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REVIEW

Adapting the cultivation of industrial hemp (*Cannabis sativa* L.) to marginal lands: A review

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Abstract

Marginal lands are increasingly being considered for cultivating industrial and bioenergy crops to reduce the direct and indirect land-use changes. This review investigates the feasibility of hemp (*Cannabis sativa* L.) cultivation under the biophysical constraints that characterize marginal lands, with the objectives of (i) determining to which extent hemp cultivation can be affected by the considered factors of marginality and (ii) determining the most pertinent adaptations of crop technical management. This work establishes that hemp is a species that can be considered particularly susceptible to adverse conditions, in particular regarding soil characteristics (heavy clay, coarse sand, shallowness) and dry climates. Heavy metals (HMs) contaminations do not appear to severely limit hemp's productivity, with the exception of thallium. The adverse effects of HMs on the profitability of hemp cultivation rather lie in limitations of the potential uses of hemp biomass for several end-uses applications (e.g., textiles, food) because of the HM contents in the raw materials. On HM polluted soils, a single-use fiber production destined to high-added value applications such as bio-based composites is the most suited production. Under dry climate, hemp productivity might be particularly affected depending on the soil quality and on the severity of the dryness. Hemp can be suited for mountain environments, in which the potential for harvesting the threshing residues as a source for medical application of cannabinoids might provide a supplemental added-value to the crop. Overall, although hemp has often been considered as able to grow in harsh conditions, this review highlights that care should be given to such statements and hemp appears to be more suited for integrating conventional agro-systems, in particular considering that it can be considered both as a food and industrial crop.

KEYWORDS

cultivation, heavy metals, hemp, marginal lands, soil characteristics, sustainability, water scarcity

1 | INTRODUCTION

The world's population reached 7.8 billion people in 2020 and is expected to reach 9.7 billion people by 2050 according to UN projections (UN, 2021). This will put ever more pressure on the environment due to the surging demand for agricultural products. To meet this challenge, global agricultural production must increase, by bringing more land into cultivation and by increasing land productivity through sustainable intensification (Tilman et al., 2011). Although food production remains the fundamental target of agricultural activities, the production of biomass for the expanding bio-based economy has put additional pressure on land use, leading to direct and indirect land-use changes. The competition for land use between food and non-food crops became apparent in 2007–2008 when the production of bioenergy was associated to a global increase of food prices (McMichael, 2010; Ribeiro, 2013; Shortall, 2013).

To contribute to the targets of the European Green Deal, the circular economy action plan and the bioeconomy strategy, an increase in global agricultural production can be achieved by cultivating the land considered as marginal, whose surface is estimated to be between 5 and 58 Mha in Europe (Gerwin et al., 2018; Kluts et al., 2017). Marginal lands were recently described according to two dimensions involving bio-physical and socio-economic factors (Elbersen et al., 2017), with the idea that inherent bio-physical constraints lead to a marginal profitability of agricultural activities by affecting the yield and/or the quality of the biomass (Elbersen et al., 2017; Shortall, 2013; Strijker, 2005; Turley et al., 2010). Elbersen et al. (2017) classified these bio-physical factors in three main categories: (i) climatic factors (e.g., low and high temperatures, low or high precipitations), (ii) soil limiting factors (e.g., shallow rooting depth, stoniness, acidity, salinity, soil pollutions), and (iii) topographic factors (e.g., steep slopes). Inherent abiotic stress factors (e.g., water stress, hypoxia, salinity, heavy metal [HM] contaminations) are a prevailing cause of marginality, and plant tolerance to abiotic stresses was described as an increasingly important target for the cultivation of biomass crops on marginal lands (Quinn et al., 2015).

Perennial biomass crops (e.g., Miscanthus, Switchgrass, Giant reed) are good candidates for cultivation on marginal lands. They have low input requirements (Corno et al., 2014; Heaton et al., 2004; McCalmont et al., 2017), their cultivation cost is relatively low and being perennial, they do not require annual re-establishment. Still, the low market value of their biomass and their high establishment costs renders their cultivation economically unattractive (Khanna et al., 2008; Witzel & Finger, 2016). Industrial crops having high-value applications for their biomass could be a valuable alternative to perennial biomass crops on marginal lands.

Hemp (*Cannabis sativa* L.) is an industrial crop that can provide a diversity of raw materials for numerous industrial applications (Crini et al., 2020). Having been abandoned during the 20th century in most countries (Amaducci et al., 2015), hemp suffers from a lack of research and development. Its genetic development remains limited to a few main traits (e.g., fiber content and flowering time) (Salentijn et al., 2015; Thouminot, 2015) and the lack of specific harvesting machinery and primary transformation processes for high value applications (e.g. textiles) (Amaducci, Müssig, et al., 2008) remain major bottlenecks in the large-scale diffusion of hemp. The limited market for hemp-based products, the lack of scale economy and the maturity issues of the hemp sector today represent a barrier to the development of hemp cultivation in Europe. Notwithstanding these issues, hemp is a high-yielding crop that was reported to produce up to 20 t ha^{-1} of dry biomass per cropping season in diverse environments (Italy, Latvia, Poland), under favourable conditions (Burczyk et al., 2008; Struik et al., 2000; Tang et al., 2016). Hemp inputs requirements are low, it does not require pesticides and has a low nitrogen demand, as shown by its low nitrogen critical dilution curve that is similar to that of C4 crops (Tang et al., 2017). Hemp has often been characterized as a crop tolerant to diverse abiotic stress factors (Angelova et al., 2004; Bourdot et al., 2017; Cao et al., 2021; Cheng et al., 2016; Citterio et al., 2003; Di Candilo et al., 2004; García-Tejero et al., 2020; Linger et al., 2002; Mohan et al., 2015; Pietrini et al., 2019; Rehman et al., 2013; Rehman et al., 2021; Rheay et al., 2021; Satriani et al., 2021; Sipos et al., 2010; van den Broeck et al., 2008), as well as being a crop able to grow under harsh environmental conditions (Burczyk et al., 2008; Huang et al., 2019; Parvez et al., 2021; Viswanathan et al., 2020). Such characteristics suggest that hemp has a high potential for cultivation on marginal lands, although the profitability of hemp cropping on marginal lands was rarely addressed. Elbersen et al. (2017) commented on the fact that studies investigating cropping on marginal lands usually tend to focus either on the socio-economic aspects, or on the aspects of the bio-physical constraints, but not both. In fact, hemp should only be considered for cultivation on marginal lands if it is profitable to do so, implying that the hemp crop must keep a good productivity under the bio-physical constraints of the marginal lands in question, compared with a cultivation on a good quality land.

Assessing the suitability of hemp cropping on marginal lands is the main objective of this work. To achieve it, this work will: (i) determine the effects of bio-physical constraints on hemp productivity and on the quality of the biomass, (ii) determine the most suited targeted production (e.g., dual-purpose production of seeds and stem, high-quality fiber production) and crop management adaptations under given bio-physical constraints. The present work will firstly present the main hemp products, their related end-applications, and the specificities of technical management for these given productions. Secondly, this work will review the effects of inherent bio-physical constraints on hemp productivity and biomass quality, with a special focus on HMs and water scarcity. In a third section, this work will propose adaptations to the production strategies and crop management practices to cope with given bio-physical constraints. A general discussion addressing the sustainability of hemp cropping on marginal lands will conclude this work.

2 | HEMP PRODUCTS AND PRODUCTION STRATEGIES

Hemp biomass can be divided into different fractions, each of them being of economic interest. The fiber contained in the stem can be used, for example, for producing cigarette paper (Rehman et al., 2021), building material (Crini et al., 2020) or paper pulp (van der Werf et al., 1994). If the quality of the fiber is high enough, it can also be used as a substrate for high added-value applications such as bio-based composites (Musio et al., 2018; Müssig et al., 2020) or textile products (Vandepitte et al., 2020). The shives produced as by-products of fiber decortication can be used for animal bedding and building material (Nguyen et al., 2016), the hemp leaves and inflorescences can be used for cosmetics and medical applications (Bertoli et al., 2010; Mead, 2017), and the seeds can be used for feed, food, and industrial purposes (Crini et al., 2020). Hemp may also be grown for bio-energy applications, using either the whole biomass or by-products of existing value chains. There are examples in literature of hemp having been studied as a potential feedstock for the production of bioethanol using the stems (Das et al., 2017; Viswanathan et al., 2021; Zhao et al., 2020), methane using the whole aboveground biomass (Kreuger et al., 2011; Prade et al., 2011), solid biofuel using preferentially the shives, but also the stems or the whole aboveground biomass (Burczyk et al., 2008; Rheay et al., 2021) and biodiesel using hempseed oil (Li et al., 2010; Parvez et al., 2021; Rheay et al., 2021).

Traditionally, hemp was cultivated for single-use fiber production (Amaducci, 2020; Tang et al., 2016). This production strategy is now mainly used for producing a high-quality fiber, and it requires monoecious or dioecious cultivars (e.g. "Kompolti," "Carmagnola Selezionata") to be sown at high densities (45–80 kg ha^{-1}) and harvested at full-flowering, so as to maximise the yield and quality of the fiber (Blandinières & Amaducci, 2022; Liu et al., 2015; Mediavilla et al., 2001; Westerhuis et al., 2019). Sowing at high density reduces the secondary growth of the stems (Amaducci et al., 2002), thus increasing the ratio of primary-to-secondary fiber (Amaducci et al., 2002; Amaducci et al., 2005; Keller et al., 2001). This is important because the short lignified secondary fibers (Liu et al., 2015; Mediavilla et al., 2001) are undesirable as they cannot be used for high added-value applications (Westerhuis et al., 2019).

An alternative to single-use fiber production is the dual-purpose production of seeds and stems, which is currently the main production strategy in Europe (Tang et al., 2016). Monoecious cultivars (e.g., "Futura 75," "Félina 32") sown at a density of 30–50 kg ha^{-1} are harvested at seed maturity with a conventional combine harvester. This sowing strategy maximises the yield of both fractions (Legros et al., 2013), although the late harvesting affects fiber quality and prevents its use in high added-value applications (Westerhuis et al., 2019).

In places where the harvest of the threshing residues (flowers and leaves) is not prohibited (e.g., France), a multi-purpose production of stems, seeds, and threshing residues can be carried out. The threshing residues, which are by-products of seed separation, can be used for extracting biomolecules (e.g., phyto-cannabinoids, essential oils) of pharmaceutical interest or for cosmetic applications, thereby increasing the added-value of the crop. This production strategy requires to grow a monoecious cultivar (e.g., "Futura 75") and to use a combine harvester equipped with a specific device for collecting the threshing residues.

A single-use seed production is common where stem processing facilities are absent, as in Canada. In this production strategy, a relatively early-flowering monoecious cultivar (e.g. "Finola," "Earlina 8") is sown at relatively low density (20–30 kg ha^{-1}) to maximise seed yield, but sowing densities lower than 20 kg ha^{-1} should be avoided as hemp's weed suppressing capacity decreases under this threshold (Legros et al., 2013).

When grown for bioenergy production, the biomass yield (t ha^{-1}) is the main driver of the energy yield (GJ ha^{-1}) (Burczyk et al., 2008; Das et al., 2017; Seleiman et al., 2013), and the producer should seek to attain high biomass yields rather than high biomass quality. This is achieved by sowing a late-flowering cultivar (e.g. "Carmagnola Selezionata," "Dioica 88") at relatively low densities: 20 kg ha^{-1} having been reported to be a good compromise for achieving a high biomass yield, for coping with weed competition and for reducing the seed cost (Legros et al., 2013).

3 | EFFECTS OF LAND MARGINALITY FACTORS ON HEMP PRODUCTIVITY AND BIOMASS QUALITY

As already stated, land marginality can be induced by inherent bio-physical constraints that include climatic factors, soil limiting factors and topographic factors. Socio-economic factors (e.g. evolution of the market prices of agricultural products, changes of agricultural policies, presence of primary processing centres) might also affect the profitability of agricultural activities, bringing a dynamic dimension to the concept of land marginality (Elbersen et al., 2017). Land marginality might therefore be induced at diverse intensities of bio-physical constraints depending on many contextual parameters. For this reason, the present work will focus on the sustainability of hemp cultivation under adverse bio-physical constraints that are susceptible to lead to land marginality.

Although the literature addressing hemp growth capacity under bio-physical constraints has recently expanded, it remains limited to two main abiotic stress factors: HMs and water scarcity. The present work will therefore focus on these two bio-physical constraints; the effect on hemp of poor soil and land characteristics will also be investigated. Other bio-physical constraints (e.g., salt stress, extreme cold climate, organic pollutants) are not being addressed in the present work due to the absence of literature at agronomic scale.

3.1 | Heavy metal contaminations

In the EU27 (with UK and without Croatia), Tóth et al. (2016) estimated that the area of agricultural lands with a concentration of at least one HM above the lower guideline value (LGV) set by the Finnish Ministry of Environment (MEF, 2007) was 1.37 10^5 km^2.

Phytoremediation consists in growing plants for removing HMs from polluted soils and hemp has extensively been studied in this frame (Ahmad et al., 2016; Griga & Bjelková, 2013; Guidi Nissim et al., 2018; Kos et al., 2003; Kumar et al., 2017; Meers et al., 2005; Rehman et al., 2021; Rheay et al., 2021). Hyperaccumulator species have a limited potential of profitability due to their low biomass and to their low economic value (Arru et al., 2004), while conventional food crops have a limited potential on such lands because of sanitary reasons (Rai et al., 2019). Other authors instead consider that phytoremediation using industrial crops such as hemp or flax could only be realised in the frame of a long-term remediation (estimated in decades or even centuries), mainly because of the low shoot bioconcentration factor ($[HM]_{shoots}/[HM]_{soil}$), (Citterio et al., 2003; Ferrarini et al., 2021; Griga & Bjelková, 2013). A low shoot bioconcentration factor, even though undesirable in the frame of phytoremediation, presents two main advantages. Firstly, it is considered a major mechanism of tolerance to HMs (Sharma & Chakraverty, 2013). Secondly, it limits the restrictions on the use of the biomass as a feedstock for industrial applications that are due to excessive HMs contents (Angelova et al., 2004; Linger et al., 2002).

At the whole-plant level, many authors have reported that hemp tends to accumulate more HMs in the roots than in the shoots for cadmium (Citterio et al., 2003; Di Candilo et al., 2004; Guidi Nissim et al., 2018; Linger et al., 2005; Luyckx et al., 2021; Shi et al., 2009; Shi & Cai, 2009), nickel (Citterio et al., 2003; Ferrarini et al., 2021; Guidi Nissim et al., 2018), arsenic (Pietrini et al., 2019), lead (Di Candilo et al., 2004; Guidi Nissim et al., 2018; Pietrini et al., 2019), chromium (Citterio et al., 2003; Ferrarini et al., 2021) and vanadium (Pietrini et al., 2019) (Supplementary material S1). Reports concerning copper and zinc, however, appear more arguable. Some authors reported higher concentrations of zinc (Luyckx et al., 2021; Shi & Cai, 2010) and copper (Bona, Marsano, et al., 2007; Ferrarini et al., 2021; Guidi Nissim et al., 2018) in the roots than in the shoots, whereas other authors reported the opposite for zinc (Angelova et al., 2004; Guidi Nissim et al., 2018; Pietrini et al., 2019) and copper (Angelova et al., 2004). Overall, these two HMs tend to be more easily translocated than others, which is not surprising given that they are micronutrients essential to plant growth. Thallium was also reported to easily enter the hemp root system and to be easily translocated toward the shoots, although it does not have a known role as a micronutrient (Di Candilo et al., 2004). Apart from the cases of thallium, zinc, and copper, the previously cited reports suggest that hemp makes use of a strategy of HM exclusion from its aerial parts by strongly limiting their translocation from roots to shoots.

Several studies have revealed other mechanisms of HM tolerance in hemp, such as increases of anti-oxidants (Citterio et al., 2003; Shi et al., 2009) and diverse detoxification mechanisms (Arru et al., 2004; Luyckx et al., 2021).

Shi and Cai (2010) compared the zinc tolerance of eight oil crops and concluded that hemp was among the most tolerant ones, with low relative decreases of total chlorophyll content and of roots and shoots biomass for zinc levels of up to 400 $mg\,kg^{-1}$ in the growth substrate. In a similar experiment involving increasing levels of cadmium from 0 to 200 $mg\,kg^{-1}$, hemp again showed signs of tolerance compared with seven other crops (including *Brassica rapa, Carthamus tinctorius, Glycine max*, and *Helianthus annuus*) (Shi & Cai, 2009).

The effects of HMs on hemp biomass production vary widely in literature (Table 1). Taking the LGV as a reference point (MEF, 2007), hemp can be said not to display significant decreases of biomass at what can be considered relatively high levels of pollution (Angelova et al., 2004; Citterio et al., 2003; Citterio et al., 2005; Di Candilo et al., 2004). On a soil with HM contents under or slightly above the LGV, hemp biomass attained 16 $t\,ha^{-1}$ and 9 $t\,ha^{-1}$ of dry matter in two consecutive years of cultivation, which is within the usual range of hemp productivity reported in literature (Guidi Nissim et al., 2018). Hemp is however particularly susceptible to thallium, as its biomass productivity decreased by 31% from the control when grown on a soil polluted with 7.9 $mg\,kg^{-1}$ of thallium (Di Candilo et al., 2004). Other experiments have also shown significant decreases of productivity. On a moderately polluted soil in which none of the HMs exceeded the LGV, hemp biomass significantly decreased from the value of the control (Pietrini et al., 2019). Other significant decreases of productivity were reported in the presence of copper (Bona, Marsano, et al., 2007), cadmium (Shi & Cai, 2009), and zinc (Shi & Cai, 2010), all of these experiments having been carried out by applying HMs in equal or higher concentrations than the LGV.

The diversity of observed responses to HMs can be explained by several factors: (i) bio-availability of HMs in the soils, which is heavily dependent on the soil's physical–chemical characteristics (Guidi Nissim et al., 2018; Marschner & Rengel, 2012; Taiz & Zeiger, 2010; Walker et al., 2003), varied among the previously cited works; (ii) The association of different HMs in the various experiments may have led to interactions of HM uptake and translocation (Tani & Barrington, 2005) that can hardly be distinguished; and (iii) different hemp genotypes may have played a prevailing role in the observed differences to HM tolerance.

Apart from the effects of HMs on productivity, it is also important to know if HMs affect the quality of the biomass. In a study by Luyckx et al. (2021), zinc and cadmium were reported to significantly affect the expression of genes involved in cell wall synthesis. Additionally, lignin levels under zinc treatment were higher than that of the control, while under cadmium treatment they were lower. According to Citterio et al. (2003), hemp plants exposed to high concentrations of cadmium, chromium, and nickel showed an increase of stem lignification, the lignin being usually associated with the secondary fibers that are shorter and of a lower quality than the primary fibers (Liu et al., 2015; Mediavilla et al., 2001; Westerhuis et al., 2019). To our knowledge, only Linger et al. (2002) studied the effects of HMs pollution on fiber quality parameters at field scale. A hemp crop grown on a highly polluted land (102 $mg_{Cd}\ kg^{-1}$, 419 $mg_{Ni}\ kg^{-1}$, and 454 $mg_{Pb}\ kg^{-1}$) displayed slightly lower levels of fiber content, fineness and resistance to traction compared with samples issued from a hemp crop grown on an unpolluted land. By considering the differences in growing conditions between the two crops and by comparing the values obtained with those reported in literature, the authors concluded that the effects of high levels of cadmium, nickel and lead on fiber quality could not be considered significant.

When cultivating hemp, it is also essential to remember that in the European Union, Δ-9-THC content must not exceed the threshold of 0.3% on a dry basis. In a study by Citterio et al. (2003) the effect of high HMs contents in soil (82 $mg_{Cd}\ kg^{-1}$, 114.6 $mg_{Ni}\ kg^{-1}$, 138.8 $mg_{Cr}\ kg^{-1}$) on the Δ-9-THC content of hemp leaves was not significant. The results obtained suggest that cultivating hemp on HM polluted land does not increase the risk of exceeding this threshold.

3.2 | Soil and land characteristics

Soil characteristics such as low fertility, poor drainage, shallowness, unfavourable soil texture, stoniness, salinity, and acidity, together with a steep terrain are essential drivers of land marginality (Elbersen et al., 2017) and can cause nutritive, water stress or other abiotic stresses such as salt stress or root hypoxia.

The main advantage of hemp over other crops is the size of its root apparatus, reported to reach at least two meters depth in a deep soil (Amaducci, Zatta, et al., 2008). However, in unfavourable soils such as shallow soils, hemp root development might be hampered. Hemp has been classified as being particularly susceptible to soils of low rooting depth (80 cm) (von Cossel et al., 2019).

Soils of fine granulometry presenting subsurface compaction layers can also severely hamper hemp root development, causing it to deviate from a vertical to an L-shape (Adesina et al., 2020; Amaducci et al., 2015; Amaducci, 2020; Desanlis et al., 2013), limiting the access of hemp to deep reserves of water and nutrients and reducing the anchorage, making the plant more susceptible to lodging. Soils of fine granulometry can also lead to water stagnation after heavy rainfalls, which was reported to be badly supported by juvenile hemp (Amaducci, 2020; Ely et al., 2022; Struik et al., 2000). Sankari and Mela (1998) experienced a dramatic decrease of hemp establishment on a "*heavy clay soil*" subjected to a heavy rain event 4 days after sowing. The passage of agricultural machinery also had negative effects on hemp establishment, and Sankari and Mela (1998) concluded that "*hemp is highly sensitive to minor changes in seedbed conditions.*".

Sandy soils may also have deleterious effects on hemp growth. In a two-site experiment involving a coarse sandy

TABLE 1 Effect of heavy metal in the substrate on hemp biomass productivity. Bold values are not presented in the corresponding reference but were calculated from the other data presented. In the study of Shi et al. (2012), the data presented refer to the two cultivars presenting the most extreme responses to cadmium stress: "Xingtai" (XT) and "Uso 31" (U31). N.d.: Not detected. The column "% from the control" display the relative biomass (in %) attained by each treatment compared with the control value

				Total dry biomass (root + shoots)			
Experimental setup	**Treatment**	**HM**	**$[HM]_{substrate}$ (ppm)**	**Measure**	**Unit**	**% from the control**	**Reference**
Field scale	control	Pb; Cu; Zn; Cd	23.7; 15.0; 32.9; 2.6	Author's statement: "*heavy metals had no influence on the crop's development and productivity*"			Angelova et al. (2004)
	polluted	Pb; Cu; Zn; Cd	191.1; 92.8; 485.1; 11.1				
Field scale	control	Cd; Pb; Tl	0.2; 12.2; 0.2	16	$t\,ha^{-1}$	100	Di Candilo et al. (2004)
	Cd1	Cd; Pb; Tl	7.8; 12.2; 0.2	15.1		94	
	Cd2	Cd; Pb; Tl	8.4; 12.2; 0.2	14.9		93	
	Pb1	Cd; Pb; Tl	0.2; 20.3; 0.2	14.6		91	
	Pb2	Cd; Pb; Tl	0.2; 35.2; 0.2	14.6		91	
	Tl1	Cd; Pb; Tl	0.2; 12.2; 3.1	13.4		84	
	Tl2	Cd; Pb; Tl	0.2; 12.2; 7.9	11.1		69	
Greenhouse/pots	control	As; Pb; V; Zn	17.3; 77; 76.5; 67.4	31.56	$g\,plant^{-1}$	100	Pietrini et al. (2019)
	polluted	As; Pb; V; Zn	22.6; 115; 106.7; 92.8	20.33		64	
Greenhouse/pots/inert substrate	control	Zn	0	394.1	$g\,plant^{-1}$	100	Shi and Cai (2010)
	Zn1	Zn	200	407.4		103	
	Zn2	Zn	400	336		85	
	Zn3	Zn	800	216.7		55	
Greenhouse/pots/inert substrate	control	Cd	0	390	$g\,plant^{-1}$	100	Shi and Cai (2009)
	Cd1	Cd	50	190		49	
	Cd2	Cd	100	230		59	
	Cd3	Cd	200	120		31	
Field scale	polluted	Cd; Cu; Ni; Pb; Zn	0.85; 64.5; 26.6; 180; 286.2	18.2–10.7	$t\,ha^{-1}$	No control treatment	Guidi Nissim et al. (2018)
Greenhouse/pots	control	Cd; Ni; Cr	n.d.; 49.6; 117.7	18.5	g	100	Citterio et al. (2003)
	polluted 1	Cd; Ni; Cr	26.6; 74.4; 126	20.4		110	
	polluted 2	Cd; Ni; Cr	82; 114.6; 138.8	17.1		92	
Greenhouse/pots	control	Cd; Ni; Cr	n.d.; 6; 50	**4.2**	$g\,plant^{-1}$	**100**	Citterio et al. (2005)
	polluted	Cd; Ni; Cr	139; 118; 360	**5**		**119**	

(Continues)

TABLE 1 (Continued)

Experimental setup	Treatment	HM	$[HM]_{substrate}$ (ppm)	Total dry biomass (root + shoots) Measure	Unit	% from the control	Reference
Greenhouse/pots/inert substrate	control	Cd	0	**1.34**	g plant^{-1}	**100**	Shi et al. (2009)
	Cd1	Cd	25	**1.22**		**91**	
	Cd2	Cd	50	**1.04**		**78**	
	Cd3	Cd	100	**0.95**		**71**	
Greenhouse/pots/inert substrate	control - XT	Cd	0.126	**0.56**	g plant^{-1}	**100**	Shi et al. (2012)
	polluted - XT	Cd	25	**0.52**		**93**	
	control – U31	Cd	0.126	**0.38**		**100**	
	polluted – U31	Cd	25	**0.06**		**16**	
Greenhouse/pots	control	Cu	0	**5.34**	g	100	Bona, Marsano, et al. (2007)
	polluted	Cu	150	**3.69**		69	
Greenhouse/pots	control	Cd	0	50	g plant^{-1}	100	Linger et al. (2005)
	polluted1	Cd	17.3	51		102	
	polluted2	Cd	71.7	0		0	

soil (5: 4: 17: 71% of clay: silt: fine sand: coarse sand) and a sandy loam soil (8: 11: 42: 36% of clay: silt: fine sand: coarse sand), Manevski et al. (2017) reported that hemp establishment failed two times out of three on the coarse sandy soil site. The sole successful cropping of hemp on this site produced little biomass (about 5.0 t ha^{-1}) whereas hemp cropping on the sandy loam site produced from 12.1 to 14.4 t ha^{-1} of biomass. All other crops tested in this trial performed well on coarse sandy soil, highlighting the susceptibility of hemp to extreme soil textures. Adesina et al. (2020) considered hemp unsuited to heavy clay and sandy soils due to the fact that these soils retain either too much or too little water, in accordance with von Cossel et al. (2019) who classified hemp as being unsuited for growth on coarse sand and on heavy clay soils.

Hemp susceptibility to stoniness is hard to evaluate. To our knowledge, only Faux et al. (2013) experimented with hemp cultivation on stony soils. They reported stem yields ranging from 7.0 to 10.8 t ha^{-1}, which are similar stem yields to those usually reported in literature.

Information on the suitability of hemp as a crop for hilly and mountain areas are scarce and inconsistent. In a recent survey that involved 30 Italian hemp farmers, hemp was reported to be a "*very good crop*" for growth on mountain territories (Giupponi et al., 2020), in agreement with Desanlis et al. (2013), who described the mountain microclimates as perfectly suiting hemp. von Cossel et al. (2019) instead classified hemp as unsuited for cultivation on steep terrains. A major issue faced by hemp on steep terrain may lie in losses during harvest. For instance, in the frame of the GRACE BBI project, a hemp crop was grown in the Apennines of Northern Italy, on steep terrain. Small plots were harvested by hand at seed maturity for determination of stem and seed yields and the remaining crop was harvested with a combine harvester specific to mountain areas (Laverda 3350). Stem and seed yields of hand-harvested plots reached 3.4 t ha^{-1} and 0.5 t ha^{-1}, while the yields of the mechanically harvested plots drastically decreased to 1.0 t ha^{-1} and 0.3 t ha^{-1}, respectively. Uneven terrain forced the harvester to raise the stubble height to about 30 cm and also led to inefficient swathing and bailing. Additionally, an inefficient separation of the inflorescences from the stems was also observed, an issue that was already reported for hemp because of the interplant heterogeneity of development (Chen & Liu, 2003).

3.3 | Water scarcity

Water shortage is a major issue in cropping activities. It can occur during a temporary drought caused by weather variability or under predominantly dry climates. The aridity index (AI—annual ratio of precipitations to potential evapotranspiration) is used to quantify the climatic dryness, AI values lower than 0.5 being considered as describing an arid climate (Jones et al., 2014; Lian et al., 2021), for qualifying a land as being "*severely affected by too dry climatic conditions*" (Jones et al., 2014), or for qualifying a land as marginal because of climatic dryness (von Cossel et al., 2019). In Europe, semi-arid areas are mainly concentrated in the Mediterranean basin and overlap the Mediterranean climate (Csa and Csb in the Köppen-Geiger climate classification) in Southern Spain, Southern Italy, Greece and on Mediterranean islands (Alessandri et al., 2014; Beck et al., 2018; Lian et al., 2021). The Mediterranean climate is characterized by hot and dry summers (Beck et al., 2018), covers approximately 6.2 10^5 km^2 and is expected to increase to 7.4 10^5 km^2 by the end of the 21st century under RCP4.5 scenario, particularly expanding northward and eastward from the actual distribution of Mediterranean climate in Europe (Alessandri et al., 2014). Concomitantly, a fraction of the areas today under Mediterranean climate are expected to turn toward arid climate (B in the Köppen-Geiger climate classification) by the end of the 21st century (Alessandri et al., 2014). Although food crops are currently being cultivated in an economically viable way in Mediterranean regions of Europe, the climatic projections for this region may well affect the profitability of cropping activities due to yield reductions and irrigation requirements. In addition, interactions between dryness and other socio-economic and bio-physical factors may lead to land marginality.

As a short-day species, the hemp growing cycle occurs during summer when rainfalls do not compensate the reference evapotranspiration during the whole growth period (Di Bari et al., 2004). Overall, hemp water requirements are usually reported to range between 250 and 700 mm during the growing season, depending on the duration of the growth cycle and on the evapo-transpirative demand (Amaducci et al., 2000; Amaducci et al., 2015; Cosentino et al., 2012; Cosentino et al., 2013; Di Bari et al., 2004).

In Mediterranean climate, hemp aboveground biomass productivity has been reported several times to be significantly affected by decreases of water availability during the growing season, decreasing by about 20% to 25% from the value of the well-irrigated control under low levels of irrigation (Amaducci et al., 2000; Cosentino et al., 2013; Di Bari et al., 2004; García-Tejero et al., 2019; Lisson & Medham, 1998) (Table 2; Supplementary material S2). Although significant, these decreases do not imply critical crop failures, and the yield losses induced by water shortages might be partially compensated with the water savings of reduced irrigation. Only Bahador and Tadayon (2020) reported critical decreases of aboveground biomass and seed productivities (decreases of 71.3% and 81.6%, respectively, from the value of the well-irrigated control) under Mediterranean climate, although they did not report the amounts of water supply for the different treatments. Strong decreases of aboveground biomass and seed productivities were also reported in an arid climate (Bsk) between two irrigation treatments: a well-irrigated treatment and a dry treatment in which the crop was only irrigated during the seedling establishment phase. As a mean of 10 cultivars, aboveground biomass and seed productivities decreased respectively by 60.3% and 67.0% from the values of the control (Campbell et al., 2019). Hemp seed yield appears to be particularly susceptible to water availability during the seed ripening phase (Bahador & Tadayon, 2020; Campbell et al., 2019) and was also recently reported to be susceptible to high temperatures (Baldini et al., 2020; Ferfuia et al., 2021).

The data provided by Herppich et al. (2020) appear as an exception, as hemp aboveground biomass productivity reached 10.0 and 17.9 $t\,ha^{-1}$ for the cultivars "Ivory" and "Santhica 27," respectively, during a hot and dry summer. The rainfalls provided only 56 mm of water during the growing season and were supplemented with 10 mm of irrigation during germination.

Overall, hemp appears to be relatively tolerant to temporary drought, but prolonged periods of water shortage under high evapotranspirative demand can lead to critical decreases of productivity (Tang et al., 2018). Several authors have reported that hemp is a water stress tolerant crop (Bourdot et al., 2017; García-Tejero et al., 2020; Rehman et al., 2013; Satriani et al., 2021; Sipos et al., 2010; van den Broeck et al., 2008; Viswanathan et al., 2020): this might be due to its capacity of developing a deep root system (Amaducci, Zatta, et al., 2008). When hemp-root development is not impaired by soil characteristics (see Section 3.2), hemp can access deep water reserves in soils. However, such depths are not attained by hemp's root apparatus during the first stage of its growth, and the status of water stress tolerant crop is therefore attained later during the growing season (Adesina et al., 2020; Ehrensing, 1998; Fike, 2016). In fact, hemp was reported to be particularly susceptible to water shortage during the phases of germination, emergence and during the early stages of its growth (Struik et al., 2000). This is particularly highlighted by the fact that most of the studies investigating hemp's tolerance to water stress at agronomic scale irrigated during the first stages of its growth and only initiated to apply the different irrigation regimes at a later growth stage (Bahador & Tadayon, 2020; Campbell et al., 2019; Cosentino et al., 2013; García-Tejero et al., 2019; Herppich et al., 2020).

The effect of water stress on fiber quality has only been addressed in a few publications. Schäfer and

TABLE 2 Effects of water availability on hemp aboveground biomass and seed productivities under Mediterranean and arid climates. Köppen-Geiger climate types attached to each environment were determined using the R code and raster files provided on the following website: http://koeppen-geiger.vu-wien.ac.at/present.htm, on the base of the work of Rubel et al. (2017). Data of seed productivity were not presented in the study of Bahador and Tadayon (2020) and were estimated from the values of oil yield and seed oil content. Treatments may refer to different irrigation regimes depending on the reference and are always ranked from the treatment with the highest level of water availability (top) to the one with the lowest water availability (bottom), within each reference. WUE refers to the water use efficiency (g of biomass produced per litre of water consumed) presented by the reference or calculated as the ratio of aboveground biomass produced to the amount of water used, except in the case of the publication of Di Bari et al. (2004), where the WUE refers to the ratio of total bark produced to water consumed

						Aboveground biomass		Seeds			
Environment	Climate	Year	Cultivar	Treatment	Water supply (mm)	Productivity (t_{DM} ha^{-1})	% from the control	Productivity (t_{DM} ha^{-1})	% from the control	WUE ($g\,L^{-1}$)	Reference
Italy (Sicily)[a]	Csa/ Mediterranean	2004	Futura 75	I_{100}	440	12.0	100.0			2.73	Cosentino et al. (2013)
				I_{50}	355	11.1	92.3			3.13	
				I_{25}	312	9.8	81.9			3.15	
				I_0	269	9.3	77.2			3.45	
Iran (North)[b]	Csa/ Mediterranean	2014–2015	unprecised	I_{100}		4.65	100.0	**1.32**	**100.0**		Bahador and Tadayon (2020)
				I_{80}		3.7	79.6	**0.83**	**63.1**		
				I_{60}		2.85	61.3	**0.41**	**31.3**		
				I_{40}		1.8	38.7	**0.24**	**18.4**		
Italy (Apulia)[b]	Csa/ Mediterranean	1999–2000–2001	Fibranova/red petiole/ Kompolti	I_{100}	613	6.2	100.0			1.04	Di Bari et al. (2004)
				I_{66}	441	5.6	95.2			1.28	
				I_{50}	338	4.4	80.2			1.31	
				I_{33}	262	4.4	79.2			1.67	
USA (Colorado)[c]	Bsk/Arid	2016	Férimon 12	I_{100}	451	6.1	100.0	1.28	100.0	1.36	Campbell et al. (2019)
			Diana		451	5.2	100.0	0.92	100.0	1.15	
			Carmaleonte		451	7.0	100.0	1.36	100.0	1.56	
			Average[e]		451	6.3	100.0	0.98	100.0	1.39	
			Férimon 12	I_0	200	2.7	44.7	0.55	43.0	1.37	
			Diana		200	1.7	33.1	0.22	23.9	0.86	
			Carmaleonte		200	2.3	33.3	0.31	22.5	1.16	
			Average[e]		200	2.5	39.7	0.33	33.0	1.24	
Spain (Andalous)[d]	Csa/ Mediterranean	2012–2013	Carma/Ermes	I_{100}	420	9.8	100.0			2.33	García-Tejero et al. (2019)
				I_{75}	337	7.7	79.3			2.31	
Australia (Tasmania)	Csb/ Mediterranean	1995–1996	Kompolti	I_{30}	468	15.5	100.0			3.32	Lisson and Medham (1998)
				I_{60}	535	15.6	100.6			2.92	
				I_{90}	524	14.5	93.5			2.77	
				I_{120}	422	14.8	95.5			3.43	
				I_0	359	12.1	78.1			3.39	

TABLE 2 (Continued)

Environment	Climate	Year	Cultivar	Treatment	Water supply (mm)	Aboveground biomass: Productivity (t_{DM} ha^{-1})	Aboveground biomass: % from the control	Seeds: Productivity (t_{DM} ha^{-1})	Seeds: % from the control	WUE ($g L^{-1}$)	Reference
Italy (North)[b]	Cfa/Temperate	1995–1997	Futura 77	I_{100}	500	14.6	100.0			2.92	Amaducci et al. (2000)
				I_0	358	13.4	91.8			3.74	

[a]The data presented only refer to the harvest performed at the end of flowering.

[b]The data presented are the mean of different environment and/or cultivars in a same study.

[c]Three cultivars presented from a set of 12 cultivars. These three cultivars were selected on the base of their difference of performance between the two treatments, when considering the aboveground biomass productivity or the seed productivity.

[d]The data presented only refer to the plant density of 3.3 plants m^{-2}, in open-field conditions.

[e]Average of 10 cultivars.

Honermeier (2006), in a 2-year experiment, found that plant height, stem diameter, layer of secondary fiber cells, proportion of cell lumen surface over that of the whole cell, and cell wall thickness were lowest in the driest year. Plant height and mean stem diameter were also significantly reduced under deficit irrigation in an arid environment (Campbell et al., 2019). From a greenhouse experiment, water shortage induced an increase in fiber dislocation and a reduction of fiber tensile strength (Thygesen & Asgharipour, 2008). In general, water stress appears to lead to a reduction of fiber quality at a physiological scale, but this might be compensated at field scale by the deleterious effects of water shortage on individual plant weight, as this parameter induces the secondary growth that negatively affects the overall quality of the fiber (Westerhuis et al., 2019). This remains hypothetical and requires further scientific assessment.

On cannabinoid content, the variability of water availability over the growing season was never reported to induce an increase of THC content over the 0.3% threshold (Calzolari et al., 2017; Campbell et al., 2019; Di Bari et al., 2004; García-Tejero et al., 2019), suggesting that water shortage would not increase the risk of exceeding the legislative threshold in effect in the EU.

4 | ADAPTING THE PRODUCTION STRATEGY AND CROP MANAGEMENT TO MARGINAL LANDS

As discussed in Section 2, hemp can be cultivated following diverse production typologies, each being characterised by specific crop management practices (Blandinières & Amaducci, 2022), providing a lever for action for adapting the cultivation of hemp to given bio-physical constraints.

4.1 | Heavy metals

The main constraint to hemp production on HM polluted soils lies in the restrictions on the potential uses of hemp biomass. HM uptake by the crop indeed leads to contaminations of the products (Supplementary material S1). If in most of the literature, hemp is considered as a suitable crop for growth on HM contaminated soils (Angelova et al., 2004; Citterio et al., 2003; Di Candilo et al., 2004; Linger et al., 2002; Pietrini et al., 2019; Rheay et al., 2021); for its cultivation to be economically viable, its products must be able to be used. The use of hempseed for food and feed purposes faces the same problems as conventional food crop, especially as hempseeds are relatively strong sinks for zinc, copper, and nickel (Angelova et al., 2004; Citterio et al., 2005; Linger et al., 2002). On the other hand, non-food applications for hemp oil (e.g. biodiesel or industrial solvents) do not seem economically valuable options, owing to the limited market value of such oil. In general, the use of hemp biomass for bioenergetic applications is of low profitability (Burczyk et al., 2008; Das et al., 2017; Rice, 2008) and Burczyk et al. (2008) considered it better to use the by-products for such applications (e.g. shives destined to solid biofuel production). As a matter of fact, the economic potential of hemp is higher if its biomass is destined for industrial applications rather than bioenergy, due to the difference in market value of the raw material produced.

The use of high-quality hemp fiber destined to high added-value applications might overcome the problem of economic viability posed by the impossibility to use seeds and threshing residues. The fiber price indeed depends on its quality and end use. Sold at around 350–400 € t^{-1} for paper production (Vilcina et al., 2014), its price rises to 550 to 800 € t^{-1} for technical applications (Grégoire et al., 2021; Pecenka et al., 2012; Vilcina et al., 2014) and can reach about 1500–1750 € t^{-1} if the fiber is of very high quality (Bourmaud et al., 2018). Considering that hemp fiber quality was not particularly affected by high levels of cadmium, nickel, and lead in soils (Linger et al., 2002), and should further field scale research confirm these findings and extend them to other HMs; then a single-use hemp crop for high-quality fiber production could be considered for cultivation on HM polluted lands. This production should, however, be restricted to bio-based composite production as HM contents in hemp fiber can exceed the standards of the Öko-Tex-Initiative for textile applications and the legislative thresholds of the EU defined for clothing applications (Linger et al., 2002; Angelova et al., 2004; EU commission regulation, 2018/1513).

Several studies have demonstrated the existence of genetic variability across diverse hemp genotypes (Di Candilo et al., 2004; Huang et al., 2019; Shi et al., 2012) in particular across Chinese genotypes that are not listed on the EU's list of commercial cultivars. As an example, the accessions “Xingtai” and “Uso 31” displayed respective decreases of 7% and 85% of shoot biomass from the value of the control, when submitted to cadmium treatment in a study by Shi et al. (2012). The use of such variability was described as a potential lever for action for growing hemp on HM polluted lands (Di Candilo et al., 2004) but requires to better characterise HM tolerance across European hemp cultivars.

4.2 | Soil and land characteristics

On heavy clay soil, the potentially high mortality rate in hemp population during plant establishment can lead to strong decreases of plant density (Sankari & Mela, 1998), which can ultimately affect the fiber quality (Westerhuis et al., 2019). Therefore, dual- and multi-purpose hemp seem more suited on heavy clay soil than single-use fiber production. Soil preparation, which is always important for hemp, becomes critical on heavy clay soils on which a deep autumn/winter ploughing and harrowing right before sowing has been recommended (Amaducci et al., 2015; Blandinières & Amaducci, 2022). On coarse sandy soil, the only available literature reported either crop failures or particularly low yields (Manevski et al., 2017) which does not allow to draw conclusions on the optimal production strategy but rather tend to imply that hemp should be avoided on such soils. In mountain areas, due to the relatively high stem losses during harvest, swathing, and baling, dual- and multi-purpose might be the most suited production strategies.

4.3 | Water scarcity

It is clear that irrigation must be contemplated when cultivating hemp in a dry climate, in particular after sowing (Cosentino et al., 2012; Di Bari et al., 2004; Herppich et al., 2020; Ranalli & Venturi, 2004). To reduce the economic cost of irrigation, Di Bari et al. (2004) proposed two management strategies for hemp cultivation in a Mediterranean climate. Firstly, the irrigation management of hemp should not aim to fully restore the water lost through evapotranspiration, but rather be limited to a partial restoration of the water losses, by supplying water up to 66% of the total soil available water in the first 40 cm of the topsoil layer. In line with this proposition, Cosentino et al. (2013) did not find significant differences of aboveground biomass productivity between irrigation treatments consisting in 100% and 50% restoration of maximum evapotranspiration (ET_M). The second strategy proposed by Di Bari et al. (2004) lies in early sowings, similarly to the strategy used for increasing the transpiration efficiency of cereal crops (Richards et al., 2002). By anticipating the sowing date, hemp would benefit from higher levels of water availability and from a reduced evapo-transpirative demand, in particular during its juvenile phase when it is particularly susceptible to water scarcity. Lower temperatures would decrease the risks of heat stress, which is thought to limit hemp photosynthesis (Cosentino et al., 2013; Herppich et al., 2020). However, early-sowing can result in pre-flowering leading to short vegetative phases and to low biomass accumulation (Faux et al., 2013; Tang et al., 2016) because flowering is under strong photoperiodic control in hemp (Amaducci, Colauzzi, et al., 2008). Both Di Bari et al. (2004) and Cosentino et al. (2012) have addressed the feasibility of early sowing in a Mediterranean climate for tackling the issue of the water shortages. By sowing on the 28 February, Di Bari et al. (2004) achieved optimum bark yields (7.6 $t\,ha^{-1}$) with a strongly reduced water consumption over conventional sowing dates. Contrary to this, Cosentino et al. (2012) reported dramatically low biomass yields ranging from 1.6 to 3.1 $t\,ha^{-1}$ for four hemp cultivars sown on the 10th of March, in Sicily, and demonstrated the critical importance of the genotype choice and of its interactions with sowing date and latitude in the frame of an early-sowing strategy, which requires further assessment for given environments.

A possible solution for the cultivation of hemp in water limited environments is the adoption of a single-purpose crop dedicated to fiber production if the availability of adequate harvesting equipment and processing facilities allows it. Harvesting at the end of flowering rather than at seed maturity would reduce the duration of the cropping cycle and thereby, the crop's water requirements. Limiting irrigation to critical developmental phases (germination and plant establishment) and avoiding critical water stress appears to be an interesting strategy for limiting yield losses and irrigation cost.

5 | IS HEMP SUITABLE FOR MARGINAL ENVIRONMENTS?

Although being considered an adaptable species able to grow in harsh environments, (Bourdot et al., 2017; Cao et al., 2021; Cheng et al., 2016; García-Tejero et al., 2020; Mohan et al., 2015; Rehman et al., 2013; Rehman et al., 2021; Rheay et al., 2021; Satriani et al., 2021; Sipos et al., 2010; van den Broeck et al., 2008), in this review, hemp appears as being relatively susceptible to biophysical constraints, especially soil characteristics such as shallowness, heavy clay, and coarse sandy soils (Adesina et al., 2020; Manevski et al., 2017; Sankari & Mela, 1998; von Cossel et al., 2019). On coarse sandy soils, hemp establishment either failed or produced a low biomass compared with a more favourable soil, while all the other crops tested grew well (Manevski et al., 2017). Several authors indeed reported hemp as being highly susceptible to soil quality issues, requiring deep, well-drained, loamy soils rich in organic matters and nutrients (Adesina et al., 2020; Burczyk et al., 2008; Desanlis et al., 2013; Ehrensing, 1998; Fike, 2016). In fact, traditional hemp cultivation was carried out in the most productive and fertile soils. In mountain areas, hemp might be able to be cultivated sustainably in the frame of dual- and multi-purpose productions, although legislative regulation might prevent the harvest of threshing residues in given countries, thereby limiting the potential added-value of the crop.

On HM polluted soils, hemp appears as a relatively potent crop if the producer targets a single-use high-quality fiber production destined to bio-based composites applications that are not subject to legislative restrictions on HM contents, while providing an important added-value to the raw fiber. In field-scale studies, HMs have in general a low effect on hemp yield, and the fiber quality was not significantly affected in a soil polluted with high levels of nickel, lead, and cadmium (Linger et al., 2002). The effects of other HMs on fiber quality at field scale still need to be assessed to clearly determine the feasibility of hemp cultivation on polluted lands. The production of seeds and threshing residues would not be suited due to legislative issues regarding their HM contents. Although several authors have considered the potential of hemp for phyto-remediation, this review highlights that such a process would be relatively slow (Citterio et al., 2003; Griga & Bjelková, 2013). The use of HMs tolerant cultivars displaying low levels of HMs uptake and translocation appears to be the most suited strategy for cultivating hemp on polluted soils, but it conflicts with a fast and efficient phyto-remediation process, which would be better achieved by using hyperaccumulator species in the frame of soil restoration programs.

In the frame of a cultivation under dry climates, hemp might be suited under specific conditions. Long periods of water shortage under a high evaporative demand can dramatically affect the yield (Bahador & Tadayon, 2020; Campbell et al., 2019). This is particularly true if the hemp crop is grown on a sandy soil that does no retain water, or if it is grown on a shallow soil or on a soil presenting a compaction layer preventing the development of the taproot. Under such combinations of adverse conditions, hemp does not appear to be a suited crop. Instead, if hemp is grown on a favourable soil, it can sustain a short-time drought once established because of its deep taproot. The adoption of several strategies (targeting a single-use fiber production, early sowing, irrigation during critical developmental stages and for avoiding deadly water stress by aiming at a partial fulfilment of water restoration) might limit water consumption while allowing sustainable yields. Irrigating in a dry climate is still a pre-requisite to avoid crop failure.

This review highlights that the viability of hemp cultivation on marginal lands requires adaptations to the production strategy, which in turn is possible because of the wide diversity of products hemp can provide, as well as the genetic diversity present in hemp germplasms. Overall, if hemp can be a profitable crop when grown in marginal conditions, it is due to the fact that its biomass can reach a relatively high market value when tailored to a specific end-use (e.g. high-quality fiber for bio-based composites or textile productions, seed for food purposes or inflorescences for medicinal applications). Despite having often been studied in the scope of bioenergy production (Burczyk et al., 2008; Das et al., 2017; Kreuger et al., 2011; Li et al., 2010; Parvez et al., 2021; Prade et al., 2011; Rheay et al., 2021; Seleiman et al., 2013; Viswanathan et al., 2021; Zhao et al., 2020), the cultivation of hemp for this purpose does not appear to be sustainable because of the low market value of raw biomass for such destinations (Burczyk et al., 2008; Das et al., 2017); this is particularly true if hemp is grown on marginal lands that will likely affect the biomass yield. Perennial bioenergy crops are more suited for bioenergy production. Even though their establishment costs can be relatively high, the input costs for these crops over the whole production cycle are relatively low (McCalmont et al., 2017) compared with annual crops that require re-establishment and fertilisation every year. The cultivation and harvest of these crops over the whole growing cycle is relatively easy while hemp, although it might be relatively easy to sow and to grow, can present difficulties at harvest if the stem becomes too lignified (Desanlis et al., 2013) or because the fiber can wrap itself around the rotative organs of the harvesters and of the balers (author's experience). Additionally, as an annual crop, hemp must be integrated into a sustainable rotation system which might be complex to develop on low productivity lands. Hemp certainly has a high potential for agricultural systems on marginal lands, although overall, it cannot be denied that it is best suited for being integrated into conventional agricultural systems in which it can be beneficial for food crops (Gorchs et al., 2017) by disrupting the weeds cycles (Desanlis et al., 2013), or by increasing the soil quality (Zegada-Lizarazu & Monti, 2011).

Several authors have addressed the possibility of breeding new cultivars for HM (Ahmad et al., 2016; Bona, Francesco, et al., 2007; Bona, Marsano, et al., 2007) and water stress (Herppich et al., 2020) tolerance. Griga and Bjelková (2013) have instead questioned the feasibility of breeding for HM tolerance considering the "*cost to success*" of this approach, while Meynard et al. (2013) outlined how the multiplicity of applications of hemp leads to a dispersion of hemp breeding activities in a sector that lacks resources. Breeding hemp with a high tolerance to HMs would be a niche market that would not justify the costs of the breeding program. Instead, using existing commercial cultivars displaying traits of tolerance to HMs would appear to be a more viable strategy. Breeding for water stress tolerance would, however, appear more relevant especially considering the projections of climatic evolution for the next decades (IPCC 2018). Because no breeding programmes have yet addressed this trait (Salentijn et al., 2015; Thouminot, 2015), there might be room for increased water stress tolerance in hemp, especially considering that recent studies have highlighted the existence of a wide variability of water stress tolerance within hemp germplasms of both industrial and drug types (Campbell et al., 2019; Babaei & Ajdanian, 2020; Blandinières et al., 2021; Sheldon et al., 2021).

Although this review does not precisely define a breakeven point of productivity under which hemp cannot be profitable, we believe it can pave the way to a dedicated work that would make use of Life Cycle Cost Analyses coupled to Sensitivity Analyses, considering the most adapted production strategies and crop management adaptations defined in the present work.

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