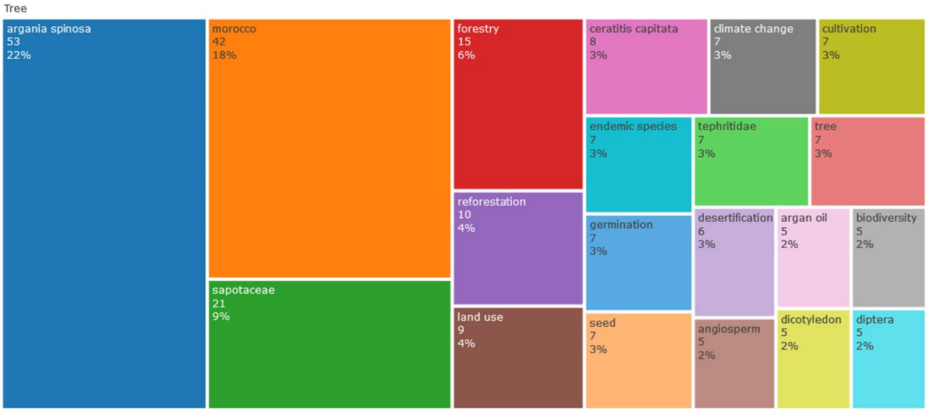

Fig. 3 Keywords-based tree map

Gallica" with 8 papers. Among the ten most relevant sources, two journals in the list are published in French. The main keyword used in argan-related literature was "*Argania spinosa*", representing 22% of the keywords, followed by "Morocco" (18%) and "*Sapotaceae*" (9%) (Fig. 3). In addition to these more general keywords, words related to the argan forest also seemed to be important, such as "forestry" (6%), "reforestation" (4%), and "land use" (4%). It is also interesting to note that keywords such as "forestry" and "reforestation" raised importance in the last 5 years, demonstrating that topics related to argan in scientific literature are changing from the final product to the management of the local forest environment.

The Thematic map (Fig. 4) describes the distribution of the different themes based on two axes, density and centrality (relevance). Themes like "ecosystems", "local population", "commercialization", and "rural society" are emerging topics, highlighting the strong connection between the argan forest ecosystems and the topic of rural development of the local communities within the ABR.

Regarding the affiliation country of the authors, Morocco, France, and Spain are at the top of the list (Table 1), with 70% of papers published only by researchers from Moroccan institutions without any collaboration with the rest of the international scientific community. In contrast, for France, Spain, Germany, and USA most of the relevant publications are carried out in the framework of international collaborations. Thus, Moroccan researchers focusing on argan-related studies are called for more international collaborations in the future.

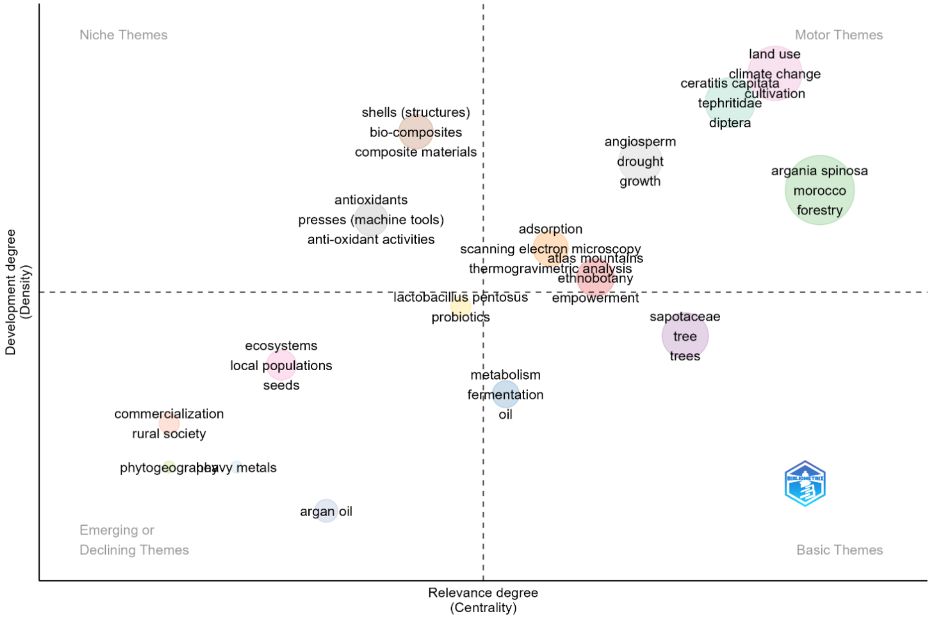

Fig. 4 Thematic map

Table 1 Top ten corresponding author's countries

Country	Number of Articles	Single Country Publications (SCP)	Multiple Country Publications (MCP)	Frequency	MCP_ Ratio
MOROCCO	108	76	32	0.441	0.296
FRANCE	20	8	12	0.082	0.6
SPAIN	16	6	10	0.065	0.625
ALGERIA	10	9	1	0.041	0.1
GERMANY	10	3	7	0.041	0.7
USA	6	2	4	0.024	0.667
ITALY	5	3	2	0.02	0.4
BELGIUM	4	3	1	0.016	0.25
ISRAEL	4	3	1	0.016	0.25

The 292 relevant papers have been published starting from 1987 to 2023, but more than 220 have been published only in the last 10 years, after the argan oil market success (Fig. 5). The 292 relevant papers have been published in 209 different journals indexed in Scopus, testifying that argan-related issues are a topic of large interest for different sectors. According to the database, 259 relevant papers out of a total of 292 have been cited at least once by other studies, with a total number of citations equal to 6557 and an average value of 25 citations/paper. This value is deeply affected by the fact that one paper (Petit et al. 1998) has received 1362 citations. This excluded, only 7 papers have been cited more than 100 times: four of them dealing with alternative uses of argan nuts-shells for the production on bioplastics and other biomaterials (Essabir et al. 2013, 2015; Elmouwahidi et al. 2012; Dahbi et al. 2017), one focusing on the evaluation of different storage conditions for argan

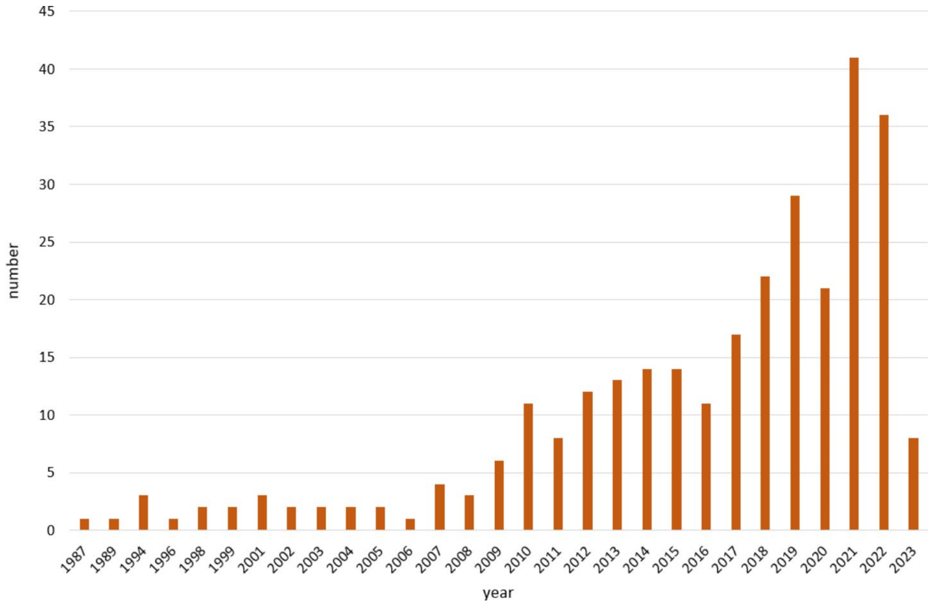

Fig. 5 Number of relevant papers according to the year of publication

nuts to achieve a better quality of the final product (Hilali et al. 2005), another one on argan forest degradation (De Waroux and Lambin 2012), and the last one dating back to 1999 and reporting different traditional uses for argan-derived products at that time (Charrouf and Guillaume 1999). Most of the papers (93%) have been published in English language.

The main current threats for argan forest conservation

Land degradation

The main threat identified for the conservation of the natural argan forest is linked to the shrinking of its overall surface and to the degradation of the forest cover. After WWII, argan forest still covered a large area, corresponding to two connected eco-zones: the coastal one and the one of the Anti-Atlas Mountains. From the '60 the argan forest has been widely replaced by different land uses in the Souss lowland due to the spread of cultivation and greenhouses to produce fresh vegetables year-round to supply major cities around the cost, while other argan forest patches have been replaced by exotic acacia plantations (Mellado 1989). At the same time, in remote mountainous regions, argan forest was largely overgrazed, especially by goats, but argan forest degradation is nowadays considered greater in the plains than in the mountains (Sinsin et al. 2020). According to Alaoui (2009), in 2009 argan forest loss rate was around 610 ha/year, while other studies highlighted a substantial maintenance of the overall area in the last 50 years, but with relevant transformations in the forest vertical and horizontal structure. In the period 1970–2007 tree density decreased by 44.5% (De Waroux and Lambin 2012), while most of the small-size argan trees have been found in a degraded state by Kirchhoff et al. (2022) in the same time interval. The reduction in tree density has potential negative effects for soil fertility, as intertree areas are less protected from soil erosion (Kirchhoff et al. 2019). The reduction of tree density and the lack of natural renovation, represent the main concern for argan forest conservation, and are mainly attributed to two interconnected factors: overexploitation of argan fruits and overgrazing.

The exponential increase of argan oil price resulted in almost no argan nuts being left on the trees or on the ground, preventing natural regeneration by sowing (Achour et al. 2021). Local farmers, in addition, tend to invest the incomes from argan oil and kernel selling, in enlarging their goat herds with further negative effects on argan forest (Lybbert et al. 2011). In fact, overgrazing is reported to be a major threat for forest renovation, not just for the direct effect on reducing argan seed availability, but also as in absence of a proper pasture management goats graze the undergrowth plants of argan forest, in particular nitrogen-fixing companion plants, reducing soil fertility. Argan is a tolerant species against herbivores, and a certain level of grazing has found to have a positive impact on the photosynthesis during the favorable season, as trees increase photosynthetic activity in leaves to compensate the loss of leaf surface after herbivore bite (maybe due to increased stomatal conductance) and they use less water showing lower oxidative stress. However, during drought these compensation mechanisms are not possible with negative effects on argan physiology (Nait Douch et al. 2022). Therefore, in order to preserve argan forest from overgrazing, but at the same time allowing local farmers to practice goat breeding, it is necessary to develop management plans that possibly limit grazing during unfavorable seasons (Zunzunegui et al. 2010).

Future climate scenarios (2050 and 2070) predict a further shrinking of the argan natural forest, as more than 32% of current surface will be unsuitable in the future (Moukrim et al. 2019), and the distribution of the argan tree could likely shifts to milder areas (Díaz-Barradas et al., 2010).

Socio-economic issues

Despite the argan oil boom improved the incomes of many farmers, this economic amelioration is not evenly spread within the argan forest area (De Waroux 2013). Argan oil products are highly valued in the EU and in other developed countries' markets, as happens for other agricultural products (i.e. acai, quinoa and shea butter) only coming from developing countries. Commercialization of argan oil and inclusion in the international market connects some of the planet's wealthiest consumers with the relatively poor smallholders. According to Zimmerer et al. (2018), the creation of cooperatives has altered the local gender dynamics, encouraging women social recognition and economic independence, and increasing the number of girls that have access to education. On the other side, the main sources of income for most Moroccan smallholders are still represented by non-farm activities and remittances, rather than by argan oil production. This inequality in the distribution of argan oil related benefits, is probably due to the fact that most of the gain is not for farmers, but for non-locals acting as intermediaries with the large market distribution (Lybbert et al. 2002). In response, there is the need to shorten the value chain, i.e. connecting women cooperatives directly with the market to capture a significant portion of the added value (De Waroux and Lambin 2013). The benefits of the argan cooperatives for rural women wellbeing are not yet completely assessed. According to some authors (Laghssais and Comins-Mingol 2021) benefits are evident, especially in terms of better access to food, medicines, clothing, water, education, improved women's health and financial freedom, allowing them to save money and access loans, and improving their overall welfare. On the other side, according to Perry et al. (2019), rural women working in cooperatives are more vulnerable to exploitation, crime, and venture failure if managers lack basic skills. In general, argan cooperatives offered an important source of income to rural women, but with limited possibilities of improving their education or of becoming independent and establishing and leading their own cooperatives.

The argan oil boom has also led to some changes in local customs, as rural families are tempted to sell the argan oil reducing or stopping the direct consumption, and replacing it in their food with cheaper and low-quality oils with negative repercussions on health (El Harousse et al. 2012). In addition, as a consequence of the argan oil boom, a new phenomenon was reported by El Wahidi et al. (2015), corresponding to the illegal occupation of argan forest parcels by local households due to the weakening of traditional common control systems.

Argan oil adulteration

The quality of argan oil and its adulteration with other vegetable oils (olive, sunflower, soybean,…) is an indirect threat to argan forest conservation and sustainable management. Although it can also ease the pressure on the argan forest, the falsification of argan oil for alimentary, medical or cosmetic purposes can be a serious problem, as can lead to a change in the organoleptic properties or in the pharmacological effects (Kurkin et al. 2021). Various relevant papers focused on proposing and testing different techniques for detection of argan oil adulteration: from spectrometry (Gonzálvez et al. 2010; Oussama et al. 2012; Stokes et al. 2018; Farres et al. 2019; El Orche et al. 2022), to the use of markers as stigmastadiene (Ourracha et al. 2012) or triacylglycerol profiles (Salgh et al., 2014), formation of gold nanoparticles and spectrophotometric analysis (Zougagh et al. 2011), or combination of a voltametric e-tongue and an e-nose based on metal oxide semiconductor sensors and pattern recognition techniques (Bougrini et al. 2014), to real-time PCR approaches (Amaral et al. 2022). Even though different techniques can be applied, authors agree with the need of developing a standardized analytical technique and procedure, fast, simple, with high sensitivity, low costs and with a high potential to be transferred to routine laboratories (Zougagh et al. 2011; Oussama et al. 2012.).

Difficulties in propagation and germination

Back in 1994, Nouaim et al. (1994) highlighted that the growth rate of argan plantlets is highly dependent upon mycorrhizal status, while propagation and germination present high rates of failure both in situ and in nurseries (Nouaim and Chaussod 1994). This explains why reforestation of argan is very difficult due to multiple causes and past attempts of artificial reforestation using nursery grown seedlings were often unsuccessful (Alouani and Bani-Aameur 2004). The root system extends deep into the soil already in the first phases of the tree growth, making transplanting difficult and rarely successful (Lybbert et al. 2004). Further, mass propagation of argan cuttings is limited due to fungi diseases (Bakry et al. 2009) and to difficulties related to rooting and survival during transplantation in the field (Amghar et al. 2021; Bousselmame et al. 2001; Benbya et al. 2019). In addition, seed propagation is challenging also due to heterogeneity in seed size, viability and dormancy, which are strongly genotype-dependent (Justamante et al. 2017).

Specialized cultivations of argan trees and possibilities for reforestation

Many relevant papers focused on studying and testing different techniques to overcome the difficulties in germination, replication and cultivation of argan, both to promote its cultivation and to facilitate reforestation and restoration of the argan forest. Different studies aimed at selecting argan genotypes with high resistance and resilience to drought (Chakhchar et al. 2017; Bouzoubaa et al. 2006) and salinity (Aameur and Sipple-Michmer-huizen 2001; Tazi et al. 2018) also in view of the possible climate changes that will affect the region in the future. Different authors agreed on the fact that ecotypes from inland areas seem to be more drought tolerant. Therefore, they are more promising for the regeneration of the Moroccan argan forest, than coastal populations that could be subject to higher water-deficit stress (Chakhchar et al. 2015, 2016; Zunzunegui et al., 2018). Other studies have correlated some phenotypic characteristics to argan oil productivity, such as the shape and size of the fruit (Gharby et al. 2013; Hilali et al. 2020; Rahmouni et al. 2020) or the ease with which the nut breaks in order to select argan trees that will smooth the oil production process (Nouaïm et al. 2007; Naima et al. 2010). According to Naima et al. (2012) high heritability has been found for the following characteristics: oil content (97.90%), seed width (72.68%) and seed length (57.55%). Aithammou et al. (2019) evaluated the characteristics of different clones on chemical composition of argan oil, finding that unsaturated fatty acids varied from 78.28 to 81.77% and total tocopherols varied from 687.40 mg/kg to 1068 mg/kg. While all the aforementioned studies are important for selecting productive and resilient genotypes, they do not consider that this genotypic selection would lead to a dramatic loss in terms of genetic diversity (Charrouf and Guillaume 2008), while it should be desiderable to preserve the maximum genotypic diversity both to maintain the argan gene pool and to have better results in argan forest restoration (Bani-Aameur and Ferradous 2001).

Argan tree has found to be dependent on mycorrhizal symbiosis, and the choice of the proper arbuscular mycorrhizal fungi, such as the ones of the genus *Glomus*, can contribute to produce high quality seedlings and, therefore, to improve argan tree adaptation and growth especially in arid regions with structural drought (Ouallal et al. 2022; Outamamat et al. 2022). According to Ajerrar et al. (2020) and to Ait Abad et al. (2022), instead, argan is a mostly self-incompatible species closely dependent on insect pollination; therefore, argan forest restoration should take into consideration the preservation of insects communities while argan orchards should be planned with a planting scheme that includes also pollinizer trees in rows or alternated to productive argan trees.

Other studies were instead based on lab and nursery tests (Mazri et al. 2022), including cuttings and rooting (Bousselmame et al. 2001), use of proper containers in nurseries (30 or 60 cm) to allow a better development of roots (Ouswati et al. 2021), micro-grafting from in vitro germinated seeds (Koufan et al. 2020), seed treatments such as pre-sowing soaking treatments (Ikinci 2014; Benaouf et al. 2016) or the use of a mixture of sand and peat as substrate for germination (Elmandouri et al. 2020) or on the effects of light on seed germination (Alouani and Bani-Aameur 2003).

Despite the difficulties in argan tree propagation, several attempts have been made in the past or are under experimentation to promote argan domestication outside its natural range. The oldest attempts have been probably made in 1800 in the colonies of the East Indies (Hooker 1854), while in 1960s several introductory trials have been made in Tunisia (Louati et al. 2021), even if already in 1924 Emberger (1924) reported the presence of argan trees around Kairouan (Tunisia) although this information has not been validated by botanists at the time. According to Louati et al. (2019) the introduction of argan in Tunisia could result in a positive impact on the economic situation of rural areas, especially as argan tree is suitable to be cultivated in less fertile and almost abandoned areas of Tunisia. Similar considerations have been proposed for the olive growing region of Argentina, where the olive sector is in crisis, or for revitalizing marginal rural areas in southern Italy, in order to improve the incomes for farmers and differentiate their production (Falasca et al. 2018; Gargano et al. 2021). Experiences of domestication and cultivation that have already started are reported for Algeria, with good development of the argan tree after 16 years of transplantation (Kechairi and Benmahioul 2019) and for the Negev Desert in Israel (Nerd et al. 1994, 1998) with problems related to the presence of *Fusarium oxysporum*, a pathogen found in most Israeli soils, which is reported to kill around 10% of the seedlings (Mizrahi 2020). Labarca-Rojas et al. (2022), applied a multivariate method using 29 different bioclimatic variables, to identify suitable areas for argan cultivation in Morocco, Algeria, Tunisia, and Spain, founding good potential areas in the western Mediterranean coast of Algeria, in the flat and coastal areas of eastern Tunisia, in southeast Spain and in the Canary Islands. The cultivation and domestication of argan outside the natural area does not seem to affect the quality of the final product, as the argan oil extracted from a plantation outside its biotope (region of Casablanca) has comparable levels of linolenic acid and tocopherols, to the one produced in the natural argan forest (Sabiri et al. 2023). It is important to highlight that the success of specialized cultivation outside Morocco might affect the exclusive and traditional status, and consequently the economic value of the “real” Moroccan argan oil with negative impact on local farmers and cooperatives incomes (Achten et al. 2014).

Few studies, but of great interest for the future of the Moroccan argan forest, report experiences of reforestation and of forest restoration. Genin et al. (2017) reported a case study based in two localities of Sidi Ifni Province, where local farmers started to develop maintenance-free prickly pear (*Opuntia ficus-indica*) cultivations both to keep their land ownership rights and to produce prickly pear fruits and seed oil, whose economic value increased in the last years, reducing the pastoral activity; results showed a positive relationship between the age of prickly pear orchards and natural argan tree regeneration. In the Province of Tiznit, plantations made in 2002–2003 winter season now cover more than 450 ha, proving that for a successful reforestation is required not only to select the more suitable sites according to ecogeographical conditions, but to apply participatory approaches for involving the local community and agreeing about the necessity to exclude the area from grazing for a certain period (Achour et al. 2021). Since overgrazing is one of the main obstacles for argan renovation and reforestation, the use of proper shelters can increase the survival rate of argan seedlings with a gain of 26% and can reduce the duration of deferred grazing with positive impacts on local communities (Defaa et al. 2015). In addition, it is important to highlight that freshly harvested seeds showed a higher germination rate (92%), while after three years of seeds storage (whatever the storage conditions are) a significant loss of germination capacity has been reported (Berka et al. 2018). Finally, according to Moukrim et al. (2018), the identification of the best suitable areas for argan forest restoration should be based on the following parameters: rainfall of the coldest quarter, seasonality of temperature, annual mean relative humidity.

Improving of the argan oil production process and/or storage to achieve a higher quality

Recent studies dealing with production processes and storage of argan kernels can contribute to the improvement of the final product quality, and consequently to its economic value and to the incomes of farmers and cooperatives. In addition, the proposed solutions do not require advanced laboratories or large investments, and therefore can represent very beneficial indications for cooperatives. Storage seems to be important for the final quality, even if sunlight does not damage argan kernels; argan kernels can be stored for up to 1 year at 4 °C without alteration of oil quality, but if they are stored at room temperature they should be processed within 10 months (Harhar et al. 2010a). According to Hilali et al. (2005) regulations should be implemented in order to define argan nuts storage length and conditions to achieve a national quality standard.

Argan oil quality is also strictly dependent on drying and roasting. Regarding drying, 10–14 days of sun-drying is found to be optimum to obtain high quality argan oil (Harhar et al. 2010b). Roasting of kernels is not necessary, but it seems to have a conservation effect, as the shelf stability of “roasted” argan oil is better than of “unroasted” (Kharbach et al. 2021), but there is no consensus on the roasting time and temperature. According to Harhar et al. (2011) 15–30 min at 110 °C is optimum to preserve nutritive properties, as if the time is prolonged to 45 min argan oil will present reduced nutritive properties due to the larger formation of secondary oxidation products and/or off-flavour, but according to Demnati et al. (2020) optimum roasting conditions are 50 min at 150 °C to reach a maximum oil yield of 32.45%. An innovative approach is the one proposed by Tannouche et al. (2015); this approach based on online control of the roasting process using images processing techniques with the proposed image recognition process resulting to be very efficient, ensuring a precise automatic stopping of the roasting once the desired quality is reached. To preserve a higher quality for a longer time, it is suggested to conserve the oil using dark-glass bottles rather than using clear plastic bottles (Kharbach et al. 2021).

Another innovative non-destructive and environmentally friendly technique that can be of interest for bigger argan oil producers is proposed by Guinda et al. (2015). It involves assessing different argan seed quality parameters (fatty acid composition, seed moisture content, seed oil content, oil stability index) based on visible/near infrared spectroscopy (Vis/NIR) measurements. Harvest period and ripening stage are also found to directly affect the chemical composition and therefore the nutritive properties of argan oil (Harhar et al. 2014). Water quality is an important, and often underestimated, parameter to consider for obtaining high quality argan oil, and the use of ultra-pure or distilled water seems to have an ameliorative effect on quality, stability, and shelf life of argan oil (Boukyoud et al. 2021). Concerning the traditional argan oil production method based on manual nut cracking, Kisaalita et al. (2010) developed and tested a simple and economic nut-cracker with the goal of increasing productivity while alleviating the dangers of hand cracking and improving the working conditions of women engaged in this task.

Innovative uses of argan products, by-products and processing waste

Use of argan processing waste for livestock feeding integration

Many papers proposed innovative uses of argan products, by-products and processing waste, offering interesting suggestions and possible solutions for the sustainable development of rural areas and for the economic valorization of the argan value chain. The use and valorization of Argan Press Cake (APC), an agricultural waste deriving from oil extraction from kernels, is particularly promising and it is of interest to different sectors. Traditionally, APC has been used by local farmers to integrate goat and cow diet because of its high energetic value (Charrouf and Guillaume 1999, 2008; Alaoui 2009), but the levels of saponins give it a very bitter flavor and make it not really appreciated by livestock; therefore, detoxifying APC will make it more appetizing for livestock and might ameliorate protein malnutrition, a major animal feed problem in Morocco (Lakram et al. 2019a). In this way, APC could replace or integrate the conventional goat diet without detrimental effects on milk quality and productivity (Lakram et al. 2019b), but also contributing to raise the amounts of total phenolic compounds and total flavonoids, with increased antioxidant activity milk (Lakram et al. 2019c). In addition, goats reared in the argan tree forest have improved meat nutritional characteristics with potential benefits regarding human health (Bas et al. 2005), while the use of APC into the lamb diet, reduced the proportion of fat and increased the weight daily gain compared to those fed only with the conventional diet, without affecting the quality of the meat (Moutik et al. 2021). APC or argan fruit pulp can also be incorporated in camel diet replacing traditionally control diet without detrimental effects on camel milk quality; moreover, the use of APC is more economic than the conventional regime and could be an efficient alternative for the valorization of argan nut processing waste, improving the livelihood of farmers in dry areas while simultaneously expanding camel milk consumption (Mercha et al. 2019, 2021). Another innovative valorization of APC for animal feeding, is its use in broiler chickens diet; broiler chickens supplemented with APC at a percentage of 5-10% performed better in terms of increase in weight gains and in the levels of essential minerals like calcium and proteins (Hilali et al., 2022). Although all these reports of integrating livestock feeding have shown promising potential in lab experiments, operational and business profitability still need to be assessed to create value for sustainable development of rural farmers. Finally, 1-2% of added argan oil can instead be used to integrate the diet of *Oreochromis niloticus* (Nile tilapia) in aquaculture plants to increase some non-specific immune parameters, in particular the survival rate against six common fish pathogens (*Lactococcus garvieae*, *Yersinia ruckeri*, *Aeromonas hydrophila*, *Listonella anguillarum*, *Edwarsiella tarda*, *Citrobacter freundii*) without negative effects on growth or feed efficiency (Baba et al. 2017; Öntaş et al. 2016).

Use of argan processing waste for biosorption and depuration

The APC can also be used to produce nanocellulose by refining, bleaching and sulfuric acid hydrolysis, obtaining a nanomaterial selective for extraction of sudan dyes (Sudan I, II, III and IV). Although they are banned in the EU as food dyes, they are still a public health issue considering the number of studies showing their presence in different foods all over the world, especially in chili, curry and paprika powders, to intensify the color at low price (Benmassaoud et al. 2017).

The potential of argan processing waste, especially of Argan Nut Shells (ANS), to produce environment-friendly and low-cost purifying and absorbent materials is particularly interesting for its economic valorization and for environmental remediation. Early studies focusing on the use of ANS or of argan bark and argan endocarp for biosorption of methylene blue, or of Cd(II) and Pb(II) dates back to 2012 (Legrouri et al. 2012; Hachem et al. 2012). Thereafter, the number of papers dealing with this issue has rapidly increased, also due to the fact that water pollution with different chemicals and/or pharmaceutical products is raising major concern for public health. ANS-derived activated carbon or biochar can be effectively used to absorb dyes such as methylene blue (Ennaciri et al. 2014; El Khomri et al. 2020; Ouedrhiri et al. 2022; Ifguis et al. 2022) or crystal violet (El Khomri et al. 2022), or pharmaceuticals such as diclofenac (DCF) (Daou et al. 2020a), carbamazepine (CBZ) and sulfamethoxazole (SMX) (Daou et al. 2020b), paroxetine (PARX) (Mokhati et al. 2021), sofosbuvir (Babas et al. 2022), amoxicillin (Belhamdi et al. 2021), or even caffeine (Bouhcain et al. 2022) during water treatments.

Beside dyes and pharmaceuticals, ANS-derived materials can be used to purify water from polycarboxy-benzoic acids (hemimellitic, trimellitic, and pyromellitic acids) (Laabd et al. 2016), bisphenol A (Zbair et al. 2018), Pb(II) and Cd(II) (Benjedim et al. 2021). Other interesting and promising uses of ANS are recently reported regarding the possibility of producing produce a biosorbent sawdust for the extraction of uranium and other heavy metals (Cd, As, Zn, Cu, Ni, Cr) from merchant-grade phosphoric acid (PA) in the phosphate fertilizer industry to reduce uranium concentrations in mineral fertilizers (Qamouche et al. 2021), or to prepare activated carbons with high capacity for capturing CO_2 (Boujibar et al. 2018). Argan leaves powder can also be used in the same industry, as it has proved to be an efficient biosorbent for hexavalent chromium (Cr(VI)) ions contaminating aqueous solutions (Ennoukh et al. 2019).

Use of argan leaves extracts

The use of argan leaves is also promising, considering that different studies have recently assessed various properties of argan leaves essential oil and extract. According to Benabdesslem et al. (2022), essential oils derived from argan leaves are rich in terpenic compounds (36 terpenic compounds have been identified), especially of cubenol (31.02%) and 1,10-di-epi-cubenol (22.50%), camphor (8.22%), viridiflorol (7.10%), linalool (5.60%), and eucalyptol (5.40%). Main properties of argan leaves essential oil and extract include antibacterial (Kabouss et al. 2002; Dakiche et al. 2016; Bonvicini et al. 2017), antioxidant (El Idrissi et al. 2021), and antihyperglycemic activity (Hebi and Eddouks 2019). In addition, argan leaves extract can potentially also be used for treatments of hypopigmentation disorders or as bioactive components of cosmetic products that aim to increase pigmentation (Bourhim et al. 2021).

Anti-corrosive properties

Argan leaves aqueous extract can also be potentially used as an industrial alternative of argan oil, as a mild steel corrosion inhibitor (Laaroussi et al. 2022). In fact, some relevant papers focused on the anti-corrosive properties of different argan extracts, especially the ones deriving from APC, ANS, or argan kernels (Afia et al. 2012a, b, 2013), but similar properties have also been found for cosmetic argan oil as it can act as an inhibitor of steel (Afia et al. 2011) and copper (Mounir et al. 2014) corrosion. These properties are interesting for the industrial valorization of the agricultural waste derived from argan nut processing, to obtain natural and environmentally friendly products that can be used as alternatives for toxic chemical inhibitors for corrosion.

Sources of bioenergy

ANS have been traditionally used as a low-cost energy source for cooking and heating by local farmers. Some studies published in the last five years (Rahib et al. 2019, 2021) highlighted their potential use as an innovative source of bioenergy; ANS can represent a low-cost biomass that should be a promising biofuel in combustion systems or a source of antioxidant additives for biofuels (Afailal et al. 2021). Argan pulp too can be used as an innovative and low-cost biomass for the bioethanol production (Zouhair et al. 2019); According to Zeghlouli et al. (2021) it is possible to obtain a production of 322.8 g of second-generation bioethanol from 1 kg of argan pulp through enzymatic hydrolysis pre-treatment. This process is economically and environmentally interesting as it produces affordable clean energy and, at the same time, valorize an agricultural waste, contributing to potentially increase the incomes of local farmers, considering that the production of argan pulp is estimated in about 215 kg/ha/year, corresponding to an industrial production of 69.4 kg of bioethanol/ha/year.

Biodiesel of good quality (in terms of performance, combustion and emission) to be used in compression ignition engines can also be obtained from argan oil, respecting the standards of both ASTM (American society for testing and materials) and European committee (Folayan and Anawe 2019) even if argan kernel oil has its own market. It is more economically and environmentally interesting the possibility of recycling an agricultural waste; i.e. APC, after lipid extraction and transesterification with 0.6 g of KOH per g of oil, can be used as a source of biodiesel with similar characteristics of petro-diesel, standard biodiesels and, most importantly, biodiesel from argan oil (Zeghlouli et al. 2022).

Sources of bioplastics and other biomaterials

Argan waste material can be utilized in creation of innovative and biodegradable plastics, for the replacement of petroleum-based plastics. APC can represent a source of proteins that combined with amylose obtained from barley can be used to produce a novel bioplastic for bio-shoppers (Famiglietti et al. 2023), or to synthesize a material that combines the physical properties and biodegradability of Poly(Lactic Acid) with antibacterial and antioxidant activity to produce a bioactive food packaging (Stoleru et al. 2021; Seyedeh et al. 2022). ANS can be used as a source for the development of wood plastic composites together with high-density polyethylene obtained from sugarcane (Bio-HDPE) according to the principles of circular and bio-economy (Jorda-Reolid et al. 2021). The addition of ANS to polypropylene can also improve tensile properties with increased Young's modulus (modulus of elasticity) up to 62% (Kuram 2022; Ait Laaziz and Hilali 2020). According to a recent study by Aragosa et al. (2023), instead, a microorganism isolated from argan soil belonging to the genus *Sphingomonas*, is able to synthesize polyhydroxybutyrate (PHB), a biodegradable bio-based polymer, in a growth culture enriched with pretreated agricultural waste from argan seed processing.

ANS can also be used to obtain a nanoporous activated carbon electrode acting as high-performance supercapacitor (Boujibar et al. 2019), a biochar that, mixed with compost, has a positive impact on soil nutrients and growth of vegetables (Bouqbis et al. 2021), or to partially substitute conventional aggregates for building (brick, mortar, concrete) as a low-cost solution able to recycle agricultural waste and to make the construction sector more environmentally sustainable (Jannat et al. 2021).

Biopesticide activity

It is known since several decades that the argan forest act as an enormous reservoir of the Mediterranean fruit fly (Medfly, *Ceratitis capitata*) (Debouzie and Mazih 1999), a major fruit pest in Morocco, causing significant losses in fruit production and quality, and limiting the exports of local fruit products into medfly-free countries. Despite this, several studies highlighted that the soil of the argan forest is rich in two natural pathogens of *Ceratitis capitata*, namely *Beauveria bassiana* and *Bacillus thuringiensis*, that can be used to control medfly (Rachid and Ahmed 2018). According to Imoulan et al. (2011), the entomopathogenic fungi *Beauveria bassiana* is found in almost every soil sample collected in the argan forest, and most of its isolates (86.44%) are virulent to Medfly pupae, with mortality rates ranging from 65 to 95% (Imoulan et al., 2014). Argan forest soils is also a major source of *Bacillus thuringiensis* (about 91% of the soil samples containes its strains), representing an interesting biopesticide towards *Ceratitis capitata,* with mortality rates up to 30% (Aboussaid et al. 2011).

Finally, essential oil from fresh and dried pulp of argan fruits is rich in camphor and 1,8-cineole, suggesting that it can be used as a natural insect repellent, therefore, providing local women cooperatives of an innovative opportunity to diversify their production and to add value to a by-product that is currently considered an agricultural waste (Harhar et al., 2010).

Conclusions and further development

Relevant studies analyzed in this literature review offer interesting insights for the future of the argan forest and for the sustainable development of the rural areas of southern Morocco (Table 2). The creation of the argan oil value chain was not a simple process, as it was necessary to involve different stakeholders (local farmers, NGOs, international and domestic development agencies, argan oil cooperatives) and to work to change perspectives and behavior of all participants (Meagher 2019). Despite the good results achieved by most of the cooperatives, it is necessary to improve the training of local women about the management side of the cooperatives to offer them the opportunity to start their own business (Huang 2017; Perry 2020). The possibility of domesticating argan trees and of developing specialized orchards for argan oil production could open up considerable economic opportunities for Morocco, as demand for quality argan oil is expected to grow, and could decrease the anthropic pressure on the natural argan forest (Chakhchar et al. 2022); on the other

Table 2 Potential main innovative uses of argan parts and byproducts are summarized in the following table

Argan part and by product	Potential uses	Operational opportunities	Related issues/risks
Argan Press Cake (APC)	- Ameliorate protein malnutrition for livestock. - Broiler chickens' diet. - Nanocellulose productions. - Bioplastics for bioshoppers or food packaging.	- Opportunity for local farmers for remediation of protein malnutrition. - Important emerging Nature Based Solutions (NBS).	- Introduction of new fodders may be resisted by farmers. - More research is needed to assess safety in the long term. - Scale-up of lab experiments needs more development.
Argan Nut Shells (ANS)	- Purifying and absorbent materials. - Water purification. - Extraction of uranium and other heavy metals. - CO_2 capturing. - Improve tensile properties of polypropylene. - Low-cost bioenergy source for cooking and heating. - Antioxidant additives for biofuels. - Nano-porous activated carbon electrode. - Biomaterials for the building sector.	- Creation of new start-up working on emerging environmental issues and circular economy (water quality, decarbonization, biogas). - Important emerging Nature Based Solutions (NBS).	- Feasibility studies of uses may not find beneficial value from a business perspective. - Lack of legislation and organizational context for operational projects. - Scale-up of lab experiments needs more development.
Argan Pulp	- Bioethanol production. - Insect repellent.	- New products for local cooperatives.	- Lack of pilot projects and training. - High technology needs advanced skills for processing.
Argan leaves	-Leaves powder as biosorbent. - Essential oil for antibacterial, antioxidant, and antihyperglycemic activity. - Leaves extract act as a mild steel corrosion inhibitor.	- Important emerging Nature Based Solutions (NBS).	- Lack of pilot projects and training.

hand, a decrease of the incomes of local women cooperatives might occur. Big specialized orchards need high economic investments in the first years that cooperatives are not able to support, and the production of argan oil from specialized cultivations could lead to a general decrease in argan oil price. The development of a standardized protocol for argan oil production, based on the environmental and sustainability narrative (fair-trade, eco-healthy, environmentally sustainable) (Turner 2014) could instead help in obtaining a high quality argan oil produced respecting the natural forest and its regeneration.

The recognition of the Moroccan argan forest by UNESCO and by the FAO GIAHS Programme, together with the valorization of argan oil on international markets, have contributed to increase the awareness of the necessity of preserving and restoring the argan forest, more among national and international bodies and experts, rather than among local farmers. The main reason is that, with some exceptions, these initiatives have only partly contributed to increase the wellbeing of local families, while most farmers were not actively involved in the argan oil market or in management and development strategies and initiatives. It is generally not easy to involve the local population in environmental-related issues, such as the argan forest preservation, especially when the resource is scarce and when the immediate exploitation of the resource leads to immediate benefits, rather than developing long-term strategies (Chamich 2021). Thus, a change in the paradigm of communities' involvement in development and conservation programs is a necessity, and represents a research gap on integrated rural development that needs to be addressed by scientific and development experts.

Results of our study highlight the necessity of involving the local communities through participatory projects in order to properly address the main vulnerabilities of the system and to identify shared solutions to the socio-environmental problems; when local ecological knowledge has been integrated into development strategies and programmes and when all the stakeholders have been involved in the management and decision-making processes, evident benefits and success of argan forest conservation have been achieved. In addition, according to Romera et al. (2021), the main challenges of the Arganeraie Biosphere Reserve are also linked to the management level (insufficient political support, lack of a shared vision, absence of a governing body, insufficient coordination and resources, poor implementation of the Framework Plan and lack of an Action Plan). Furthermore, it seems crucial to improve the legal framework related to argan forest management, exploitation and conservation, considering that the argan forest is a common good, hence its management needs to be addressed at the local level through local institution empowerment in a bottom up management approach.

Based on the recent advances of the research focusing on argan products and by-products, potential innovative uses have been developed. Despite the recent findings and advances, the impact of innovative uses in terms of socio-economic development and ecological preservation are still limited. The research development is appealing to play its role to solve multiple challenges facing Arganeraie Biosphere Reserve (ABR) for inclusive and sustainable development of the territory. Different innovative uses of these waste products are proposed, and the integration of these opportunities into the activity of cooperatives could be crucial for actively pursuing and promoting a development model that is equitable from a social and environmental point of view and able to contribute to the wellbeing of local rural communities. To this end, boosting innovation in the research development sector in complete harmony with local stakeholders and communities, is an issue crucial to solve applying an integrated approach able to include the three pillars of sustainable development: environmental, economic and social.

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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