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Review

Cynara cardunculus L. as a biomass and multi-purpose crop: A review of 30 years of research

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ABSTRACT

This review covers 30 years on cardoon (*Cynara cardunculus* L.); a perennial plant adapted to the Mediterranean climate conditions of low rainfall and hot dry summers. Its potential as a non-food agricultural crop for set-aside lands and the excellent biomass production created an enthusiastic research interest in this plant and its uses.

The review starts with the plant morphology, ecology and development, followed by the agricultural aspects related to crop establishment and harvest, giving the available data on the production yields by biomass component, from small research plots to large-scale plantations. The biomass components are characterized regarding anatomical, chemical and physical properties in view of their use as feedstock for the different applications. The use of *Cynara* biomass for energy was assessed according to its fuel properties and performance under the various processes *e.g.* combustion, gasification and pyrolysis. *Cynara* seeds contain a linoleic acid rich oil that may be processed into a biodiesel with properties similar to commercial diesel. The production of biomethane and of ethanol were also studied with promising results. *Cynara* was tested as a fibre source for production of pulp and paper using different delignification processes (kraft, soda, ASAM and organosolvs) with good pulp yields and adequate physical and mechanical properties. More recently, the phytochemical and pharmacological activities of different compounds extracted from Cynara biomass are also being investigated. This plant is a good candidate to be grown in the dry lands of the Mediterranean region as a perennial field crop for multi-purposes and non-conventional uses.

1. Introduction

Cardoon (*Cynara cardunculus* L.), also called Cynara or Castile thistle is a plant of the *Compositae* (=*Asteraceae*) family, closely related to globe artichoke (*C. cardunculus* var. *scolymus* (L.) Fiori) [1]. Both varieties are included in the same botanical species (*Cynara cardunculus* L.), along with various wild types, and both are native to the Mediterranean basin [2]. Both have been traditionally cultivated as vegetables in South Europe for centuries although for different crop products [3]. Globe artichoke is grown for edible phyllary bases and receptacles of its floral heads, whereas the cardoon (*C. cardunculus* var. *altilis* (L.) DC) stalks is eaten, as these are the artificially bleached leaf rachises following high-input management techniques. Without such management, cardoon behaves as a hardy crop, featuring characteristics such as perennial life form, annual growing cycle, vigorous regrowth, bee-attractive flowers, and adaptation to drought stress, that make this plant a good candidate to be grown in the dry lands of the Mediterranean region as a perennial field crop for multi-purposes and non-conventional uses.

The proposal to grow Cynara as a perennial field crop for biomass was first made by the Technical University of Madrid (Spain), in the framework of the European project "*Lignocellulosic biomass production from annual energy crops*" (1986–1988) [4]. Various national and European projects followed - *e.g.* under the EU Programmes FP2-JOULE1 [5], FP3-AIR [6], FP5-EESD [7], FP6-SUSTDEV [8], FP7-KBBE [9] and H2020 [10], that resulted in extensive literature on different aspects of this alternative crop. Also, an indicator of the interest in this crop is the fact that cardoon has been one of the main topics in international conferences organized by the International Society for Horticultural Science [11], such as the International Congresses on Artichoke, Cardoon and Wild Relatives [12]. In addition, cardoon has been the subject of presentations to several European Biomass Conferences since 1989 [13]. The number of articles published on this subject also measures the interest of the scientific community. To the best of our knowledge, the first publication on the applications of *Cynara cardunculus* was made in 1937 regarding the influence of its calcium content on the properties of

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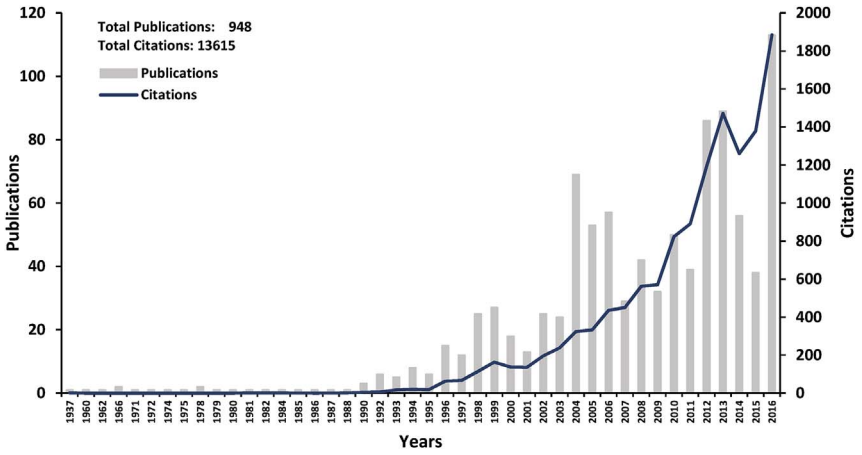

Fig. 1. Annual number of publications and number of citations in WOS searched for TOPIC: *Cynara cardunculus* L. for the period 1937–2016. This report reflects citations to source items indexed within all Databases.

cow's milk [14]. A search of the title *Cynara cardunculus* as a topic in WoS (Web of Science™) for the period 1937–2016, resulted in 948 publications, of which 646 journal articles, that received 13615 citations. Fig. 1 shows the steady increase of publications, starting in 1990 and increasing rapidly after 2004.

A synthesis of what is known on the various aspects of cardoon growth, characterization and uses is therefore needed. This work makes a review and compiles the scientific information regarding plant description, agronomy, crop production, environmental issues, biomass characterization, chemical and food-related applications and other final uses. The focus is placed on the cardoon that is oriented as a field crop (*C. cardunculus* var. *altilis*); the terms “Cynara” or “cardoon” are used interchangeably in this work. It should be pointed out that in the literature on cardoon, some authors specify the botanical variety *e.g.* mostly *C. cardunculus* var. *altilis* (*C. cardunculus* var. *sylvestris* was experimented as well) but most authors only refer the name of the species, *Cynara cardunculus* L. Whenever the traditional or horticultural cultivation is mentioned, the name “white cardoon” is preferred, although some authors call it “cultivated cardoon” [15].

This review is organized sequentially as follows: (*i*) a description of the plant including morphology, ecology, and plant development; (*ii*) the agricultural aspects of the crop production *e.g.* establishment, fertilisation, protection and harvest; (*iii*) the production yields by component and the biomass characteristics regarding anatomical and chemical features, and properties; and (*iv*) the multiple uses that include energy and biofuels, cellulosic pulps, phytochemicals as well as food and feed. An appraisal on knowledge gaps and a proposal for future research lines are presented as concluding remarks.

2. Plant description

2.1. Morphology

The botanical description of *Cynara cardunculus* L. can be found in *Flora Iberica* [16], *Flora Europaea* [17] or *Flora d’Italia* [18]; the study by Wiklund [2] provides a detailed description of this species and subspecies. A summary of these data are given here, however the values should be used as indicative ones, and not generalized since plant size [19] and morphology vary considerably with growing conditions and phenological stage [15] as well as with ecotype/variety [2,20–22].

Cardoon is described as a stout plant that can reach over 2 m of height and often shows richly branched stems at maturity. Stems can be densely tomentose to subglabrous, with 14–44 ribs. Leaves are basally rosulate (basal leaves in a rosette) and more or less densely set along the stem (cauline leaves) (Fig. 2a), they are lanceolate in outline and variously pinnatifid, approximately 21–88 cm x 10–33 cm in size; the leaf base is wide (app. 30 mm), with marginal spines. Leaves exhibit from 11 to 25 segments narrowly ovate to ovate in outline, 29–170 mm x 7–78 mm, narrowly triangular-lobed to serrate, apically caudate, with a yellowish spine. Leaf abaxial surface colour ranges from pale greyish to whitish green depending on leaf indument (moderately to densely woolly); the adaxial surface is green, moderately pilose to glabrescent. There is a deep and fleshy taproot. Commercial varieties or cultivars of white cardoon usually have short - or do not have - leaf spines and leaf segments are often broader.

Like in other species in the *Compositae* family, the cardoon flowers (‘florets’) are aggregated in inflorescences called capitula or heads. Heads are usually arranged in corymb-like groups and are cyathiform to ovate, 33–75 mm x 32–95 mm in size. Involucral bracts (65–110 bracts per capitulum) are arranged in 5–8 series (Fig. 2b); bracts gradually change in shape from the outside inwards, with the outer ones narrowly triangular, and the inner ones narrowly oblong and sometimes with an aristate appendage; the middle involucral bracts lack broad scarious margins and are basally dark brown. Inside the receptacle, 80–240 florets are found subtended by conspicuous receptacular bristles (Fig. 2i) that are 16–49 mm long according to Wiklund [2], or 40 mm x 0.1–0.2 mm as reported by Gominho et al. [23]. Floret corolla is 32–53.4 mm x 1.6–2.3 mm, dark or pale lilac. Florets have a strong fragrance and abundant nectar.

The Cynara fruit is a cypsela (an achene fruit from an inferior ovary) (Fig. 2d, f, g) crowned by a pappus (*i.e.* a group of 16–41 mm plumose filaments of calycine nature) (Fig. 2e and h), which shows a flattened form in cross-section [23]. Cypselae are laterally compressed, more or less obovate in outline, apically convex, greyish brown and usually with dark brown dots and short longitudinal lines. The size of the cypsela is reported as 3.7–7 mm x 2.2–4.5 mm for wild plants [2] but Cynara fruits of field crops were larger with 6.5–8.1 mm x 2.8–3.5 mm [24]. Similarly as with other dry fruits (*e.g.* the caryopside, fruit of *Gramineae*), cypselae are commonly known as “seeds” [24] or “grains”’ [25].

It is worth noting that the morphological characteristics of *C. cardunculus* are used to make decisions regarding distinctiveness of cardoon varieties, in accordance with the International Union for the Protection of New Varieties of Plants [26]. Of particular importance for the examination of candidate cardoon varieties are the following traits: thickness, colour and spines length of leaf midrib, height and diameter of main stem, length and diameter of central flower head, thickness of the outer bract, number of lateral heads on main stem, intensity of leaf lobing [26]. Therefore, the varieties of cultivated cardoon may have short or no leaf spines, and leaf segments are usually broader and more rounded at the apex than those of the wild specimens.

2.2. Ecology

The ecological requirements of *C. cardunculus* correspond to the environmental conditions of the Mediterranean basin, where this species originated [2]. The FAO ecological data sheet can be considered as