Agronomy for Sustainable Development (2021) 41: 71
https://doi.org/10.1007/s13593-021-00725-9

REVIEW ARTICLE

Introduction of alternative crops in the Mediterranean to satisfy EU Green Deal goals. A review

Ioanna Kakabouki[1] · Alexandros Tataridas[1] · Antonios Mavroeidis[1] · Angeliki Kousta[1] · Ioannis Roussis[1] · Nikolaos Katsenios[2] · Aspasia Efthimiadou[2] · Panayiota Papastylianou[1]

Accepted: 16 September 2021 / Published online: 25 October 2021

Abstract

Climate change affects the sustainability of farming systems by downgrading soil fertility and diminishing crop yields. Agenda 2030 for Sustainable Development Goals aims to achieve key performance indicators to convert effectually currently degraded agroecosystems into smart, climate-resilient, and profitable farming systems. The introduction of alternative crops could equilibrate the negative impact of increased temperatures and water scarcity to ensure sufficient farm profitability. Alternative crops such as quinoa, teff, tritordeum, camelina, nigella, chia, and sweet potato show a high acclimatization potential to various conditions and could be components of novel re-designed agroecosystems, satisfying the goals the EU Green Deal for reduced chemical input use by 2030. In certain occasions, they adapt even better than conventional or traditional crops and could be integrated in crop rotations, demonstrating multiple uses that would benefit farmers. This review aimed to (i) evaluate seven alternative crops based on their potential contribution to climate change mitigation, in compliance with the EU (European Union) Green Deal objectives and the SDGs (Sustainable Development Goals) of the UN (United Nations), and (ii) examine the factors that would determine their successful integration in the Mediterranean Basin. These limiting factors for crop establishment included (i) soil properties (soil texture, pH value, salinity, and sodicity), (ii) environmental parameters (temperature, altitude, latitude, photoperiod), and (iii) crop performance and dynamics regarding water demands, fertilization needs, light, and heat requirements. All proposed crops were found to be adaptable to the Mediterranean climate characteristics and promising for the implementation of the goals of EU and UN.

Keywords Alternative crops · Climate change · Temperature · Adaptability · Soil properties · Profit · Growth physiological parameters · EU Green Deal · EU Climate Law

✉ Ioanna Kakabouki
i.kakabouki@gmail.com

Alexandros Tataridas
a.tataridas@gmail.com

Antonios Mavroeidis
antoniosmauroeidis@gmail.com

Angeliki Kousta
aggelikh.kousta@gmail.com

Ioannis Roussis
roussis@aua.gr

Nikolaos Katsenios
nkatsenios@gmail.com

Aspasia Efthimiadou
sissyefthimiadou@gmail.com

Panayiota Papastylianou
ppapastyl@aua.gr

1 Laboratory of Agronomy, Department of Crop Science, Agricultural University of Athens, 11855 Athens, Greece

2 Department of Soil Science of Athens, Institute of Soil and Water Resources, Hellenic Agricultural Organization DEMETER, Sofokli Venizelou 1, 14123 Lykovrissi, Greece

Contents

1 Introduction

Alternative crops are defined as crops that can be inserted into a new ecosystem to substitute the traditionally cultivated crops and surpass production obstacles provoked by biotic stress (diseases, viruses, pests, etc.) and abiotic stress (salinity, heat, drought, etc.) (Sauer and Sullivan 2000). These crops could be classified into two main categories, the innovative and the retrovative crops, as they are also mentioned by Bilalis et al. (2017). Alternative-innovative crops are cultivated due to their possibly elevated profit or their ability to acclimatize to a specific ecosystem (Isleib 2012). According to this definition, a crop can be considered conventional in one geographical area and innovative in another. Therefore, the classification of a crop as innovative is attributed to the area of adaptation and not to the area of origin. In the case of the Mediterranean Basin, typical instances of alternative-innovative crops are teff, quinoa, camelina, nigella, and chia (Bilalis et al. 2017). On the other hand, the interest for retrovative crops is usually rekindled by the emergence of alternative uses and/or harvested products. The retrovative crops of the Mediterranean include flax and emmer wheat (Bilalis et al. 2017).

In our days, alternative crops seem to be of paramount importance due to their adaptation capabilities (Fig. 1). As the adverse effects of climate change occupy the whole world, policymaking aims to support the agricultural sector. According to the literature, water scarcity and droughts could be tackled by the adaptation of such crops (Metz et al. 2007; FAO 2008). The current Common Agricultural Policy (CAP) of the EU recognizes this role of the alternative crops and has already included them in the second pillar of rural development programs (EIP-AGRI 2016). In fact, the new CAP that will be initiated in 2023 sets nine objectives to

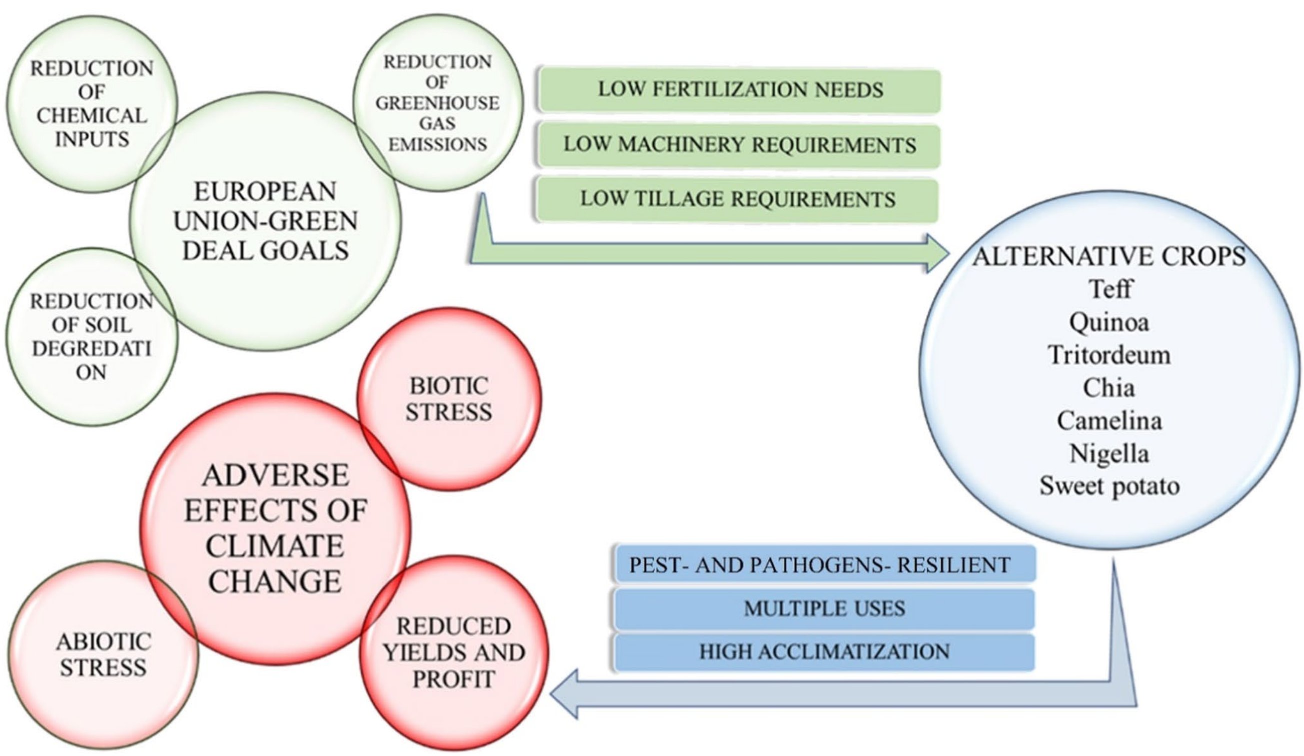

Fig. 1 Alternative crop integration in EU farming systems for mitigating the impact of climate change and satisfying EU Green Deal goals in the long term.

transform societies, environment, and value chains by focusing on resilience and sustainability. CAP Strategic Plans will set goals at national level, and in accordance with the specific needs and characteristics of each country member of EU, in order to foster the implementation of the new green policy measures. This CAP will consist of two pillars (pillar I, direct payments and pillar II, rural development policy) and will be strongly associated with EU Green Deal goals, specifically those related to Farm to Fork and Biodiversity Strategies. The anticipated eco-schemes will support multiple actions for the sustainable transition of the agricultural sector. Novel agricultural practices that focus on the agro-ecological transformation of agriculture, such as the introduction of crops resilient to climate change, will be the core of upcoming policies. On this axis, the new CAP regulations and payments should be harmonized with EU Green Deal targets for 50% reduction of pesticides input by 2030, the adoption of organic farming, and the achievement of long-term soil health. Overall, numerous global, European, national, and regional programs set similar frameworks for action at the crop farm level, including the FAO-Adapt, the Horizon 2020, LIFE AGRI ADAPT, and EIP-AGRI (EIP-AGRI 2016).

In order to select and introduce an alternative crop, it is necessary to classify them. The separation of crops into categories is based on the use of plants and their final products. Alternative crops may provide raw materials for the production of food, oil, fiber, or even pharmaceuticals.

Cereals, as some of the earliest domesticated plants, include numerous retrieved crops. Some of them (such as emmer wheat, tritordeum, and einkorn crops) are distinguished by the high protein content of their grains intended for human nutrition (Marino et al. 2011; Kakabouki et al. 2020a). Pseudocereals, such as Amaranthus (*Amaranthus retroflexus* L.), are also important nutritional crops with multiple uses in the food industry (Saunders and Becker 1984). Several of these crops produce grains with zero or low levels of gluten. For instance, quinoa (*Chenopodium quinoa* Willd.) grains are gluten-free, while the grains of teff (*Eragrostis tef* Trotter) contain low gluten; thus, both can be consumed by people with gluten intolerance or celiac disease (Pulvento et al. 2010; Abewa et al. 2019). Tritordeum (x *Tritordeum*) is another retrieved cereal that is considered superior to rye for bread or pasta production, and it is also used in ethanol production. Other alternative crops included in this category are the buckwheat (*Fagopyrum esculentum* Moench), a known superfood crop, and the wheatgrass (*Triticum aestivum* L.), a soil-stabilizing crop.

Besides their nutritional value for humans, the products of alternative crops can also be included in livestock rations. These crops can be cultivated for their fresh vegetative matter, hay, silage, or pasture. Fenugreek (*Trigonella foenum-graecum* L.) is a typical alternative crop that produces seeds capable of increasing milk production when consumed by ruminants (Degirmencioglu et al. 2016). Jerusalem artichoke (*Helianthus tuberosus* L.) is another important crop that is used as livestock feed. This plant is grown for its tubers which have prebiotic effects in the gastrointestinal tract of monogastric animals providing alternatives to antibiotics of livestock production (Wang et al. 2020).

Oilseed alternative crops are usually cultivated for the oils contained in their seeds. In this category, flax (*Linum usitatissimum* L.) and camelina (*Camelina sativa* L.) are distinctive examples as the oils of their seeds are the richest sources of omega-3 fatty acid and α-linolenic acid (Crowley and Fröhlich 1998; Madhusudhan 2009). Additional examples of crops with high oilseed content include chia (*Salvia hispanica* L.), nigella (*Nigella sativa* L.), and hemp (*Cannabis sativa* L.) (Üstun et al. 1990; Rodriguez-Leyva and Pierce 2010; Mohd Ali et al. 2012). Both flax and industrial cannabis are also fiber crops with high-quality fibers widely used in textile and paper industries. Several alternative crops are exploitable in more than one way. In Table 1, the crops are categorized in food crops, oilseed crops, feed, and industrial crops emphasizing their more common use.

The objective of the present study was to examine the introduction of specific alternative crops (Fig. 2) in the

Table 1 Typical cases of alternative field crops

Category	Alternative Field Crops
Food crops	Amaranthus (*Amaranthus retroflexus* L.) Buckwheat (*Fagopyrum esculentum* Moench) Einkorn (*Triticum monococcum* L.) Emmer wheat (*Triticum dicoccon* Schrank ex Schübl.) Quinoa (*Chenopodium quinoa* Willd.) Teff (*Eragrostis tef* Trotter) Triticale (×*Triticosecale* Wittmack) Tritordeum (x *Tritordeum martinii* A. Pujadas)
Oilseed crops	Black mustard (*Brassica nigra* L.) Borago (*Borago officinalis* L.) Camelina (*Camelina sativa* (L.) Crantz) Canola (*Brassica napus* L.) Chia (*Salvia hispanica* L.) Jojoba (*Simmondsia chinensis* (Link) C. K.) Nigella (*Nigella sativa* L.) Sesame (*Sesamum indicum* L.) Flax (*Linum usitatissimum* L.)
Feed crops	Fenugreek (*Trigonella foenum-graecum* L.) Jerusalem artichoke (*Helianthus tuberosus* L.) Lupin (*Lupinus albus* L.) Spelt wheat (*Triticum spelta* L.)
Industrial crops	Hemp (*Cannabis sativa* L.) Hop (*Humulus lupulus* L.) Kenaf (*Hibiscus cannabinus* L.) Milkweed (*Asclepias syriaca* L.) Stevia (*Stevia rebaudiana* Bertoni) Sweet potato (*Ipomoea batatas* Lam.) Urtica (*Urtica dioica* L.)

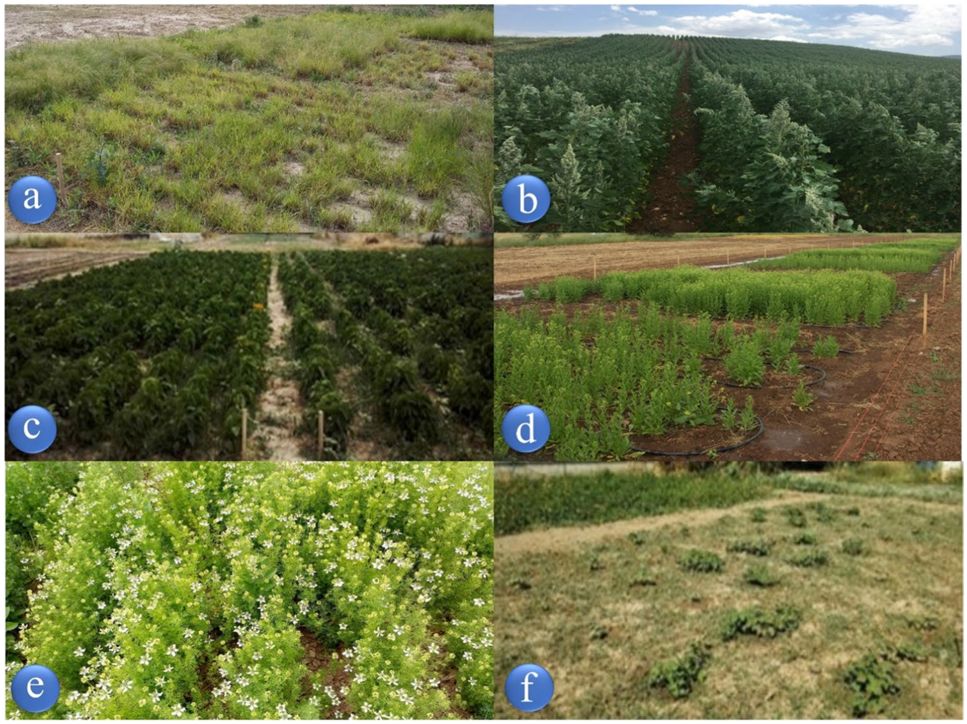

Fig. 2 Some of the proposed alternative crops cultivated in experimental fields in Greece: (**a**) teff, (**b**) quinoa, (**c**) chia, (**d**) camelina, (**e**) nigella, and (**f**) sweet potato. Photographs by Dr. Dimitrios Bilalis and Dr. Ioanna Kakabouki

Mediterranean Basin, taking into consideration several limiting factors. The territorial, climatic, growth physiological requirements, uses, and profits of each crop were investigated as the major points for a successful selection. Seven food, seed oil, and industrial alternative crops were proposed and evaluated according to these parameters for their adaptation in the Mediterranean Basin. Furthermore, characteristics of these crops, their performance risks, and compliance with the EU Green Deal goals were assessed. The assessment was also based on each crop's capacity for integration in crop rotations and on the chemical input demands.

2 Criteria for selection of a suitable alternative field crop

Soil type (clay, loam, sand) and soil properties are important factors for crop selection. Soil pH, salinity, and sodicity can be limiting factors for the establishment of a new crop. Salinity and sodicity limit crop production in cases of degraded soils as they may cause stress to plants (Szypłowska et al. 2017). Each crop is characterized by different levels of tolerance to these factors (Szypłowska et al. 2017); therefore, they should always be considered when selecting a suitable alternative field crop. Equations such as Eq. 1 (Table 2) (Jahany and Rezapour 2020) allow the estimation of salinity levels of the soil.

Moreover, the soil type is correlated with water storage (Almendro-Candel et al. 2018), though agronomic practices such as tillage (zero, minimum, or conservative) may affect soil water storage in certain occasions (Lampurlanés et al. 2016). Water demand must also be taken into account when selecting a suitable crop. Climate change leads to a rise in temperatures and consequently to water scarcity and intensification of drought in the Mediterranean Basin, especially in the Southern countries. Therefore, it is crucial to increase water use efficiency (Eq. 2) (Abdelhakim et al. 2021) where water is limited in many arid and semi-arid regions (Hossain et al. 2020).

Besides their water demands, crops are also characterized by their fertilization needs. Fertilization with nitrogen remains crucial for both conventional, conservative, and organic crop systems. As climate change aggravates nitrogen leaching, an alternative crop should be superior to typical cultivated species in terms of nitrogen efficiency. Under this context, farmers should expect to receive maximum yields under optimum nitrogen supply. Nitrogen use efficiency (NUE) is a common index that was conservatively used for cereals and recently for new crops to determine the nitrogen uptake by plants per rate of nitrogen applied (Eq. 3) (Goulding et al. 2008). Crops with high NUE are preferred in cases of high-productive fields and intensive crop systems. Moreover, the nitrogen agronomic efficiency (NAE) index describes the nitrogen supply from an agronomic perspective. This index shows yield per nitrogen rate applied (Eq. 4) (Niaz et al. 2015) and is useful to determine the actual demands of alternative crops for nitrogen to achieve sufficient yields.

Table 2 List of equations used for the selection of an alternative field crop. T_{max} and T_{min} represent the maximum and minimum daily air temperature respectively (in °C), T_{base} represents the minimum base temperature (threshold temperature) for a crop (in °C), *EYD* (equivalent yield under diversified cropping system) and *EYE* (equivalent yield under existing cropping system) represent the equivalent yield of the improved/diversified cropping system and the current yield of cropping system, respectively, and the *MDD* (man days required under diversified cropping system) and the *MDE* (man days required under existing cropping system) represent the total number of person-days that are required in a diversified cropping system or cultivation and the current total number of person-days that are required in the existing system, respectively.

Index	Equation	Equation number	Reference
Sodium adsorption ratio	$SAR = \frac{[Na^+]}{\sqrt{[Ca^{2+}]+[Mg^{2+}]}}$	1	Jahany and Rezapour (2020)
Water use efficiency	$WUE = \frac{\text{Biomass [plant volume } (dm^3)]}{Cumulativewateramountrequired}$	2	Abdelhakim et al. (2021)
Nitrogen use efficiency	$NUE = \frac{\text{Nuptake fert} - \text{Nuptake control}}{\text{Rate N applied}}$	3	Goulding et al. (2008)
Nitrogen agronomic efficiency	$NAE = \frac{\text{Grain Yield fert} - \text{Grain Yield control}}{\text{Rate N applied}}$	4	Niaz et al. (2015)
Growing degree days	$GDD = \Sigma\left(\frac{T_{max}+T_{min}}{2}\right) - T_{base}$	5	Zhang et al. (2020)
System profitability	$SP\left(\frac{\frac{€}{ha}}{day}\right) = \frac{\text{net income/ha}}{365}$	6	Nagoli et al. (2017)
Relative production efficiency	$RPE = \frac{(EYD-EYE)}{EYE} \text{ x } 100$	7	Nagoli et al. (2017)
Relative employment generation efficiency	$REGE(\%) = \frac{MDD-MDE}{MDE} \text{ x } 100$	8	Nagoli et al. (2017)
Specific energy	$SE = \frac{\text{Grain Yield (kg/ ha)}}{\text{Energy Input (MJ/ha)}}$	9	Virk et al. (2020)

Growth and crop yield are significantly affected by topographic and environmental parameters, such as photoperiod, altitude, rainfall, and temperature (Zhang et al. 2021). These parameters in combination to irrigation and the biological cycle of each crop determine the sowing date (Saadi et al. 2015) and the selection of proper cultivars (He et al. 2020) under climate change. Therefore, for the successful introduction of an alternative crop, the photoperiodic requirements (Kobayashi and Weigel 2007), growing degree days (GDDs) (Eq. 5) (Zhang et al. 2020), and altitude-related acclimatization potential of each crop should be regarded.

Finally, an important parameter for the selection of a suitable alternative crop is the economic viability of the crop. The integration of alternative crops in existing farming systems should focus on potential maximum net returns to farmers by keeping the profitability rates high. For this purpose, the system profitability (SP) index (Eq. 6) (Nagoli et al. 2017) could be a useful tool to determine the actual profit per day for a specific crop. Under this context, comparisons between different crops become easier and demonstrate which crop is the most profitable for a specific environment and farming system. Easy access to markets is crucial, though, to ensure the positive economic impact of alternative crop production either by new or retrovative crops (Akinola et al. 2020). Economic benefits are important stimuli for the adoption of alternative crops and cultivation practices by farmers (Toma et al. 2018). Another practical index that could be used to compare two different crop systems, i.e., organic and conventional maize or organic and conventional fertilization, is the relative production efficiency (RPE) (Eq. 7) (Nagoli et al. 2017). This index indicates the relative yield production. If it is positive, then the new system is superior to the previous and should be chosen in favor of productivity potential. Moving from extensive to intensive cultivation, the required number of employers and the intense of labor is strongly diversified. Many crops require more person days and are considered useful for the mitigation of unemployment by increasing employment rates. Under this context, the relative employment generation efficiency (REGE) index could sufficiently describe the possibility of new employment regarding the economic benefits and the required labor (Eq. 8) (Nagoli et al. 2017). Concurrently, machinery plays a vital role in crop selection. The 2030 Agenda for Sustainable Development clarifies that environmental sustainability must be achieved by dealing with societal, economic, and environmental challenges. Due to immense climatic changes, SDG12 (ensure sustainable consumption and production patterns) and SDG13 (take urgent action to combat climate change and its impacts) could be associated with the demand for agricultural production with less energy consumption and overuse of natural resources. The reduction of greenhouse gases that occur from agricultural activities is crucial for the mitigation of the adverse effects of climate change (Su et al. 2017). The specific energy (SE) or energy productivity index describes the energy that is required to produce 1 kg of end product and is expressed as megajoules per product kilogram (MJ kg^{-1}). This index is useful for comparisons among different crop systems, aiding farmers to choose the least energy-consuming (Eq. 9) (Virk et al. 2020; Bilalis et al. 2013).

All the aforementioned criteria are standard for the selection of any crop, not only alternative ones. As the climatic change forces farmers to cope with new challenges, additional criteria should be considered while selecting an alternative crop (Fig. 3). Invasive weeds, alien pests, and pathogens are promoted by the adverse effects of climate change (Meybeck et al. 2012). This may result to an increment of agrochemical inputs (e.g., herbicides and pesticides). EUs' Green Deal, though, aims to reduce these inputs at least by 50% by 2030 (EU Commission 2020a). A simple way to tackle these challenges would be the introduction of weed-competitive and pathogen-resilient alternative crops. Concurrently, EUs' new Soil Strategy (2021) (EU Commission 2021) aims to reduce soil degradation. After all, soil management is crucial for the mitigation of climate change (Escolano et al. 2018; Auerswald and Menzel 2021). Therefore, the conservation agriculture practices and the introduction of crops that require minimum or no tillage should also be considered.

It should be mentioned here that the introduction of an alternative crop to a new cultivation area would probably face some additional challenges. For instance, the availability of appropriate herbicides, pesticides, etc. that are recommended for these novel crops may be an obstacle for the farmers of the area of introduction (Meynard et al. 2018). The availability of appropriate machinery and/or the farmer's lack of technical knowledge might also constrain the adoption of an alternative crop. Farmers need time to get familiar with the management of a crop, a process that might take several seasons (Chantre and Cardona 2014). During this process, the yields will be probably lower than expected; thus, farmers might abandon the new crop (Conley and Udry 2010). Finally, the formation of new processing and distribution networks, or the inclusion of the products of alternative crops in the already-existing ones, is a crucial (Meynard et al. 2018; Gaitán-Cremaschi et al. 2019) yet potentially slow process that may discourage farmers to adopt an alternative crop.

3 Typical cases of alternative crops in the Mediterranean Basin

Seven typical alternative crops are listed below, according to their classification as food crops (quinoa, teff, tritordeum, sweet potato and chia), oilseed crops (camelina and nigella), and industrial crops (camelina). The proposed alternative crops will be examined based on the aforementioned criteria for the selection of the most suitable for the Mediterranean Basin conditions.

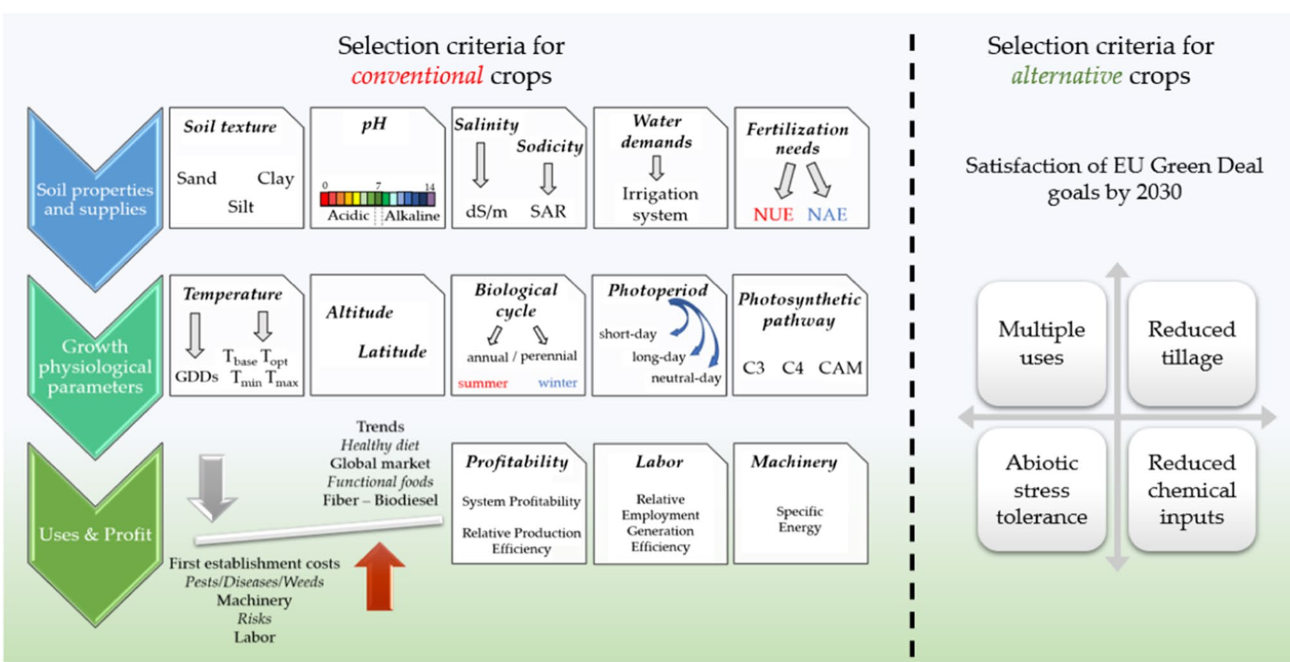

Fig. 3 Criteria for crop selection. CAM crassulacean acid metabolism, GDD growing degree-days, NUE nitrogen use efficiency, NAE nitrogen agronomic efficiency.

3.1 Teff

Teff (*Eragrostis Tef* (Zucc.) Trotter) is an annual cereal of the Poaceae family and the only cultivated crop of the *Eragrostis* genus (Assefa et al. 2015). It originates from Ethiopia (National Research Council 1996) where it was domesticated by presemantic inhabitants around 4000 BC (Abewa et al. 2019). Nowadays, teff remains a major product of the Ethiopian economy (Minten et al. 2016), and it is considered superior to other cereals due to its adaptability, low input demand, nutritional value, and cultural importance (VanBuren et al. 2020). The nutritional profile of its grains makes it an ideal superfood (Mekonen et al. 2019). In particular, teff is a rich source of energy since 100 g of its grains contains 357 kcal (Zhu 2018). Teff grains contain 11% of protein and high levels of lysine, in contrast to other grains that are often insufficient in amino acids. The crude protein and starch content of teff grains resemble or even exceed those of oat, maize, sorghum, and wheat (Ravisankar et al. 2018). In addition, teff grains are characterized by a low glycemic index, a fact that makes them appropriate for people who suffer from celiac disease or gluten intolerance (Del Rio et al. 2013). Even though it is cultivated primarily for its grains, teff can also be utilized for the production of high-quality straw and fuels (Cheng et al. 2017). Over the last decades, teff is evolving globally into a popular crop due to the anti-hypertensive, anti-inflammatory, antioxidant, and anti-atherosclerotic effects of various compounds of its grains (Assefa et al. 2001; Roussis et al. 2019).

Teff is a warm seasonal and C4 plant species. Using the photosynthetic pathway of C4 carbon fixation, the photorespiration is avoided, and teff presents a significant tolerance to drought. The optimal mean temperature for its cultivation is estimated between 10 and 27 °C (Lombamo 2020). The extended and fibrous root system of teff enhances the resistance to waterlogging. This tolerance to extreme environmental conditions makes teff an adaptable crop for climate destabilization conditions. Moreover, in Ethiopia, teff can be cultivated at medium altitudes approximately 1,700–2,400 m above sea level (Lombamo 2020). Even though this crop can acclimatize in various types of soil, it is susceptible to salinity-induced stress; therefore, it does not tolerate soils with high salinity levels (Gorham and Hardy 1990).

From an agronomical point of view, teff needs a plane and stable seedbed, free from stumps and clods, suitable for the sowing of its tiny seeds (Roussis et al. 2019). In order to prepare the seedbed, numerous and frequent tillage treatments are required increasing the machinery and fuel costs of the cultivation. Regarding water demand, this crop needs 750–850 mm of water to achieve sufficient seed yields (Birhanu et al. 2020). Organic fertilization seems to have a beneficial impact on the number of grains per panicle and on their quality traits, such as crude protein, under Mediterranean conditions (Roussis et al. 2019). Concerning sowing, teff seems to be positively affected by plant density. In contrast with other cereals, at the period of storage, teff grains are more resilient in weevils than other crops (Woldeyohannes et al. 2020). According to Kakabouki et al. (2020d), teff can adapt to the Mediterranean climatic conditions and produce satisfactory yields.

3.2 Quinoa

Quinoa (*Chenopodium quinoa* (Willd.)) is a C3 annual dicotyledonous pseudocereal belonging to the Amaranthaceae family (Bilalis et al. 2019). This plant is believed to be native to many Southern American countries, whereas there are recordings for quinoa cultivations prior to 3000 BC–5000 BC (Jancurová et al. 2009). However, the crop gained attention the last decades and was re-introduced in crop systems worldwide due to the high protein content of its gluten-free seeds (greater than 16%) and various nutraceutical traits such as antioxidant compounds that made quinoa attractive (Martínez et al. 2009; Pulvento et al. 2010; Bilalis et al. 2012; Kakabouki et al. 2014; Lavini et al. 2014; De Santis et al. 2016). Alternatively, quinoa may be included in livestock rations by replacing legumes or be used as an energy source (Angeli et al. 2020). The Food and Agriculture Organization of the United Nations (FAO) honored the quinoa crops for feeding the world population and declared 2013 as the International Year of Quinoa (Ruiz et al. 2014).

Quinoa is a promising crop for less fertile soils, as it can be adapted in various soil types (Noulas et al. 2017), with high salinity levels (Cocozza et al. 2013), and on semi-arid conditions (Fghire et al. 2015). Many studies have shown that this alternative crop is capable of acclimatization in several Mediterranean countries (Lavini et al. 2014), such as Greece (Noulas et al. 2017), Italy (De Santis et al. 2018), and Israel (Asher et al. 2020). Quinoa has been characterized as both a short-day and a day-neutral plant, thus explaining its adaptability in environments with varying photoperiods (Asher et al. 2020). As a summer annual crop, high growing degree days (GDDs) are required until harvest. Under typical Mediterranean conditions in Greece, quinoa required 159 days after sowing and approximately 3,445 GDDs to reach maturity (Kakabouki et al. 2019). Altitude is not a limiting factor for quinoa cultivation, since it has been cultivated even at 4000 m above sea level. The tolerance to high temperatures, and eventually to frost (Aguilar and Jacobsen 2006), is a key trait that makes this crop suitable for a broad range of cultivation zones. Quinoa also shows tolerance to both slightly acidic and alkaline pH soils in the range of 4.5–9 (Didier et al. 2016).

The small-sized seeds of quinoa require typical seedbed preparations to ensure proper germination, which occurs after precipitations or irrigation (Aguilar and Jacobsen 2006). Furthermore, quinoa is positively correlated to organic fertilization and has recorded high yields under minimum tillage systems, indicating that machinery and labor costs could remain low in organic farming systems (Papastylianou et al. 2014). It should be noted though that other studies claim that minimum tillage results in lower yields in quinoa and increased weed competition (Kakabouki et al. 2015). Regarding fertilization, application of 150 kg N ha^{-1} provided the best grain yield and crude protein content (Geren 2015). However, nitrogen rates greater than 100 kg N ha^{-1} do not significantly increase the nitrogen agronomic efficiency index (Kakabouki et al. 2018). Profitability remains high as the quinoa market expands globally (Ruiz et al. 2014). Harvest is conducted either manually or mechanically using combine harvesters. The important traits of this crop are the post-harvest treatments (Domínguez 2006). These processes entail a risk of reducing profit (Domínguez 2006). Moreover, quinoa is vulnerable to diseases, with downy mildew (*Peronospora farinosa*) being among the most common ones (Ruiz et al. 2014).

3.3 Tritordeum

Tritordeum (x *Tritordeum* (Ascherson et Graebner)) is a hybrid cereal that derives from the crossing of durum wheat (*Triticum turgidum* ssp. *Durum* (Desf.)) and wild relative of barley (*Hordeum chilense* (Roem. et Schultz)) (Martín et al. 1999). Tritordeum is used in the cereal food industry and breadmaking due to several desirable biochemical properties of its grains, such as high protein content (Kakabouki et al. 2020a, b, c, d) and lower gluten content than wheat (Vaquero et al. 2018). Recently, tritordeum malt was reported as a potential additive in brewing, adding one more use for this alternative crop (Zdaniewicz et al. 2020).

There is ongoing and upcoming research on various advanced tritordeum lines in Southern Mediterranean countries. Under Greek conditions, head emergence was observed approximately at 134 to 146 days after sowing, while plants required 474–610 GDDs depending on the advanced line and variety level and 1020–1380 GDDs from head emergence to harvest, presenting relatively low fungi infection. Moreover, tritordeum lines show varying resistance to common fungi (Rubiales et al. 1993, 1996). Tritordeum shows tolerance to salinity and drought stresses (Villegas et al. 2010) and could be acclimatized in several semi-arid environments in the Mediterranean Basin since it appears adaptable to water deficit conditions (Martín et al. 1999). Farmers should be cautious with nitrogen supply via fertilizers because gluten content increases may occur (Folina et al. 2020).

3.4 Chia

Chia (*Salvia hispanica* L.) is a C3 summer annual pseudocereal belonging to the family Lamiaceae dating back to the era of Aztecs in Central America (Joseph 2014). Similar to quinoa, chia was re-introduced in modern agriculture as a functional food due to its extensive nutritional and nutraceutical profile (Caruso et al. 2018). This plant species features remarkably high ω3 fatty acid concentration and especially α-linolenic fatty acid, a compound that confers an interest in chia consumption and use in modern diets (Ayerza and Coates 2009).

Chia is short-day plant species that shows sensitivity to photoperiod (Baginsky et al. 2016) and requires approximately 3 weeks and roughly up to 13-h day length for flowering (Jamboonsri et al. 2012). The growing period lasts approximately 130 days. Flowering initiation of chia requires approximately 600–700 GDDs at a $T_{base} = 10$ °C under challenging climates (Baginsky et al. 2016). Cultivation of chia shares the same pattern with quinoa crop regarding establishment in high altitude. In Andean valleys, chia is cultivated more than 2000 m above sea level. Potential farmers that plan to cultivate chia should be cautious about the acclimatization environment since seed protein content decreases as altitude raises and linolenic acid increases with altitude elevation. Moreover, seed production is constrained by high latitude (Jamboonsri et al. 2012). A typical Mediterranean environment exhibiting frost in June with a mean temperature equal to 12 °C, slightly alkaline soil, and high salinity reduced severely chia production. Chia shows drought tolerance, whereas irrigation with a total supply of 4100 m^3 ha^{-1} in a Mediterranean environment in Chile provided the best yield components but not the highest water use efficiency (Herman et al. 2016). Crop growth is favored by moderate pH values at a range of 6.5–8.5 and loamy clay soil texture (Benetoli da Silva et al. 2020).

Chia performance depends on cultivar selection and is strongly moderated by environmental conditions. In Southern Mediterranean environments, long-day cultivars are recommended for early flowering in summer (Benetoli da Silva et al. 2020). Furthermore, irrigation with less than 20 mM NaCl concentration is highly recommended for chia cultivation to overcome chia's sensitivity to salinity (Raimondi et al. 2017). Management of chia interference with weeds is crucial for crop success (Karkanis et al. 2018).

3.5 Camelina

Camelina or false flax (*Camelina sativa* L. (Grantz)) is a retraced oilseed crop and a member of Brassicaceae family (Zubr 1997). Archeological evidence confirms that this ancient crop is native to Central Asia and the Mediterranean region (Falasca et al. 2014). Even though the cultivation of camelina dates back to the Bronze and Iron Age (Bouby 1998), the crop has recently regained attention as it can be used as biodiesel feedstock (Chaturvedi et al. 2018; Neupane et al. 2018). Seeds of camelina are an excellent source of oil (Moser 2010). Seed oil yields of camelina are estimated at 106 to 907 L ha^{-1}, remarkably higher than the respective seed oil yields of sunflower and soybean crops (Moser 2010). From a nutritional point of view, camelina seed oil is exceptional as it contains unsaturated fatty acids (Dharavath et al. 2016). Besides human consumption (Koçar 2017), camelinas' seed oil is also used in animal rations (Adhikari et al. 2016; Kakabouki et al. 2020b) and industrial products (such as resins, adhesives, coatings, gums) (Sainger et al. 2017).

Being a short-cycle species, camelina is harvested 70–250 after sown (for spring or winter crops respectively) (Masella et al. 2014). Alternatively, this crop requires approximately 2,900 GDDs from sowing to harvest. The optimum temperatures range between 10 and 24 °C during the vegetative stages, while the range of temperatures differs during flowering and seed filling from 24 to 32 °C (Waraich et al. 2020). It can also withstand temperatures below − 15 °C, and thus, it has adapted to regions of the Boreal Hemisphere (Schillinger et al. 2012). Moreover, camelina is tolerant to drought stress conditions in areas with inadequate rainfall and is more adaptable to dry places than other oleaginous crops (Hirich et al. 2020). Regarding soil requirements, camelina can be cultivated in several types of soils, including acidic, alkaline, and less fertile. However, soils with high salinity levels and soils applied herbicides are not suitable for the establishment of this crop (Khalid et al. 2015). Poorly draining soils are better to be avoided.

From an agronomic perspective, camelina is a low input crop that requires reduced tillage (Angelopoulou et al. 2020a). The average annual water needs of camelina are estimated at 350 to 500 mm (optimal conditions include 150 mm of water during the vegetative phase and 200 mm of water during reproduction) (Moser 2010). Even though camelina has low nutritional demands, it responds well to the application of nitrogen fertilization (Solis et al. 2013). Supply with organic fertilizers, such as compost and vermicompost, seemed to increase the seed and oil yield under Mediterranean conditions (Angelopoulou et al. 2020b). Weed competition is a major problem for this crop as weeds can impact both the quantity and quality of seeds (Berti et al. 2011). Considering pests and diseases, camelina appears resistant and requires limited use of pesticides constituting an ideal alternative crop for diversification (Li et al. 2005). The aforementioned low inputs reduce the labor and machinery requirements and save fuel costs as well. Additionally, as camelina produces high-quality biodiesel and the demand for renewable jet fuel and biodiesel increases, its profitability persists high. Since jet fuel produced by camelina oil causes lower emissions, the crop also contributes to more environmentally friendly management (Shonnard et al. 2010).

3.6 Nigella

Nigella (*Nigella sativa*) is an annual, dicot herb that belongs to the Ranunculaceae family (Salem 2005), native to the Mediterranean Basin (Iqbal et al. 2019). Nowadays, it is cultivated in many countries such as Egypt, Iran, India, Saudi Arabia, Syria, Pakistan, and Turkey as an annual oilseed crop (Papastylianou et al. 2018). Apart from its intense usage in eastern cuisine as a spice, the increased demand for herbal medicinal products and supplements has recently aroused the agricultural interest of this crop (Kara et al. 2015; Roussis et al. 2017). Black cumin's (seeds of nigella) therapeutic properties, which are mainly attributed to the high concentration of thymoquinone in its seeds (D'Antuono et al. 2002), have been known for centuries. The plant's anti-diabetic, antihistaminic, anti-hypertensive, anti-inflammatory, and many other effects have been proven in more than 150 studies in the course of the last 60 years. Black cumin has been also used in apiculture (Engels et al. 1994).

According to the findings of Ghaderi et al. (2008), a mean temperature of 10–30 °C results in seed germination rates between 88 and 96%, whereas optimum germination is achieved at 28.6 °C. Deviation from optimum temperature seems to affect the sensitivity of seeds to salinity-induced stress (Papastylianou et al. 2018). Literature indicates that at 15 °C seeds become significantly more susceptible to salinity, thus posing a challenge to Mediterranean regions with saline soils since temperatures during the months the seeds are sown tend to drop to such levels (Papastylianou et al. 2018). As black cumin acclimatizes on semi-arid areas (D'Antuono et al. 2002), researchers estimated that 724 mm of water per crop season is sufficient to cover its water needs (Ghamarnia et al 2014). It is worth noting that this estimation is not absolute since different climates and soil properties affect the crop's total water requirements. Calcareous soils seem to be unsuitable for nigella due to low P availability, which causes a reduction in seed quality (Seyyedi et al. 2015). Black cumin is adaptable to higher altitudes as it has been cultivated successfully at 1870 m above sea level (Merajipoor et al. 2020). As reported by various studies, fertilization increases the crop's yield. Particularly, the application of N:P fertilizers at a ratio of 60:120 kg ha^{-1} maximized the yield (6416.7 kg ha^{-1}) in field trials performed in Ethiopia (Rana et al. 2012). Besides the success of inorganic fertilization (Roussis et al. 2017), the combined application of inorganic and organic fertilizers and combined application of inorganic fertilizers and biofertilizers led to promising results. Notably, according to a study conducted in Greece, organic crop production of black cumin could potentially be more profitable than conventional crop production (Stefanopoulou et al. 2020). Plant density should be taken into consideration prior to the installment of the crop since densities greater than 200 plants per m^2 decrease the yield. Conclusively, the plant's low susceptibility to diseases has been occasionally reported (D'Antuono et al. 2002).

3.7 Sweet potato

Sweet potato (*Ipomoea batatas* L. (Lam.)) is a perennial plant that belongs to the family of Convolvulaceae and produces edible storage roots (Padmaja 2009). It is considered an ancient crop that its cultivation derives from Central or Northwestern South America (O'Brien 1972). Sweet potato is mainly cultivated for food consumption and livestock feed, and it is also used as a raw material in industrial applications. The comestible parts of the plant are the roots, or tubers, as well as the leaves (Loebenstein 2009). Sweet potato tubers can be treated in a wide range of secondary food products and in industrial items such as starch, flour, sugar syrup, ethanol, alcohol, and cosmetic compounds, as well as in health and pharmaceutical products (Onwude et al. 2018). In the last decades, sweet potato became a popular crop in European countries (O'Brien 1972). As stated by FAO (2019), in 2018 the global sweet potato cultivation area was 8,062,737 ha, while the yield reached 114,037 kg ha^{-1}.

Sweet potato is considered a tropical and subtropical plant, suitable to adjust in various temperatures, and at altitudes even 2000 m above sea level (Nedunchezhiyan et al. 2012). The crop thrives in mild temperatures between 21 and 26 °C, while lower temperatures during the night endow the formation of tubers, and high temperatures by day promote the vegetative growth (Eisenbach et al. 2018; Kakabouki et al. 2020c). As a short-day plant with a growing season of 90–150 days, the fluctuations in temperature accompanied with short days promote the growth of tubers. In addition, sweet potato requires sufficient sunlight, while shading provokes a reduction in the final production. Sweet potato is resilient to drought and water deficiency (Onwude et al. 2018). Well-drained sandy-clay soils with clayey subsoil are considered ideal for this crop. Heavy clay soils inhibit tuber formation due to soil compactness in comparison with sandy soils where the growth of cylindrical tubers is promoted. Sweet potato can normally be grown in soils with pH values ranging from 5.5 to 6.5, while higher and lower pH can lead to abnormalities of tubers and aluminum toxicity, respectively. Besides, the crop is vulnerable to alkaline soils and salinity (Nedunchezhiyan et al. 2012).

Sweet potato cuttings are planted in embankments or ditches, where they grow rapidly and spread throughout the soil. Several measures are required to control weeds, especially in the initial stages, such as mechanical pruning or the application of herbicides. Regarding water efficiency, water availability is critical during the first weeks of planting until the good establishment of the crop. Sweet potato demands a low nutrient input, and its needs can be met with organic and inorganic fertilizers. Nitrogen needs are estimated at a dose of 50–70 kg ha^{-1}, phosphorus at 25–50 kg ha^{-1}, and potassium at 75–100 kg ha^{-1} (Eisenbach et al. 2018). Several studies reported that increased nitrogen uptake augmented the tuber dry matter, carotenoid, and protein content (Meehan et al. 2013). In Greece, the harvest takes place from the end of July until the beginning of November. Storage of tubes plays a crucial role in the availability and sustainability of sweet potatoes in the market. Special attention must be given to the enemies of crops such as nematodes, pests, and fungal disease during the vegetative growth and storage (Fernandes et al. 2020).

4 Discussion

The aforementioned problems need to be handled out as challenges for the sustainability of agricultural holdings globally. Therefore, a multi-actor approach including beneficiaries from different sectors should be adopted to prepare the so-called 4.0 Agriculture (Rose and Chilvers 2018). Policymakers need to re-design many guidelines/protocols/directives to comply with the actual needs of societies (Zorpas 2020) and to meet the requirements for more sustainable agriculture. Scientists and agricultural advisors should consider the varying conditions of the agricultural sector and deliver feasible, environmentally friendly, and economically approved solutions to farmers regarding sustainable agricultural production. Most importantly, farmers are encouraged to act on three axes: (1) diversify the structure of their farming system; (2) integrate alternative crops that are adapted to climate change to secure and even increase their income; and (3) mitigate water and nitrogen losses, reduce chemical input, and lessen CO_2 emissions. The selection of an alternative crop is the key to address the challenge for systems adaptability to climate change. Farmers who operate in degraded semi-arid or arid environments need to modify their targeting regarding crop production and integrate new genetic material and technologies. Under this context, the aforementioned limiting factors should be taken into account so that the alternative crops are properly acclimatized in new areas (Table 3) (Kourgialas et al. 2018; Cortinovis et al. 2020).

This review aimed to examine all limiting factors that guide alternative crop selection and performance under Southern Mediterranean conditions. Crops demonstrate different sensitivity and tolerance to important soil and environmental factors. For instance, 5 out of 7 alternative crops are vulnerable to moderate to high salinity levels. Quinoa and tritordeum seem promising for introduction in various farming systems across the Mediterranean since they could tolerate harsh growing conditions without demanding an oversupply of water and nutrients. Chia is

Table 3 Crop characteristics and compliance with specific farming systems components. Numbers in the column of each crop indicate their response to each limiting factor. Limiting factors are listed in the factor column. The potential outcome of each factor was assigned a number (1, 2, or 3) in the rate column. A crop with a wide range of responses to the limiting factors is assigned with multiple numbers (1, 2, and/or 3).

Factor	Rate	Food field crops					Oilseeds field crops	Industrial field crops
		Teff	Quinoa	Tritordeum	Chia	Sweet potato	Nigella	Camelina
Crop system	(Organic = 1, integrated = 2, conventional = 3)	3	1, 3	3	3	3	1, 3	1, 3
Soil type	(Sandy = 1, mean = 2, heavy = 3)	2	1, 2, 3	2	2	1, 2	1	1, 2, 3
Soil pH	(Acidic = 1, neutral = 2, alkaline = 3)	1, 2	2	2	2	1, 2	2	2
Water demand	(Low = 1, mean = 2, high = 3)	3	1	1	1	1	3	1
Fertilization needs	(Via nitrogen use efficiency index; low = 1, high = 2)	1	2	1	1	1	1	1
Altitude	(Neutral between 0 and 3000 m = 1, < 2000 m = 2)	1	1, 2	1	1, 2	1, 2	1	1
Soil salinity	(Resistant = 1, sensitive = 2)	2	1	1	2	2	2	2
Temperature	(Spring crop = 1, winter crop = 2, both = 3)	1	1	2	1	1	1	3
Plant material	(Seed = 1, other = 2)	1	1	1	1	2	1	1
Biological cycle	(Short = 1, mean = 2, long perennial = 3)	1	2	3	2	3	2	1
Photoperiod	(Short-day = 1, long-day = 2, neutral = 3)	1	3	2	1	1	1	2
Photosynthetic pathway	(C3 = 1, C4 = 2)	2	1	1	1	1	1	1
Profitability	(Positive related to common crop/system = 1, negative = 2)	1	1	1	1	1	1	1
Labor (increasing employment rates)	(Positive related to employment rate/system = 1, neutral = 2)	1	2	2	2	2	1	1
CO_2 emissions (from machinery and chemical input)	(Positive related to energy consumption and low input = 1, negative and high input = 2)	1	2	1	1	2	1	1
Uses	(Multiple uses = 1, one product = 2)	1	1	1	2	1	1	1

significantly affected by changes in environment and soil properties, showing relatively low adaptability to new cultivation zones. Quinoa, sweet potato, and camelina displayed the highest adaptability as they acclimatize to various soil types, with different properties, and in a wide range of pH values (Table 3). Furthermore, quinoa and camelina could perform successfully under both organic and conventional systems. It should be noted though that quinoa has reportedly high fertilization needs. Teff and sweet potato can also adequately adapt to different soil types though teff's water demands are rather high. Quinoa and sweet potato are also able to grow in high altitudes, in some cases over 2000 m above sea level. Among these cultivations, sweet potato is the only one being susceptible to high salinity levels while at the same time has the longest biological cycle as a perennial crop. Notably, among these 7 crops, camelina has the shortest biological cycle (approx. 70 days) and can be cultivated either as a summer or winter crop. A wide variety of end products with multiple applications can be produced by the aforementioned alternative crops, implying potentially high profitability. Quinoa and sweet potato though were the only ones with high CO_2 emissions which do not cope with EU's new Climate Law (EU Commission 2020b).

Overall, in an attempt to evaluate these crops, Table 4 is formed. Based on the literature and the guidelines regarding soil degradation and reduction of agrochemicals, 9 factors were chosen for this evaluation. Initially, the adaptability of each crop on different soil types, with

Table 4 Score table for the compliance of the alternative crops with several EU directives and Green Deal principles.

Factor	Teff	Quinoa	Tritordeum	Chia	Sweet potato	Nigella	Camelina	Wheat	Maize
Adaptability on different soil types	3	5	3	2	4	2	4	4	3
Reduced water demands	0	1	1	1	1	0	1	1	0
Reduced fertilization needs	1	0	1	1	1	1	1	0	0
Labor	1	0	0	0	0	1	1	0	0
Reduced CO_2 emissions	1	0	1	1	0	1	1	0	0
Reduced agrochemical inputs	1	0	1	0	0	1	0	0	0
Reduced tillage	0	1	0	1	0	0	1	1	1
Multiple uses	1	1	0	0	1	1	1	0	1
Total score	8	8	7	8	7	7	10	6	5

different characteristics, pH values, and salinity levels, were assessed. For this purpose, crops scored additional points according to their adaptability. Quinoa, namely, can be cultivated on sandy, mean, and heavy soils (3 points, one for each), but only under neutral pH values (1 point), and tolerates high salinity levels (1 point), therefore scored 5 points. Teff on the other hand prefers mean soils (1 point), with either acidic or neutral pH values (2 points), and does not tolerate salinity (0 points), thus scoring 3 points. This scoring system, obviously, rather than being absolute tries to depict potential advantages of an alternative crop compared to the rest of the crops. Also, it should be mentioned that the scoring was performed based on the literature; therefore, due to conflicting information or further research, these scores could be possibly altered in the future. Nevertheless, each crop that is characterized as a reduced water or fertilizer-demanding crop scored 1 additional point. Likewise, increased labor, reduced CO_2 emissions, and reduced chemical input needs (herbicides, pesticides) were also rewarded by 1 point each. Finally, the crops that can be successfully cultivated under no or conservation tillage systems and the crops with multiple uses scored 1 additional point for each of these factors. Besides the 7 alternative crops, wheat and maize, two of the most successful cultivations of the Mediterranean, were also evaluated with the same scoring system.

According to the scores of the score table (Table 4), all 7 of the proposed alternative crops seem suitable for the Mediterranean Basin, under the context of SDGs and the New Soil Strategy of EU. The fact that the total scores of the alternative crops surpass those of wheat and maize does not imply that these crops are superior to wheat and maize. Such statements need validation via multi-factor analysis far too complicated to be depicted on a single score table. On the contrary, these scores function as a mere indication of the potential success of these crops. Camelina recorded the highest score (10 points), as it only lacks in the agrochemical input factor. Teff, chia, and quinoa followed, scoring 8 points each. Out of these 3 crops, teff is the least susceptible to pests and weed competition, though in contrast to quinoa and chia requires tillering. Lastly, tritordeum, sweet potato, and nigella scored 7 points. Among them, sweet potato was the only crop without multiple uses and the crop with the highest needs of agrochemical inputs.

Although in many cases there are no available public data, some of these crops have already been cultivated in Mediterranean countries, possibly on a small scale (Gómez et al. 2021; Zanetti et al. 2021). Quinoa production, for instance, has been, reportedly, increased in southern regions of Spain in the last few years (Gómez et al. 2021), while Greece produced 3.3 thousand tonnes of sweet potato in 2016 (FAO 2019). In fact, official data (regarding the production of the seven alternative crops proposed by the present study in the Mediterranean Basin) exist only for sweet potato, and only up until 2019 (Fig. 4). It should be mentioned though that even though most of these crops are not cultivated intensively or in a large scale in the Mediterranean Basin, research has been conducted regarding their potential inclusion in existing crop rotation systems. Tekin et al. (2017) evaluated the introduction of quinoa on crop rotation systems alongside wheat (*Triticum aestivum* L) and chickpea (*Cicer arietinum*) in Turkey, though their results were not promising. However, Royo-Esnal and Valencia-Gredilla (2018) concluded that camelina could be cultivated as a rotation crop in winter cereals in Spain. Similarly, Mack (2020) proposed that chia could be rotated with maize, sorghum, soybean, or vegetables in Egypt.

Regarding the mitigation of climate change, each of the proposed crops could contribute to this common aim of the SDGs, Green Deal, and the CAP (Fig. 5). Even though an accurate prediction of this contribution ahead of time is at risk of being unreliable, the assessment of their potential is possible. For instance, teff and tritordeum would require reduced (or even potentially non) amounts of pesticides and fungicides due to their resilience, while sweet potato has low nutrient demands. These crops, hence,

Fig. 4 Production of sweet potato (in tonnes) per Mediterranean country and per year, according to FAOSTAT (http://www.fao.org/faostat/en/#data/QCL).

comply with SDG 15 and the aim of the Green Deal to significantly reduce chemical inputs by 2030. Likewise, the reported high profitability of nigella under organic farming systems complies with the effort to increase organic farming. Quinoa and chia are drought-tolerant crops with high nutrition value. As a global food shortage is anticipated by 2050 (partially due to the adverse effects of climate change) (Ray et al. 2013; Pradhan et al. 2015), these crops could contribute to the effort to tackle the upcoming hunger crisis. Camelina is a promising crop for biodiesel production that would ultimately reduce greenhouse gas emissions. Concurrently, these crops fulfill the objectives of the new CAP regarding climate change mitigation, sustainable management of natural resources, enhanced biodiversity, and societal prosperity (Fig. 5).

5 Conclusion

Since climate change causes adverse effects on natural resources reducing the productivity of agriculture, new agronomic practices must be developed to maintain the sustainability of crop systems and every correlated socio-economic activity. A means for achieving this objective is the diversified crops via the introduction of innovative and/or retrovative plant species. To select suitable crops, territorial, climatic, and growth physiological requirements need to be taken into consideration. In the case of the seven alternative crops that are proposed for adaptation in the Mediterranean Basin, the study resulted in the following endpoints: (i) even though chia presents difficulty in adapting to new cultivation zones and is vulnerable to most soil properties and growth physiological parameters, it could be potentially introduced in the Mediterranean Basin; (ii) a moderate potential to acclimatization is demonstrated in the case of sweet potato and nigella under the Mediterranean environments; (iii) teff and camelina could be adapted to Mediterranean conditions, while quinoa and tritordeum are distinguished as the most resilient in risks of territorial and growth physical effects; (iv) soil salinity and sodicity seem to affect more negatively almost all crops, whereas temperature and latitude are the least aggravating factors in the adaptability of the mentioned crops; (v) considering the water demand for crops, teff and nigella require greater amounts of water; and (vi) the majority of crops except quinoa meet their needs of nutrient fertilizer with low inputs.

Beyond the capability of the crop in adjustment, it is just as important to consider the environmental, social, and economic footprint that each crop leaves. Given this parameter, this review results in the undermentioned findings: (i) almost all alternative crops produce a wide range of end products with multiple uses and applications; (ii) all the proposed alternative crops comply with at least one SDG, Green Deal KPI, and CAP 2023–2027 objective; (iii) the vast majority of the proposed crops demonstrate high profitability as their

Crop	Advantages	Compliance with SDGs of U.N.	Compliance with E.U. Green Deal KPIs	Compliance with new CAP 2023-2027 objectives
Teff	Pest-resilient, reduced chemical inputs for pest management	N° 15 Life on Land	Reduce the use of pesticides by 50% by the year 2030	• SO 4: Contribute to climate change mitigation and adaptation of agriculture • SO 5: Foster sustainable management of natural resources, such as soil and water • SO 6: Enhance biodiversity • SO 7: Attract new generation in the agricultural sector due to the formation of new food-related production chains • SO 9: Satisfy societal demands for safe nutritious sustainable food
Quinoa	Adaptability on less fertile soils, with high salinity, and under semi-arid conditions. High nutritional value	N° 2 Zero Hunger	Create sustainable food labeling	
Tritordeum	Resilient to fungi, reduced fungicide inputs	N° 15 Life on Land	Reduce the use of antimicrobials in agriculture by 50% by 2030	
Chia	Drought tolerant. High nutritional value	N° 2 Zero Hunger	Create sustainable food labeling	
Camelina	Biodiesel production	N° 13 Climate Action	Achieve net-zero greenhouse gas emissions by 2050	
Nigella	Organic production is potentially more profitable than the convetional one	N° 15 Life on Land	Increase organic farming	
Sweet potato	Low nutrient demand that can be met with organic fertilizers	N° 15 Life on Land	Reduce the use of Fertilizers by 20% by the year 2030	

Fig. 5 The potential contribution of the seven alternative crops in the mitigation of climate change and their compliance with the Sustainable Development Goals of the UN (SDGs), the Key Performance Indices (KPIs) of EU Green deal, and the objectives of the new Common Agricultural Policy (CAP) 2023–2027. The SO in the CAP column represent the Specific Objects of CAP. Graphic images representing each SDG were taken from https://sdgs.un.org/goals.

products respond to the market needs and human nutrition trends; and (iv) these crops might be promising alternatives for crop rotations and contribute to the reduction of chemical input to design toxic-free environment by 2030.

Even though the findings of these alternative crops are encouraging respecting their introduction in the Mediterranean Basin, further research must be conducted to enrich our arsenal of tools against climate change.

Authors' contributions Conceptualization, I.K.; methodology, I.K., A.T., and P.P.; validation, I.K., A.E., N.K., and I.R.; formal analysis, I.K., A.T., and A.E.; investigation, I.K., A.T., A.M., I.R., and A.E.; data curation, A.M., A.K., and A.T.; writing original draft preparation, I.K., A.T., A.K., and A.M.; writing, review and editing, I.K., A.T., A.K., A.M., and P.P.; visualization, I.K., A.T., A.K., and N.K.; supervision, I.K. and P.P.; and project administration, I.K.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Abdelhakim LOA, Rosenqvist E, Wollenweber B, Spyroglou I, Ottosen CO, Panzarová K (2021) Investigating combined drought- and heat stress effects in wheat under controlled conditions by dynamic image-based phenotyping. Agronomy 11(2):364. https://doi.org/10.3390/agronomy11020364

Abewa A, Adgo E, Yitaferu B, Alemayehu G, Assefa K, Solomon JKQ, Payne W (2019) Teff grain physical and chemical quality responses to soil physicochemical properties and the environment. Agronomy 9(6):283. https://doi.org/10.3390/agronomy9060283

Adhikari PA, Heo JM, Nyachoti CM (2016) Standardized total tract digestibility of phosphorus in camelina (*Camelina sativa*) meal fed to growing pigs without or phytase supplementation. Anim Feed Sci Technol 214:104–109. https://doi.org/10.1016/j.anifeedsci.2016.02.018

Aguilar PC, Jacobsen SE (2006) Cultivation of quinoa on the Peruvian altiplano. Food Rev Int 19(1–2):31–41. https://doi.org/10.1081/FRI-120018866

Akinola R, Pereira LM, Mabhaudhi T, de Bruin FM, Rusch L (2020) A review of indigenous food crops in Africa and the implications for more sustainable and healthy food systems. Sustainability 12(8):3493. https://doi.org/10.3390/su12083493

Almendro-Candel MB, Lucas IG, Navarro-Pedreño J, Zorpas AA (2018) Physical properties of soils affected by the use of agricultural waste. In: Agricultural waste and residues. IntechOpen, London, pp. 9–27. https://doi.org/10.5772/intechopen.77993

Angeli V, Silva PM, Massuela DC, Khan MW, Hamar A, Khajehei F, Graeff-Hönninger S, Piatti C (2020) Quinoa (*Chenopodium quinoa* Willd.): an overview of the potentials of the "golden grain" and socio-economic and environmental aspects of its cultivation and marketization. Foods 9(2):216. https://doi.org/10.3390/foods9020216

Angelopoulou F, Tsiplakou E, Bilalis D (2020a) Tillage intensity and compost application effects on organically grown camelina productivity, seed and oil quality. Not Bot Horti Agrobot Cluj Napoca 48(4):2153–2166. https://doi.org/10.15835/nbha48412056

Angelopoulou F, Anastasiou E, Fountas S, Bilalis D (2020b) Evaluation of organic camelina crop under different tillage systems and fertilization types using proximal remote sensing. Bull Univ Agric Sci Vet Med Cluj-Napoca, Hortic *77* (1). https://doi.org/10.15835/buasvmcn-hort:2019.0025

Asher A, Galili S, Whitney T, Rubinovich L (2020) The potential of quinoa (*Chenopodium quinoa*) cultivation in Israel as a dual-purpose crop for grain production and livestock feed. Sci Hortic 272:109534. https://doi.org/10.1016/j.scienta.2020.109534

Assefa K, Tefera H, Merker A, Kefyalew T, Hundera F (2001) Variability, heritability and genetic advance in pheno-morphic and agronomic traits of tef [*Eragrostis tef* (Zucc) Trotter] germplasm from eight regions of Ethiopia. Hereditas 134(2):103–13. https://doi.org/10.1111/j.1601-5223.2001.00103.x

Assefa K, Cannarozzi G, Girma D, Kamies R, Chanyalew S, Plaza-Wuthrich S, Blosch R, Rindisbacher A, Rafudeen S, Tadele Z (2015) Genetic diversity in tef [*Eragrostis tef* (Zucc) Trotter]. Front Plant Sci 6:177. https://doi.org/10.3389/fpls.2015.00177

Auerswald K, Menzel A (2021) Change in erosion potential of crops due to climate change. Agric for Meteorol 300:108338. https://doi.org/10.1016/j.agrformet.2021.108338

Ayerza R, Coates W (2009) Influence of environment on growing period and yield, protein, oil and α-linolenic content of three chia (*Salvia hispanica* L.) selections. Ind Crops Prod 30(2):321–324. https://doi.org/10.1016/j.indcrop.2009.03.009

Baginsky C, Arenas J, Escobar H, Garrido M, Valero N, Tello D, Pizarro L, Valenzuela A, Morales L, Silva H (2016) Growth and yield of chia (*Salvia hispanica* L.) in the Mediterranean and desert climates of Chile. Chil J Agric Res 76(3):255–264. https://doi.org/10.4067/S0718-58392016000300001

Benetoli da Silva TR, de Melo SC, Nascimento AB, Ambrosano L, Bordin JC, Alves CZ, Secco D, Santos RF, Gonçalves-Jr AC, da Silva GD (2020) Response of chia (*Salvia hispanica*) to sowing times and phosphorus rates over two crop cycles. Heliyon 6(9):e05051. https://doi.org/10.1016/j.heliyon.2020.e05051

Berti M, Wilckens R, Fischer S, Solis A, Johnson B (2011) Seeding date influence on camelina seed yield, yield components, and oil content in Chile. Ind Crops Prod 34(2):1358–1365. https://doi.org/10.1016/j.indcrop.2010.12.008

Bilalis D, Kakabouki I, Karkanis A, Travlos I, Triantafyllidis V, Hela D (2012) Seed and saponin production of organic quinoa (*Chenopodium quinoa* Willd.) for different tillage and fertilization. Not Bot Horti Agrobot Cluj Napoca 40(1):42–46. https://doi.org/10.15835/nbha4017400

Bilalis D, Kamariari PE, Karkanis A, Efthimiadou A, Zorpas A, Kakabouki I (2013) Energy inputs, output and productivity in organic and conventional maize and tomato production, under Mediterranean conditions. Not Bot Horti Agrobot Cluj Napoca 41(1):190–194. https://doi.org/10.15835/NBHA4119081

Bilalis D, Roussis I, Fuentes F, Kakabouki I, Travlos I (2017) Organic agriculture and innovative crops under Mediterranean conditions. Not Bot Horti Agrobot Cluj Napoca 45(2):323–331. https://doi.org/10.15835/nbha45210867

Bilalis DJ, Roussis I, Kakabouki I, Folina A (2019) Quinoa (*Chenopodium quinoa* willd.) crop under Mediterranean conditions: a review. Cienc Investig Agrar 46(2):51–68. https://doi.org/10.7764/rcia.v46i2.2151

Birhanu A, Degenet Y, Tahir Z (2020) Yield and agronomic performance of released Tef [*Eragrostis tef* (Zucc.) Trotter] varieties under irrigation at Dembia, Northweastrn, Ethiopia. Cogent Food Agric 6 (1). https://doi.org/10.1080/23311932.2020.1762979

Bouby L (1998) Two early finds of gold-of-pleasure (*Camelina sp.*) in middle Neolithic and Chalcolithic sites in western France. Antiquity 72(276):391–398. https://doi.org/10.1017/S0003598X0008666X

Caruso MC, Favati F, Di Cairano M, Galgano F, Labella R, Scarpa T, Condelli N (2018) Shelf-life evaluation and nutraceutical properties of chia seeds from a recent long-day flowering genotype cultivated in Mediterranean area. Lebensm Wiss Technol 87:400–405. https://doi.org/10.1016/j.lwt.2017.09.015

Chantre E, Cardona A (2014) Trajectories of French field crop farmers moving toward sustainable farming practices: change, learning, and links with the advisory services. Agroecol Sustain Food Syst 38(5):573–602. https://doi.org/10.1080/21683565.2013.876483

Chaturvedi S, Bhattacharya A, Khare SK, Kaushik G (2018) *Camelina sativa*: an emerging biofuel crop. In: Handbook of environmental materials management. Springer International Publishing pp. 1–38. https://doi.org/10.1007/978-3-319-73645-7_110

Cheng A, Mayes S, Dalle G, Demissew S, Massawe F (2017) Diversifying crops for food and nutrition security – a case of teff. Biol Rev 92(1):188–198. https://doi.org/10.1111/brv.12225

Cocozza C, Pulvento C, Lavini A, Riccardi M, D'Andria R, Tognetti R (2013) Effects of increasing salinity stress and decreasing water availability on ecophysiological traits of quinoa (*Chenopodium quinoa* Willd.) grown in a Mediterranean-type agroecosystem. J Agron Crop Sci 199:229–240. https://doi.org/10.1111/jac.12012

Conley TG, Udry CR (2010) Learning about a new technology: pineapple in Ghana. Am Econ Rev 100(1):35–69. https://doi.org/10.1257/aer.100.1.35

Cortinovis G, Di Vittori V, Bellucci E, Bitocchi E, Papa R (2020) Adaptation to alternative environments during crop diversification. Curr Opin Plant Biol 56:203–217. https://doi.org/10.1016/j.pbi.2019.12.011

Crowley JG, Fröhlich A (1998) Factors affecting the composition and use of camelina. Teagasc, End of Project Reports, Teagasc. https://t-stor.teagasc.ie/handle/11019/1481

D'Antuono LF, Moretti A, Lovato AFS (2002) Seed yield, yield components, oil content and essential oil content and composition of *Nigella sativa* L and *Nigella damascena* L. Ind Crops Prod 15(1):59–69. https://doi.org/10.1016/S0926-6690(01)00096-6

De Santis G, D'Ambrosio T, Rinaldi M, Rascio A (2016) Heritabilities of morphological and quality traits and interrelationships with yield in quinoa (*Chenopodium quinoa* Willd.) genotypes in the

Mediterranean environment. J Cereal Sci 70:177–185. https://doi.org/10.1016/j.jcs.2016.06.003

De Santis G, Ronga D, Caradonia F, Ambrosio TD, Troisi J, Rascio A, Fragasso M, Pecchioni N, Rinaldi M (2018) Evaluation of two groups of quinoa (*Chenopodium quinoa* Willd.) accessions with different seed colours for adaptation to the Mediterranean environment. Crop Pasture Sci 69(12):1264–1275. https://doi.org/10.1071/CP18143

Degirmencioglu T, Unal H, Ozbilgin S, Kuraloglu H (2016) Effect of ground fenugreek seeds (*Trigonella foenum-graecum*) on feed consumption and milk performance in Anatolian water buffaloes. Arch Anim Breed 59(3):345–349. https://doi.org/10.5194/aab-59-345-2016

Del Rio D, Rodriguez-Mateos A, Spencer JPE, Tognolini M, Borges G, Crozier A (2013) Dietary (poly)phenolics in human health: structures, bioavailability, and evidence of protective effects against chronic diseases. Antioxid Redox Signal 18(14):1818–1892. https://doi.org/10.1089/ars.2012.4581

Dharavath RN, Singh S, Chaturvedi S, Luqman S (2016) *Camelina sativa* (L.) Crantz A mercantile crop with speckled pharmacological activities. Ann Phytomed 5(2):6–26. https://doi.org/10.21276/ap.2016.5.2.2

Didier B, Cataldo P, Alexis V, Al-Nusairi Mohammad S, Djibi B, Joelle B, Layth H, Maarouf IM, Omurbek M, Munira O, Sepahvand Niaz A, Amr S, Djamel S, Khaled M, Stefano P (2016) Worldwide evaluations of quinoa: preliminary results from post international year of quinoa FAO projects in nine countries. Front Plant Sci 7:850. https://doi.org/10.3389/fpls.2016.00850

Domínguez SS (2006) Quinoa - postharvest and commercialization. Food Rev Int 19(1–2):191–201. https://doi.org/10.1081/FRI-120018885

EIP-AGRI (2016) Focus Group Water & agriculture: adaptive strategies at farm level FINAL REPORT, Climate change and food security: risks and responses. European Innovation Partnership (EIP-AGRI). https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_water_and_agriculture_final-report_en.pdf

Eisenbach LD, Folina A, Zisi C, Roussis I, Tabaxi I, Papastylianou P, Kakabouki I, Efthimiadou A, Bilalis DJ (2018) Effect of biocyclic humus soils on yield and quality parameters of sweet potato *(Ipomoea batatas L.)*. Sci Papers Ser A, Agron 61(1):210. ISSN:2285–5785

Engels W, Schulz U, Radle M (1994) Use of Tübingen mix for bee pasture in Germany. In Forage for bees in an agricultural landscape. International Bee Research Association, Aberystwyth, pp. 57–65

Escolano JJ, Pedreño JN, Lucas IG, Candel MBA, Zorpas AA (2018) Decreased organic carbon associated with land management in Mediterranean environments. In: Soil management and climate change. Academic Press, Cambridge, pp. 1–13. https://doi.org/10.1016/B978-0-12-812128-3.00001-X

EU Commission (2020a) Farm to fork strategy. European Commission. https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf

EU Commission (2020b) Establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020PC0080&from=EN

EU Commission (2021) Commission consults on new EU soil strategy. European Commission. https://ec.europa.eu/environment/news/commission-consults-new-eu-soil-strategy-2021-02-02_en

Falasca S, del Fresno M, Waldman C (2014) Developing an agroclimatic zoning model to determine potential growing areas for *Camelina sativa* in Argentina. QSci connect 4.https://doi.org/10.5339/connect.2014.4

FAO (2008) Climate change and food security: a framework document. Food Agriculture Organization United Nations. http://www.fao.org/3/k2595e/k2595e00.pdf

FAO (2019) Food and Agriculture Organization of United Nations. http://www.fao.org/faostat/en/#data/QC

Fernandes AM, Assunção NS, Ribeiro NP, Gazola B, da Silva RM (2020) Nutrient uptake and removal by sweet potato fertilized with green manure and nitrogen on sandy soil. Rev Bras Ciênc Solo 44:1–25. https://doi.org/10.36783/18069657RBCS20190127

Fghire R, Anaya F, Ali OI, Benlhabib O, Ragab R, Wahbi S (2015) Physiological and photosynthetic response of quinoa to drought stress. Chil J Agric Res 75(2):174–183. https://doi.org/10.4067/S0718-58392015000200006

Folina A, Kakabouki I, Kontonasaki E, Karydogianni S, Voskopoulos D, Beslemes DF, Bilalis D (2020) Effect of organic and inorganic fertilization on yield and quality traits of tritordeum, 'Bulel' variety under dry conditions in Greece. Bull Univ Agric Sci Vet Med Cluj-Napoca Hortic 77(2):10–14. https://doi.org/10.15835/buasvmcn-hort:2020.0056

Geren H (2015) Effects of different nitrogen levels on the grain yield and some yield components of quinoa (*Chenopodium quinoa* Willd.) under Mediterranean climatic conditions. Turk J Field Crop 20(1):59–64. https://doi.org/10.17557/.39586

Ghaderi FA, Soltani A, Sadeghipour HR (2008) Cardinal temperatures of germination in medicinal pumpkin (Cucurbita pepo convar. pepo var. styriaca), borago (*Borago officinalis* L.) and black cumin (*Nigella sativa* L.). Asian J Plant Sci 7(6):574–578. https://doi.org/10.3923/ajps.2008.574.578

Ghamarnia H, Miri E, Ghobadei M (2014) Determination of water requirement, single and dual crop coefficients of black cumin (*Nigella sativa* L.) in a semi-arid climate. Irrig Sci 32:67–76. https://doi.org/10.1007/s00271-013-0412-2

Gómez MJR, Prieto JM, Sobrado VC, Magro PC (2021) Nutritional characterization of six quinoa (*Chenopodium quinoa* Willd) varieties cultivated in Southern Europe. J Food Compos Anal 99:103876. https://doi.org/10.1016/j.jfca.2021.103876

Gorham J, Hardy CA (1990) Response of *Eragrostis tef* to salinity and acute water shortage. J Plant Physiol 135(6):641–645. https://doi.org/10.1016/S0176-1617(11)80873-4

Goulding K, Jarvis S, Whitmore A (2008) Optimizing nutrient management for farm systems. Philos Trans R Soc B 363(1491):667–680. https://doi.org/10.1098/rstb.2007.2177

He L, Jin N, Yu Q (2020) Impacts of climate change and crop management practices on soybean phenology changes in China. Sci Total Environ 707:135638. https://doi.org/10.1016/j.scitotenv.2019.135638

Herman S, Marco G, Cecilia B, Alfonso V, Luis M, Cristián V, Sebastián P, Sebastián A (2016) Effect of water availability on growth, water use efficiency and omega 3 (ALA) content in two phenotypes of chia (*Salvia hispanica* L.) established in the arid Mediterranean zone of Chile. Agric Water Manag 173:67–75. https://doi.org/10.1016/j.agwat.2016.04.028

Hirich A, Allah RC, Ragab R (2020) Emerging research in alternative crops. Environment & Policy. Springer International Publishing, Cham. ISBN:9783319904719

Hossain A, Sabagh ELA, Barutcular C, Bhatt R, Çiğ F, Seydoşoğlu S, Turan N, Konuskan O, Iqbal MA, Abdelhamid M et al (2020) Sustainable crop production to ensuring food security under climate change: a Mediterranean perspective. Aust J Crop Sci 14(3):439–446. https://doi.org/10.21475/ajcs.20.14.03.p1976

Iqbal MS, Ghafoor A, Akbar M, Akhtar S, Fatima S, Siddqui EH (2019) Genetic variation and path analysis for yield and other agronomic traits in *Nigella sativa* L. germplasm. Bangladesh J Bot 48(3):521–527. https://doi.org/10.3329/BJB.V48I3.47913

Isleib J (2012) Exploring alternative field crops. Michigan State University Extension, East Lansing, MI. https://www.canr.msu.edu/news/exploring_alternative_field_crops
Jahany M, Rezapour S (2020) Assessment of the quality indices of soils irrigated with treated wastewater in a calcareous semi-arid environment. Ecol Indic 109:105800. https://doi.org/10.1016/j.ecolind.2019.105800
Jamboonsri W, Phillips TD, Geneve RL, Cahill JP, Hildebrand DF (2012) Extending the range of an ancient crop, *Salvia hispanica* L.-a new ω3 source. Genet Resour Crop Evol 59:171–178. https://doi.org/10.1007/s10722-011-9673-x
Jancurová M, Minarovičová L, Dandár A (2009) Quinoa - a review. Czech J Food Sci 27(2):71–79
Joseph PC (2014) Genetic diversity among varieties of Chia (*Salvia hispanica* L.). Genet Resour Crop Evol 51:773–781. https://doi.org/10.1023/B:GRES.0000034583.20407.80
Kakabouki I, Bilalis D, Karkanis A, Zervas G, Tsiplakou E, Hela D (2014) Effects of fertilization and tillage system on growth and crude protein content of quinoa (*Chenopodium quinoa* Willd.): an alternative forage crop. Emir J Food Agric 26(1):18–24. https://doi.org/10.9755/ejfa.v26i1.16831
Kakabouki I, Karkanis A, Travlos IS, Hela D, Papastylianou P, Wu H, Chachalis D, Sestras R, Bilalis D (2015) Weed flora and seed yield in quinoa crop (*Chenopodium quinoa* Willd.) as affected by tillage systems and fertilization practices. Int J Pest Manag 61(3):228–234. https://doi.org/10.1080/09670874.2015.1042413
Kakabouki IP, Hela D, Roussis I, Papastylianou P, Sestras AF, Bilalis DJ (2018) Influence of fertilization and soil tillage on nitrogen uptake and utilization efficiency of quinoa crop (*Chenopodium quinoa* Willd.). J Plant Nutr Soil Sci 18(1):220–235. https://doi.org/10.4067/S0718-95162018005000901
Kakabouki IP, Roussis IE, Papastylianou P, Kanatas P, Hela D, Katsenios N, Fuentes F (2019) Growth analysis of quinoa (*Chenopodium quinoa* Willd.) in response to fertilization and soil tillage. Not Bot Horti Agrobot Cluj Napoca 47(4):1025–1036. https://doi.org/10.15835/nbha47411657
Kakabouki I, Beslemes DF, Tigka EL, Folina A, Karydogianni S, Zisi C, Papastylianou P (2020a) Performance of six genotypes of tritordeum compare to bread wheat under east Mediterranean condition. Sustainability 12(22):1–14. https://doi.org/10.3390/su12229700
Kakabouki I, Folina A, Karydogianni S, Zisi C, Efthimiadou A (2020) The effect of nitrogen fertilization on root characteristics of *Camelina sativa* L. in greenhouse pots. Agron Res 18(3):2060–2068. https://doi.org/10.15159/AR.20.178
Kakabouki I, Togias T, Folina AE, Karydogianni S, Zisi C, Bilalis D (2020) Evaluation of yield and nitrogen utilisation with urease and nitrification inhibitors in sweet potato crop (*Ipomoea batatas* L.). Folia Hortic 32(2):147–157. https://doi.org/10.2478/fhort-2020-0014
Kakabouki I, Tzanidaki A, Folina A, Roussis I, Tsiplakou E, Papastylianou P, Kanatas P, Bilalis DJ (2020) Teff (*Eragrostis tef* (Zucc.) trotter) fodder yield and quality as affected by cutting frequency. Agron Res 18(2):422–431. https://doi.org/10.15159/AR.20.156
Kara N, Katar D, Baydar H (2015) Yield and quality of black cumin (*Nigella sativa* L.) populations: the effect of ecological conditions. Turk J Field Crop 20(1):9–14. https://doi.org/10.17557/.23190
Karkanis AC, Kontopoulou CK, Lykas C, Kakabouki I, Petropoulos SA, Bilalis D (2018) Efficacy and selectivity of pre- and post-emergence herbicides in chia (*Salvia hispanica* L.) under Mediterranean semi-arid conditions. Not Bot Horti Agrobot Cluj Napoca 46(1):183–189. https://doi.org/10.15835/nbha46110979
Khalid H, Kumari M, Grover A, Nasim M (2015) Salinity stress tolerance of camelina investigated in vitro. Sci Agric Bohem 46(4):137–144. https://doi.org/10.1515/sab-2015-0028
Kobayashi Y, Weigel D (2007) Move on up, it's time for change - mobile signals controlling photoperiod-dependent flowering. Genes Dev 21(19):2371–2384. https://doi.org/10.1101/gad.1589007
Koçar G (2017) Oil crops for energy. In Encyclopedia of sustainable technologies. Elsevier Science & Technology, Amsterdam pp. 121–130. ISBN 9780128046777
Kourgialas NN, Anyfanti I, Karatzas GP, Dokou Z (2018) An integrated method for assessing drought prone areas - water efficiency practices for a climate resilient Mediterranean agriculture. Sci Total Environ 625:1290–1300. https://doi.org/10.1016/j.scitotenv.2018.01.051
Lampurlanés J, Plaza-Bonilla D, Álvaro-Fuentes J, Cantero-Martínez C (2016) Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res 189:59–67. https://doi.org/10.1016/j.fcr.2016.02.010
Lavini A, Pulvento C, d'Andria R, Riccardi M, Choukr-Allah R, Belhabib O, Yazar A, Incekaya C, Metin Sezen S, Qadir M, Jacobsen SE (2014) Quinoa's potential in the Mediterranean region. J Agron Crop Sci 200(5):344–360. https://doi.org/10.1111/jac.12069
Li H, Barbetti MJ, Sivasithamparam K (2005) Hazard from reliance on cruciferous hosts as sources of major gene-based resistance for managing blackleg (*Leptosphaeria maculans*) disease. Field Crops Res 91(2–3):185–198. https://doi.org/10.1016/j.fcr.2004.06.006
Loebenstein G (2009) Origin, distribution and economic importance. In: The sweetpotato. Springer, Dortrecht, pp. 9–12. https://doi.org/10.1007/978-1-4020-9475-0_2
Lombamo T (2020) Review Paper on: Potential and constraints of teff row planting for enhancing productivity. J Biol Agric Healthc 10(3):55–63. https://doi.org/10.7176/jbah/10-3-06
Mack L (2019) Developing cropping systems for the ancient grain chia (*Salvia hispanica* L.) in two contrasting environments in Egypt and Germany. Dissertation, University of Hohenheim. http://opus.uni-hohenheim.de/volltexte/2020/1784/pdf/Diss_Laura_Mack.pdf
Madhusudhan B (2009) Potential benefits of flaxseed in health and disease-a perspective. Agric Conspec Sci 74:67–72
Marino S, Tognetti R, Alvino A (2011) Effects of varying nitrogen fertilization on crop yield and grain quality of emmer grown in a typical Mediterranean environment in central Italy. Eur J Agron 34(3):172–180. https://doi.org/10.1016/j.eja.2010.10.006
Martín A, Alvarez JB, Martín LM, Barro F, Ballesteros J (1999) The development of tritordeum: a novel cereal for food processing. J Cereal Sci 30(2):85–95. https://doi.org/10.1006/jcrs.1998.0235
Martínez EA, Veas E, Jorquera C, San Martín R, Jara P (2009) Re-introduction of Quínoa into arid Chile: cultivation of two lowland races under extremely low irrigation. J Agron Crop Sci 195(1):1–10. https://doi.org/10.1111/j.1439-037X.2008.00332.x
Masella P, Martinelli T, Galasso I (2014) Agronomic evaluation and phenotypic plasticity of *Camelina sativa* growing in Lombardia. Italy Crop Pasture Sci 65(5):453–460. https://doi.org/10.1071/CP14025
Meehan TD, Gratton C, Diehl E, Hunt ND, Mooney DF, Ventura SJ, Barham BL, Jackson RD (2013) Ecosystem-service tradeoffs associated with switching from annual to perennial energy crops in Riparian zones of the US Midwest. PLoS ONE 8(11):e80093. https://doi.org/10.1371/journal.pone.0080093
Mekonen S, Ambelu A, Spanoghe P (2019) Reduction of pesticide residues from teff (*Eragrostis tef*) flour spiked with selected

pesticides using household food processing steps. Heliyon 5(5):e01740. https://doi.org/10.1016/j.heliyon.2019.e01740

Merajipoor M, Movahhedi Dehnavi M, Salehi A, Yadavi A (2020) Improving grain yield, water and nitrogen use efficiency of *Nigella sativa* with biological and chemical nitrogen under different irrigation regimes. Sci Hortic 260:108869. https://doi.org/10.1016/j.scienta.2019.108869

Metz B, Davidson O, Bosch P, Dave R, Meyer L (2007). Climate change 2007: mitigation of climate change. IPCC - Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg3_full_report-1.pdf

Meybeck A, Lankoski J, Redfern S, Azzu N, Gitz V (2012) Building resilience for adaptation to climate change in the agriculture sector. Proceedings of a Joint FAO/OECD Workshop 23–24 Apiril 2012, Rome

Meynard JM, Charrier F, Le Bail M, Magrini MB, Charlier A, Messéan A (2018) Socio-technical lock-in hinders crop diversification in France. Agron Sustain Dev 38(5):1–13. https://doi.org/10.1007/s13593-018-0535-1

Minten B, Tamru S, Engida E, Kuma T (2016) Feeding Africa's cities: the case of the supply chain of Teff to Addis Ababa. Econ Dev Cult Change 64(2):265–297. https://doi.org/10.1086/683843

Mohd Ali N, Yeap, SK, Ho WY, Beh BK, Tan SW, Tan SG (2012) The promising future of chia, *Salvia hispanica* L. J Biomed Biotechnol. https://doi.org/10.1155/2012/171956

Moser BR (2010) Camelina (*Camelina sativa* L.) oil as a biofuels feedstock: golden opportunity or false hope? Lipid Technol 22(12):270–273. https://doi.org/10.1002/lite.201000068

Nagoli SB, Basavanneppa MA, Sawargaonkar GL, Biradar DP, Biradar SA, Tevari P (2017) Diversification of rice-rice (*Oryza sativa* L.) cropping systems for productivity, profitability and resource use efficiency in Tunga Bhadra Project Command Area. Bull Environ Pharmacol Life Sci 6 (3):108–114. ISSN:2277–1808

National Research Council (1996) Lost crops of Africa: Volume I: grains. The National Academies Press, Washington DC. https://doi.org/10.17226/2305

Nedunchezhiyan M, Byju G, Ray RC (2012) Effect of tillage, irrigation, and nutrient levels on growth and yield of sweet potato in rice fallow. ISRN Agron 4:291285. https://doi.org/10.5402/2012/291285

Neupane D, Solomon JKQ, Davison J, Lawry T (2018) Nitrogen source and rate effects on grain and potential biodiesel production of camelina in the semiarid environment of northern Nevada. GCB Bioenergy 10(11):861–876. https://doi.org/10.1111/gcbb.12540

Niaz A, Yaseen M, Arshad M, Ahmad R (2015) Response of maize yield, quality and nitrogen use efficiency indices to different rates and application timings. J Anim Plant Sci 25 (4):1022–1031. ISSN: 1018–7081

Noulas C, Tziouvalekas M, Vlachostergios D, Baxevanos D, Karyotis T, Iliadis C (2017) Adaptation, agronomic potential, and current perspectives of quinoa under Mediterranean conditions: case studies from the lowlands of Central Greece. Comm Soil Sci Plant Anal 48 (22):2612–2629. ISSN:1532–2416

O'Brien PJ (1972) The sweet potato: its origin and dispersal. Am Anthropol 74:342–365. https://doi.org/10.1525/aa.1972.74.3.02a00070

Onwude DI, Hashim N, Abdan K, Janius R, Chen G (2018) Combination of computer vision and backscattering imaging for predicting the moisture content and colour changes of sweet potato (*Ipomoea batatas* L.) during drying. Comput Electron Agric 150:178–187. https://doi.org/10.1016/j.compag.2018.04.015

Padmaja G (2009) Uses and nutritional data of sweetpotato. In: The sweetpotato. Springer, Dortrecht, pp. 189–234. https://doi.org/10.1007/978-1-4020-9475-0

Papastylianou P, Kakabouki I, Tsiplakou E, Travlos I, Bilalis D, Hela D, Chachalis D, Anogiatis G, Zervas G (2014) Effect of fertilization on yield and quality of biomass of quinoa (*Chenopodium quinoa* Willd.) and green amaranth (*Amaranthus retroflexus* L.). Bull Univ Agric Sci Vet Med Cluj Napoca 71 (2):288–292. https://doi.org/10.15835/buasvmcn-hort:10411

Papastylianou P, Bakogianni NN, Travlos I, Roussis I (2018) Sensitivity of seed germination to salt stress in black cumin (*Nigella sativa* L.). Not Bot Horti Agrobot Cluj Napoca 46(1):202–205. https://doi.org/10.15835/nbha46110861

Pradhan P, Fischer G, van Velthuizen H, Reusser DE, Kropp JP (2015) Closing yield gaps: how sustainable can we be? PLoS ONE 10(6):e0129487. https://doi.org/10.1371/journal.pone.0129487

Pulvento C, Riccardi M, Lavini A, D'Andria R, Iafelice G, Marconi E (2010) Field trial evaluation of two *Chenopodium quinoa* genotypes grown under rain-fed conditions in a typical Mediterranean environment in South Italy. J Agron Crop Sci 196(6):407–411. https://doi.org/10.1111/j.1439-037X.2010.00431.x

Raimondi G, Rouphael Y, Di Stasio E, Napolitano F, Clemente G, Maiello R, Giordano M, De Pascale S (2017) Evaluation of *Salvia hispanica* performance under increasing salt stress conditions. Acta Hortic 1170:703–708. https://doi.org/10.17660/ActaHortic.2017.1170.88

Rana S, Singh PP, Naruka IS, Rathore SS (2012) Effect of nitrogen and phosphorus on growth, yield and quality of black cumin (*Nigella sativa* L.). Int j Seed Spices 2:5–8

Ravisankar S, Abegaz K, Awika JM (2018) Structural profile of soluble and bound phenolic compounds in teff (*Eragrostis tef*) reveals abundance of distinctly different flavones in white and brown varieties. Food Chem 263:265–274. https://doi.org/10.1016/j.foodchem.2018.05.002

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. PLoS ONE 8(6):e66428. https://doi.org/10.1371/journal.pone.0066428

Rodriguez-Leyva D, Pierce GN (2010) The cardiac and haemostatic effects of dietary hempseed. Nutr Metab 7(1):1–9. https://doi.org/10.1186/1743-7075-7-32

Rose DC, Chilvers J (2018) Agriculture 4.0: broadening responsible innovation in an era of smart farming. Front sustain food syst 2:87. https://doi.org/10.3389/fsufs.2018.00087

Roussis I, Travlos I, Bilalis D, Kakabouki I (2017) Influence of seed rate and fertilization on yield and yield components of *Nigella sativa* L. cultivated under Mediterranean semi-arid conditions. AgroLife Sci J 6 (1):218–223. ISSN:2286–0126

Roussis I, Folina A, Kakabouki I, Bilalis D (2019) Effect of organic and inorganic fertilization on yield and yield components of teff [*Eragrostis tef* (Zucc.) Trotter] cultivated under Mediterranean semi-arid conditions. Scientific Papers Series A Agronomy 62 (1):138–144. ISSN:2285–5807

Royo-Esnal A, Valencia-Gredilla F (2018) Camelina as a rotation crop for weed control in organic farming in a semiarid Mediterranean climate. Agriculture 8(10):156. https://doi.org/10.3390/agriculture8100156

Rubiales D, Niks RE, Dekens RG, Martín A (1993) Histology of the infection of tritordeum and its parents by cereal brown rusts. Plant Pathol 42:93–99. https://doi.org/10.1111/j.1365-3059.1993.tb01474.x

Rubiales D, Snijders CH, Nicholson P, Martin A (1996) Reaction of tritordeum to *Fusarium culmorum* and *Septoria nodorum*. Euphytica 88:165–174. https://doi.org/10.1007/BF00023887

Ruiz KB, Biondi S, Oses R, Acuña-Rodríguez IS, Antognoni F, Martinez-Mosqueira EA, Coulibaly A, Canahua-Murillo A, Pinto M, Zurita-Silva A, Bazile D, Jacobsen SE, Molina-Montenegro MA (2014) Quinoa biodiversity and sustainability for food security under climate change. A review. Agron Sustain Dev 34:349–359. https://doi.org/10.1007/s13593-013-0195-0

Saadi S, Todorovic M, Tanasijevic L, Pereira LS, Pizzigalli C, Lionello P (2015) Climate change and Mediterranean agriculture: impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. Agric Water Manag 147:103–115. https://doi.org/10.1016/j.agwat.2014.05.008

Sainger M, Jaiwal A, Sainger PA, Chaudhary D, Jaiwal R, Jaiwal PK (2017) Advances in genetic improvement of *Camelina sativa* for biofuel and industrial bio-products. Renew Sust Energ Rev 68(1):623–637. https://doi.org/10.1016/j.rser.2016.10.023

Salem ML (2005) Immunomodulatory and therapeutic properties of the *Nigella sativa* L. seed. Int Immunopharmacol 5(13–14):1749–1770. https://doi.org/10.1016/j.intimp.2005.06.008

Sauer PA, Sullivan P (2000) Alternative agronomic crops. Appropriate Technology Transfer for Rural Areas-ATTRA, Fayetteville

Saunders RM, Becker R (1984) Amaranthus: a potential food and feed resource. Advances in Cereal Science and Technology, vol 6. American Association of Cereal Chemists, St Paul, pp. 357–396

Schillinger WF, Wysocki DJ, Chastain TG, Guy SO, Karow RS (2012) Camelina: planting date and method effects on stand establishment and seed yield. Field Crops Res 130:138–144. https://doi.org/10.1016/j.fcr.2012.02.019

Seyyedi SM, Moghaddam PR, Khajeh-Hosseini M, Shahandeh H (2015) Influence of phosphorus and soil amendments on black seed (*Nigella sativa* L.) oil yield and nutrient uptake. Ind Crops Prod 77:167–174. https://doi.org/10.1016/j.indcrop.2015.08.065

Shonnard DR, Williams L, Kalnes TN (2010) Camelina-derived jet fuel and diesel: sustainable advanced biofuels. Environ Prog Sustain Energy 29:382–392. https://doi.org/10.1002/ep.10461

Silva D (2020) Keep calm and carry on: climate-ready crops and the genetic codification of climate myopia. Sci Technol Human Values. https://doi.org/10.1177/0162243920974092

Solis A, Vidal I, Paulino L, Johnson BL, Berti MT (2013) Camelina seed yield response to nitrogen, sulfur, and phosphorus fertilizer in South Central Chile. Ind Crops Prod 44:132–138. https://doi.org/10.1016/j.indcrop.2012.11.005

Stefanopoulou E, Roussis I, Tsimpoukas K, Karidogianni S, Kakabouki I, Folina A, Bilalis D (2020) A comparative techno-economic analysis of organic and conventional *Nigella sativa* L. crop production in Greece. Bull Univ Agric Sci Vet Med Cluj-Napoca, Hortic 77 (1):150–153. https://doi.org/10.15835/buasvmcn-hort:2019.0018

Su M, Jiang R, Li R (2017) Investigating low-carbon agriculture: case study of China's Henan Province. Sustainability 9(12):2295. https://doi.org/10.3390/su9122295

Szypłowska A, Kafarski M, Wilczek A, Lewandowski A, Skierucha W (2017) Salinity index determination of porous materials using open-ended probes. Meas Sci Technol 28 (1). https://doi.org/10.1088/1361-6501/28/1/014006

Teixeira E, Kersebaum KC, Ausseil AG, Cichota R, Guo J, Johnstone P, George M, Liu J, Malcolm B, Khaembah E, Meiyalaghan S, Richards K, Zyskowski R, Michel A, Sood A, Tait A, Ewert F (2021) Understanding spatial and temporal variability of N leaching reduction by winter cover crops under climate change. Sci Total Environ 771:144770. https://doi.org/10.1016/j.scitotenv.2020.144770

Tekin S, Yazar A, Barut H (2017) Comparison of wheat-based rotation systems vs monocropping under dryland Mediterranean conditions. Int J Agric Biol Eng 10(5):203–213. https://doi.org/10.25165/j.ijabe.20171005.3443

Toma L, Barnes AP, Sutherland LA, Thomson S, Burnett F, Mathews K (2018) Impact of information transfer on farmers' uptake of innovative crop technologies: a structural equation model applied to survey data. J Tech Tran 43:864–881. https://doi.org/10.1007/s10961-016-9520-5

Üstun G, Kent L, Çekin N, Civelekoglu H (1990) Investigation of the technological properties of *Nigella sativa* (black cumin) seed oil. J Am Oil Chem Soc 67(12):958–960. https://doi.org/10.1007/BF02541857

VanBuren R, Man Wai C, Wang X, Pardo J, Yocca AE, Wang H, Chaluvadi SR, Han G, Bryant D, Edger PP, Messing J, Sorrells ME, Mockler TC, Bennetzen JL, Michael TP (2020) Exceptional subgenome stability and functional divergence in the allotetraploid Ethiopian cereal teff. Nat Commun 11(1):884. https://doi.org/10.1038/s41467-020-14724-z

Vaquero L, Comino I, Vivas S, Rodríguez-Martín L, Giménez MJ, Pastor J, Sousa C, Barro F (2018) Tritordeum: a novel cereal for food processing with good acceptability and significant reduction in gluten immunogenic peptides in comparison with wheat. J Sci Food Agric 98(6):2201–2209. https://doi.org/10.1002/jsfa.8705

Villegas D, Casadesús J, Atienza SG, Martos V, Maalouf F, Karam F, Aranjuelo I, Nogués S (2010) Tritordeum, wheat and triticale yield components under multi-local Mediterranean drought conditions. Field Crops Res 116(1–2):68–74. https://doi.org/10.1016/j.fcr.2009.11.012

Virk HK, Singh G, Manes GS (2020) Nutrient uptake, nitrogen use efficiencies, and energy indices in soybean under various tillage systems with crop residue and nitrogen levels after combine harvested wheat. J Plant Nutr 43(3):407–417. https://doi.org/10.1080/01904167.2019.1683190

Wang Y, Zhao Y, Xue F, Nan X, Wang H, Hua D, Liu J, Yang L, Jiang L, Xiong B (2020) Nutritional value, bioactivity, and application potential of Jerusalem artichoke (*Helianthus tuberosus* L.) as a neotype feed resource, Anim Nutr 6 (4):429–437 ISSN 2405–6545

Waraich EA, Ahmed Z, Ahmad Z, Ahmad R, Erman M, Cig F, El Sabagh A (2020) Alterations in growth and yield of camelina induced by different planting densities under water deficit stress. Phyton 89(3):587–597. https://doi.org/10.32604/phyton.2020.08734

Woldeyohannes AB, Accotto C, Desta EA, Kidane YG, Fadda C, Pè ME, Dell'Acqua M (2020) Current and projected eco-geographic adaptation and phenotypic diversity of Ethiopian teff (*Eragrostis teff*) across its cultivation range. Agric Ecosyst Environ 300(15):107020. https://doi.org/10.1016/j.agee.2020.107020

Zanetti F, Alberghini B, Jeromela AM, Grahovac N, Rajković D, Kiprovski B, Monti A (2021) Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A Review Agron Sustain Dev 41(2):1–18. https://doi.org/10.1007/s13593-020-00663-y

Zdaniewicz M, Pater A, Hrabia O, Duliński R, Cioch-Skoneczny M (2020) Tritordeum malt: an innovative raw material for beer production. J Cereal Sci 96:103095. https://doi.org/10.1016/j.jcs.2020.103095

Zhang S, Wang H, Sun X, Fan J, Zhang F, Zheng J, Li Y (2021) Effects of farming practices on yield and crop water productivity of wheat, maize and potato in China: a meta-analysis. Agric Water Manag 243:106444. https://doi.org/10.1016/j.agwat.2020.106444

Zhang Y, Lu P, Ren T, Lu J, Wang L (2020) Dynamics of growth and nitrogen capture in winter oilseed rape hybrid and line cultivars under contrasting N supply. Agronomy 10(8):1183. https://doi.org/10.3390/agronomy10081183

Zorpas AA (2020) Strategy development in the framework of waste management. Sci Total Environ 716:137088. https://doi.org/10.1016/j.scitotenv.2020.137088

Zhu F (2018) Chemical composition and food uses of teff (*Eragrostis tef*). Food Chem 239:402–415. https://doi.org/10.1016/j.foodchem.2017.06.101

Zubr J (1997) Oil-seed crop: *Camelina sativa*. Ind Crops Prod 6(2):113–119. https://doi.org/10.1016/S0926-6690(96)00203-8