ARTICLE IN PRESS

Industrial Crops & Products xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Agronomic performance and seed quality attributes of Camelina (*Camelina sativa* L. crantz) in multi-environment trials across Europe and Canada

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ARTICLE INFO

Keywords:
Oilseed
Oil
Protein
Oil yield
α-linolenic acid
Eicosenoic acid
TKW

ABSTRACT

Camelina (*Camelina sativa* L. Crantz) is considered a relatively new oilseed *Brassicacea* in both Europe and North America, even though its history as a crop dates back to the Bronze Age. Camelina has recently received renewed interest from both the scientific community and bio-based industries around the world. The main attractive features of this species are: drought and frost tolerance, disease and pest resistance, a unique seed oil composition with high levels of n-3 fatty acids, a considerably high seed oil content, and satisfactory seed yields, in particular under low-input management and in limiting environments. Aiming at evaluating the feasible introduction of recently released camelina breeding lines under different environmental conditions and their productive potential a multi-location trial was set up. The agronomic performance of nine improved genotypes of camelina was evaluated in a wide range of environments in Europe (Greece, Italy, Poland) and in five locations across Canada, in two consecutive growing seasons (2015 and 2016). Sowing time was optimized for each location according to the different climatic conditions. Camelina proved to be a highly adaptable species, reaching seed yields of about 1 Mg DM ha^{-1} under the most limiting conditions (i.e., low precipitation, poor soil quality, extremely high temperature at flowering). Growing environments characterized by mild temperatures and adequate rainfall (> 170 mm, during the growing season) resulted in higher average seed yields. The length of the growing cycle varied greatly between different locations (80–110 d), but the cumulative thermal time was quite stable (~1200 GDD, growing degree days). The advanced breeding line 787–08, which possesses up to 30% larger seed compared to the mean seed size of all other test entries, proved to be the most promising genotype across all locations in Europe and Canada, combining high seed yields (1.1–2.7 Mg DM ha^{-1}) with improved yield stability. To the best of our knowledge, for the first time, camelina lines with improved oil composition (i.e., increased oleic and α-linolenic and lower linoleic acid contents) for feed, food and industrial applications were identified (789–02 and 887).

1. Introduction

Camelina [*Camelina sativa* (L.) Crantz] is currently enjoying the attention of both research and industry in Europe and North America (Berti et al., 2016; Zanetti et al., 2013) due to its environmental adaptability, satisfactory seed yields, combined with a unique oil suitable for a multitude of bio-based applications (i.e., biofuels, jet fuel, oleochemical compounds, feed, and food). Camelina is native to Southeast Europe and Southwest Asia (Larsson, 2013; Radatz and Hondelmann, 1981) and has an ancient history dating back to 4000 BCE. Recently, camelina has been sporadically cultivated, especially around its centre of origin, until the middle of the 20th century (Knörzer, 1978). Thereafter, more productive oilseeds, such as rapeseed (*Brassica napus* L. var. *oleifera*), became the primary source of vegetable oil in continental Europe. Interestingly, camelina was "rediscovered" in the last decade and has gained considerable research attention, as

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http://dx.doi.org/10.1016/j.indcrop.2017.06.022
Received 1 February 2017; Received in revised form 7 June 2017; Accepted 9 June 2017
0926-6690/

demonstrated by the high number of recently published scientific papers (reviewed in Berti et al., 2016) and the considerable number of large EU projects (i.e., ICON; ITAKA, CORE, COSMOS), funded either within the FP7 (Framework Program 7) or Horizon 2020. In North America, camelina has been identified as a promising oilseed crop in view of relatively low agricultural input requirements (Ehrensing and Guy, 2008; Obour et al., 2015; Robinson, 1987), resistance to common *Brassica* pests (Carcamo et al., 2007; Deng et al., 2004; Pachagounder et al., 1998; Singh and Sachan, 1997), and diseases (reviewed in: Séguin-Swartz et al., 2009; Vollmann and Eynck, 2015), as well as tolerance to drought (Hunsaker et al., 2011, 2013) and low temperature (Putnam et al., 1993).

The environmental adaptability and the recent commercial availability of both winter and spring cultivars (Mirek, 1980) confer an enormous advantage to camelina over other emerging oilseed crops, even those belonging to the same botanical family (*Brassicaceae*), such as Indian mustard (*B. juncea*), Ethiopian mustard (*B. carinata*), or crambe (*Crambe abyssinica)*, for the inclusion in traditional crop rotations primarily based on cereals (wheat and corn) or pulses (soybean) (Chen et al., 2015; Gesch et al., 2014). Different from other cultivated *Brassicaceae*, camelina has a unique seed oil composition (reviewed in: Righini et al., 2016; Vollmann and Eynck, 2015) with a high content of α-linolenic acid (20 to > 35%), eicosenoic acid (11–19%) and tocopherols (Vitamin E), (Abramovic et al., 2007; Zubr, 1997; Zubr and Matthäus, 2002) as well as a naturally low content of the undesirable fatty acid erucic acid (< 4%), rendering camelina oil well-suited for a variety of food, feed or non-food applications (Berti et al., 2016; Eynck and Falk, 2013; Faure and Tepfer, 2016; Murphy, 2016; Waraich et al., 2013; Zubr, 1997). On the other hand, some negative traits of camelina obviously exist that hinder readily adoption by farmers and there is a strong need to improve them through breeding; in particular, the small seed size (thousand seed weight ~1.0 g) can cause difficulties in stand establishment as well as for harvesting of the crop (Sintim et al., 2016).

In the framework of an international project a close collaboration was built between Canada and Europe aiming at studying the agronomic potential of improved camelina lines under different climatic conditions in order to possibly select the most suitable genotype for each environment. In the present study, the productive performance (seed yield, seed oil and protein content, seed size and oil composition) of eight new spring camelina breeding lines and one cultivar was tested in Canada and Europe for two consecutive years.

2. Material and methods

Nine different spring-type camelina lines (Table 1) were tested in a multi-location (three locations in Europe and five in Canada) and multi-year (2015 and 2016) screening trial aimed at identifying the most suitable breeding line(s) for different environments. All genotypes, except for the cultivar Midas (Table 1), are advanced breeding lines developed at Linnaeus Plant Sciences, Inc. in Saskatoon (Canada). Midas was developed at the Saskatoon Research and Development Center of Agriculture and Agri-Food Canada (AAFC-SRDC).

Table 1
Camelina lines tested in the screening trials in Europe and Canada for two consecutive growing seasons (2015 and 2016).

Accession number/Variety name	Study ID	Source
Midas	*Midas*	Agriculture and Agri-food Canada, Saskatoon, Canada
14CS0886	886	Linnaeus Plant Sciences, Inc., Saskatoon, Canada
14CS0887	887	
13CS0787-05	787 − 05	
13CS0787-06	787 − 06	
13CS0787-08	787 − 08	
13CS0787-09	787 − 09	
13CS0787-15	787 − 15	
13CS0789-02	789 − 02	

Plot size was 10 m^2 in all European trials and ranged from 7.4 m^2 (Saskatoon and Swift Current) to 18 m^2 (Vanguard) in Canada. At all sites, seeding was accomplished using a plot drill, apart from Greece where sowing was carried out manually. The trials were arranged as completely randomized blocks with three or four replicates. Characteristics of soil and climate at each study site are summarized in Table 2.

2.1. Experimental set up of trials in Europe

The European trials were set up according to a commonly agreed-upon experimental protocol, in order to be able to easily compare results. The three locations (Table 2), covering a large geographical area from 38 to 53° North latitude and from 11 to 23° East longitude, are highly representative of very different environments potentially suitable for growing camelina. Sowing took place between mid-March and mid-April, while harvesting occurred three to four months later depending on location (Table 3). The same sowing density (500 seeds m^{-2}), row distance (0.15 m) and fertilization (ranging from 40 to 60 kg of N ha^{-1}, depending on available soil N) were used in all locations. Nitrogen fertilizer was manually broadcasted at the beginning of stem elongation as urea. Trials were all rain fed, except in Greece where supplemental water was applied by means of a sprinkler irrigation system (20 and 40 mm of water in 2015 and 2016, respectively). Neither pesticide application nor chemical weed control were necessary during the growing season, and weeds were controlled by hand weeding.

2.2. Experimental set up of trials in Canada

Field trials in Canada were seeded at Fort St. John in the Peace River area of Northern British Columbia and four locations in the Prairie Provinces, Alberta (AB) and Saskatchewan (SK): Oyen (AB), Vanguard, Swift Current and Saskatoon (SK), (Table 2). Prior to seeding, soil fertility was determined and adjusted to 150 kg N ha^{-1} (optimal level for canola) by applying urea. In 2015, trials were seeded between May 4 (VAN) and May 21 (OYE). In the second trial year, seeding occurred between early May (May 6, VAN) and early June (June 3, OYE). The seeding rate was 500 seeds m^{-2} at all locations except for SAK (350 seeds m^{-2}). Row spacing ranged from 0.2 m in Fort St. John to 0.3 m in Saskatoon. Weeds were controlled either entirely by hand weeding or a combination of hand weeding and pre-emergence application and incorporation of ethalfluralin (5%, at 17 kg ha^{-1}), trifluralin (480 g l^{-1}, at 1.7 l ha^{-1}) or glyphosate (540 g l^{-1}, at 0.61 l ha^{-1}). Plots were either left standing in the field until they were completely ripe, swathed or treated with diquat and subsequently combined with a plot combine. Harvest dates in 2015 ranged from end of August (August 31, SAK and SWC) to mid-late October (October 19, OYE). The late harvest in OYE was caused by dry conditions in early summer and wet conditions in July and August. In 2016, plots were combined between mid-late August (August 18, SWC) to late September (September 27, OYE, Table 3).

2.3. Meteorological data

Main meteorological data, including air temperature (minimum and maximum) and precipitation, were collected by weather stations located nearby each experimental location for the two growing seasons (Table 3). Since the test lines did not present significant differences regarding their phenological development, growing degree days (GDD) were calculated for each location and growing season (Table 3) as follows:

$$GDD = \Sigma[(T_{max} + T_{min})/2 - T_{base}]$$