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REVIEW ARTICLE

Alternative methods to synthetic chemical control of *Cynodon dactylon* (L.) Pers. A systematic review

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Abstract

Cynodon dactylon (L.) Pers. is one of the worst agricultural weeds and invasive species in the world, being widely established in many countries. Despite its impact on agriculture and the growing awareness of authorities and consumers about the consequences of synthetic herbicides, alternative control methods for this weed have been poorly reviewed. A systematic review of the literature published over the last 50 years was used to assess the most studied control methods of *C. dactylon* (excluding synthetic herbicides) and to summarize the trends and knowledge gaps. The major findings are as follows: (1) the number of publications that studied alternative methods to synthetic chemical control in *C. dactylon* management has been increasing exponentially since 1972; (2) most of the studies were made under controlled conditions (57%) and lack observations under real production conditions; (3) most of the field experiments were carried out in Asia (42%), under temperate subtropical and arid climates; (4) the publication of articles studying allelopathy stands out significantly (50% of the papers found), with two species from the Poaceae family, rice (*Oryza sativa* L.) and sorghum (*Sorghum bicolor* (L.) Moench), showing very high allelopathic inhibitory effects (often above 80%), especially under open field conditions; and (5) preventive soil tillage is the most studied treatment among indirect weed control treatments, and although there is a high risk of propagation, the results indicate that tillage can significantly contribute to control *C. dactylon*, when compared to no-tillage treatments. Further research is needed to optimize treatments and methods so that they can be applied by farmers under real production conditions.

Keywords Bermudagrass · Physical weed control · Biological weed control · Allelopathy · Farm management practices · Tillage · Mulching

1 Introduction

Weed control is a major challenge nowadays, considering the urgent need to feed a growing population, while reducing the environmental impacts of food production. Through allelopathy, competition for natural resources, and/or hosting pests, weeds can interfere with crops causing serious impacts on crop yields (Oerke 2006; Ntidi et al. 2015; Gharde et al. 2018). To control weeds, modern agricultural systems tend to rely heavily on the long-term use of synthetic herbicides (MacLaren et al. 2020), which have been leading to detrimental consequences, such as widespread evolution of herbicide-resistant weeds, threatening crop production practices that depend on herbicide application (Green 2014); risks to human health (Davoren and Schiestl 2018; Magalhães et al. 2018; Ingaramo et al. 2020; Peillex and Pelletier 2020); and negative effects to non-target organisms, such as pollinators, soil organisms, and water-living organisms (Singh

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et al. 2017; Masiol et al. 2018; Sartori and Vidrio 2018; Thiour-Mauprivez et al. 2019; Meena et al. 2020; Battisti et al. 2021; Brêda-Alves et al. 2021; Onur et al. 2022).

Thus, a number of ecological alternatives to control weeds have been suggested (Bagavathiannan and Davis 2018; MacLaren et al. 2020), which aim to reduce weed competitiveness and its detrimental effects, while promoting a diverse weed community, by manipulating crop diversity, management practices, and available resources. This is strongly endorsed by both the United Nations and the European Commission, which encourage sustainable and resilient food production systems, protecting ecosystems for future generations, as evidenced by the 2030 Agenda and the European Green Deal, respectively (United Nations General Assembly (2015) Transforming our world: the 2030 Agenda for Sustainable Development.A/RES/70/1 2015; European Commission 2019). Under the strategic plan "Farm to Fork," the European Commission aims to reduce by half the use and risk of chemical pesticides and the use of more hazardous pesticides by 2030 (European Commission 2020). Considering such ambitious goals, research must address alternative methods to chemical weed control in order to maintain or increase crop yields, without increasing the environmental burden of food production.

Cynodon dactylon (L.) Pers., commonly known as bermudagrass, is a perennial, stoloniferous grass listed by Holm et al. (1977) as the second worst weed in the world, after *Cyperus rotundus* L. only—a classification that is still considered today by several authors (Ringselle et al. 2020; Wang and Wan 2020; Teshirogi et al. 2022). As many grasses, *C. dactylon* exhibits high dispersal ability, high establishment ability, and high tolerance to chronic disturbance, namely fire and herbivores (Linder et al. 2018). It exhibits C4 photosynthesis, a photosynthetic pathway that enables efficient carbon fixation even under high temperatures and water stress (Du et al. 2011). Although it forms inflorescences with several fingerlike spikes (Fig. 1), the seed production is generally sparse, and reproduction is mainly vegetative through rhizomes and stolons (Horowitz 1996; Abdessatar and Skhiri-Harzallah 2011). *C. dactylon* possesses ground runners and underground rhizomes that allow it to quickly colonize areas, forming dense mats (Dong and de Kroon 1994; Rojas-Sandoval and Acevedo-Rodríguez 2022). Moreover, it possesses allelopathic substances that suppress other species, increasing its ability to dominate different environments (Smith et al. 2001; Vasilakoglou et al. 2005; Mahmoodzadeh and Mahmoodzadeh 2014). Due to these characteristics, *C. dactylon* can successfully compete with crops. Several studies have reported crop yield losses due to its presence, e.g., corn, wheat, cotton, and sugarcane (Vasilakoglou et al. 2005; Yarnia 2010; Dalley et al. 2013). Nowadays, *C. dactylon* is considered a cosmopolitan species, occurring in tropical, subtropical, and temperate areas all over the world, including Asia; North, Central, and South America; and Europe, besides Africa, the continent from which it supposedly originated (Rojas-Sandoval and Acevedo-Rodríguez 2022).

Fig. 1 Illustration of *Cynodon dactylon* (L.) Pers. with inflorescences and rhizomes, which are key reproductive and vegetative structures, respectively. The inflorescences represent the flowering phase of *C. dactylon*, while the rhizomes are underground stems crucial for its vegetative propagation and dispersal potential. Figure credit: João Gonçalves.

Despite the worldwide importance of this weed, to the best of our knowledge, *C. dactylon* control methods have been poorly reviewed in the last two decades, especially in a systematic way. Horowitz (1996) conducted an exhaustive comprehensive review on *C. dactylon* control methods focusing on the reality of Israel at the time. However, considering the current goals regarding the reduction of chemical weed control methods (Tataridas et al. 2022), an updated systematic review on alternative methods to control *C. dactylon* is critical to guide future strategies, research, and effective change.

1.1 Objectives and structure

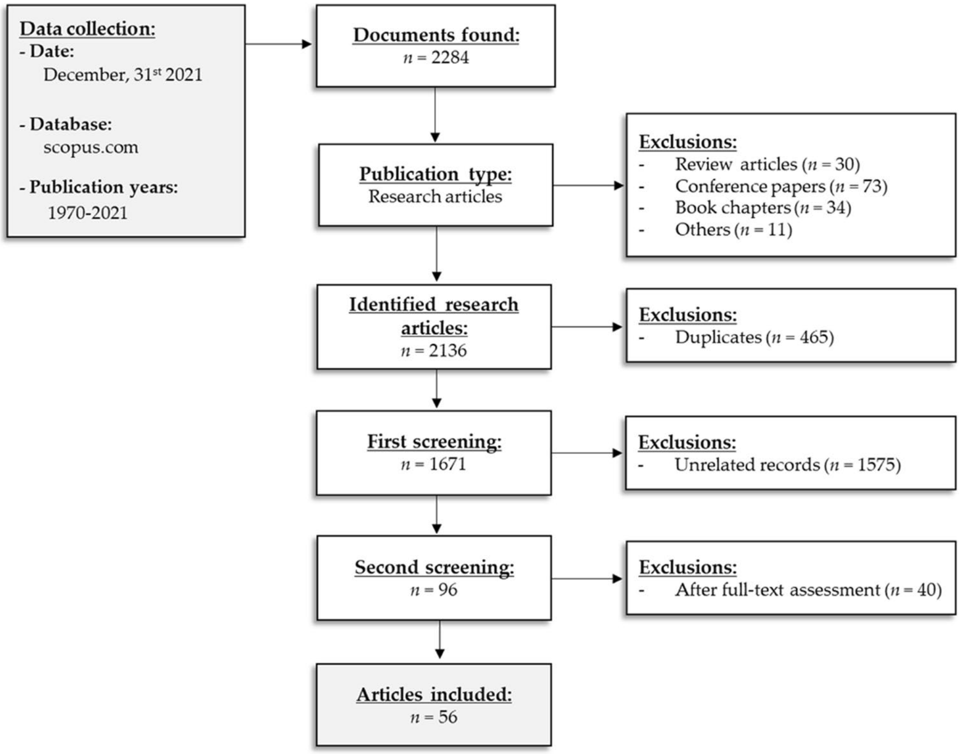
This work aims to systematically review alternative weed control methods against *C. dactylon*, identifying the most studied treatments in the past 50 years and the most efficient treatments to control this weed. The paper is structured as follows. After an introductory part (Section 1), Section 2 ("Methodology") describes the adopted methodology to collect data. Section 3 ("Results") presents and synthesizes the main results, being organized in three sub-sections: Section 3.1 ("General analysis"), Section 3.2 ("Direct weed control methods"), and Section 3.3 ("Indirect weed control methods"). We based this structure according to the concepts of direct and indirect weed control methods presented by Boller et al. (2004). In this review, direct control methods include physical and biological methods that aim to directly combat and, if possible, destroy crop enemies to prevent likely and imminent damage (methods with synthetic chemicals were not evaluated), whereas indirect control methods include preventive methods, usually farm management practices, that aim to foster unfavorable conditions for the development of crop enemies over time. Following the presentation of results, Section 4 ("Knowledge gaps and further research") summarizes the main knowledge gaps found and suggests future research, and Section 5 ("Conclusions") presents the main conclusions.

2 Methodology

2.1 Data collection and analysis

A systematic literature review was conducted to identify effective alternative methods for controlling *Cynodon dactylon*, a common weed, as substitutes to synthetic herbicides. The review analyzed scientific literature from Scopus database between 1970 and December 31, 2021, following the framework developed by Koutsos et al. (2019). The terms *Cynodon dactylon* (weed's scientific name) and its most common name "bermudagrass" were combined through the Boolean operator "OR." Then, both these terms were combined using the Boolean operator "AND" with each of the following terms in individual searches (Appendix 1): "allelopathy," "allelopathic," "bioherbicides," "insects," "arthropods," "fungi," "bacteria," "livestock," "poultry," "laying hens," "broilers," "fowl," "geese," "ducks," "horses," "cattle," "goats," "pigs," "sheep," "thermal," "flame," "hot water," "hot foam," "microwave," "solarization," "infrared radiation," "electrocution," "steaming," "mulching," "mulch," "mechanical," "cultivator," "tractor hoes," "brush weeders," "harrows," "hand weeding," "cover crop," "green manure," "tillage," "crop rotation," "succession planting," "cropping," "intercropping," "row spacing," and "crop competition." The terms were searched in the titles, abstracts, and keywords of the records. During the course of our

Fig. 2 Diagram of the general research methodology.



search, 2284 records were identified and retrieved (Fig. 2). Thereafter, records were analyzed and selected according to the following inclusion criteria: (1) papers written in the English language (excluding papers written in different languages, even if they have an English abstract), (2) papers that were research articles, and (3) papers that evaluate at least one alternative weed control treatment against *C. dactylon* (excluding papers that do not specifically report the treatments' effects on *C. dactylon* and papers that evaluate weed control treatments to protect *C. dactylon* from other weeds). In accordance with these criteria, 30 review articles, 73 conference papers, 34 book chapters, and 11 other documents were automatically excluded, resulting in 2136 research articles for analysis. Of the research articles retrieved, in a first screening, 465 records were excluded for being duplicates, and 1575 were excluded for fitting the remaining exclusion criteria. In a second screening, 96 papers were full-text assessed and 40 were excluded for not fitting the inclusion criteria 3. After the second screening, 56 papers were considered eligible for the systematic review (Appendix 2). The papers were analyzed, and the general conclusions of the various studies were collected and organized by the type of treatment. Plotted data was extracted directly, and data within graph images was extracted using the PlotDigitizer software (Version 3.1.4, 2022). Relevant information was also collected to contextualize the data obtained by the various authors, such as specific characteristics of the treatments and controls, geographic distribution of the field experiments, and duration of the studies, among others. Main results for treatments with a low volume of studies (five papers or less) are reported in the text, while results for treatments with a higher volume of studies have been organized in tables according to the inhibition levels of each treatment and the main parameters studied. Chemical herbicide treatments were not evaluated, but they were considered for comparison purposes when no other comparable treatments were available.

3 Results

3.1 General analysis

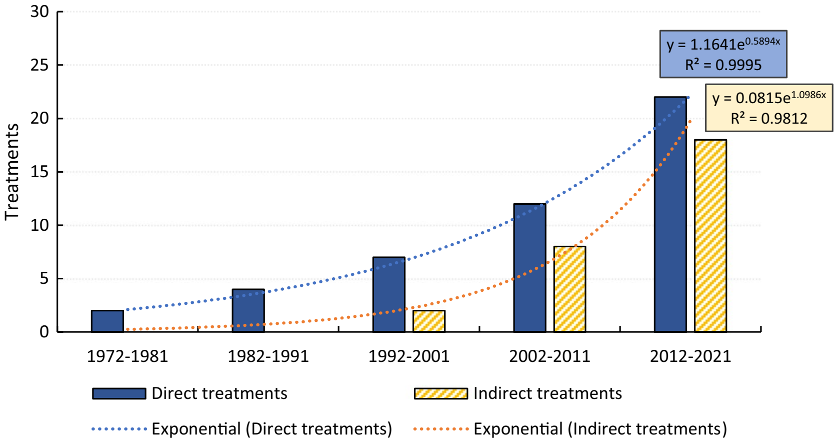
3.1.1 Controlling Cynodon dactylon using alternative control treatments: research trend

This review identified 56 research articles, published between 1970 and 2021, focused on controlling *C. dactylon* through various types of treatments, excluding synthetic herbicides. The majority of the studies assessed direct weed control treatments ($n = 36$). Some studies focused on indirect weed control treatments ($n = 11$), while a smaller proportion of the studies evaluated both direct and indirect treatments ($n = 9$).

Over the decades, the number of publications has increased significantly, with the exploration of a wider range of direct and indirect treatments in recent years, specifically studies focused on the evaluation of indirect treatments began after 1992, and studies evaluating both direct and indirect treatments emerged after 2002. Figure 3 illustrates the number and type of treatments applied in the 56 research articles, showing a clear upward and exponential trend over time for both direct and indirect treatments ($R^2 = 0.9995$ and $R^2 = 0.9812$, respectively).

According to our results, direct treatments, such as thermal treatments and control by animals, and indirect treatments, such as mulching, crop rotation, crop succession, crop competition, and intercropping, have only been explored after 2002 and not before that (Fig. 4). When considering direct treatments, the publication of articles using allelopathy stands out significantly (17 out of 28 since 2002). However, after 2012, the number of publications using allelopathy ($n = 8$) was close to those using mechanical treatments ($n = 7$). Among indirect treatments, the number of articles using tillage and mulching is dominant, with nine and eight articles, respectively, dedicated to their evaluation.

Fig. 3 Number of treatments studied in the 56 research articles found. Exponential trend lines are exposed for the number of direct and indirect treatments.



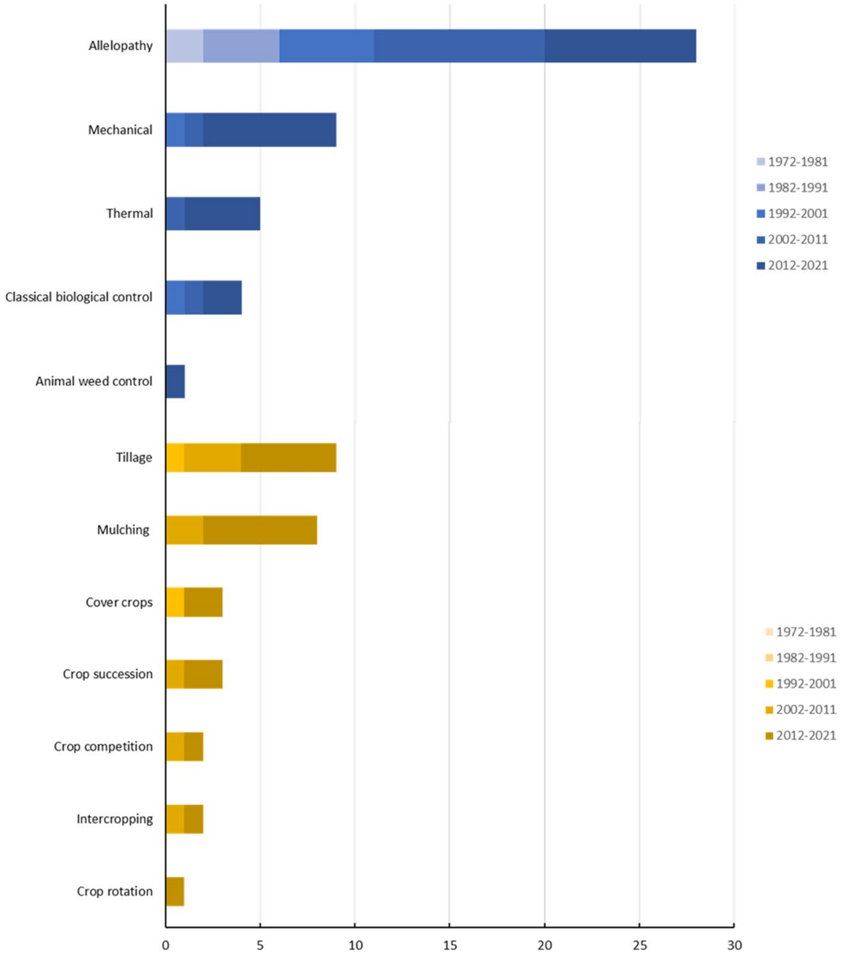


Fig. 4 Number of specific direct (in blue) and indirect treatments (in yellow) reported in the 56 research articles published since 1972, per decade.

3.1.2 Geographical distribution of the field experiments

A total of 24 field experiments were conducted across five continents, namely Africa, North America, South America, Asia, and Europe (Fig. 5). Most of these field experiments were conducted in Asia ($n = 10$). However, an uneven distribution across this continent was observed, with most studies located in South Asia (India and Pakistan), under arid and temperate subtropical climates. Only one study was identified in Asia under a continental climate. This limited number of studies in continental climates is understandable, as *C. dactylon* is known to be sensitive to prolonged frosts (Satorre et al. 1996; Ackerson et al. 2015). In Europe, a total of three studies were found, located in northeastern Spain and southern and central Italy, respectively. All of these studies were conducted under the Mediterranean climate. Across North and South America, five studies were identified, with four conducted in a temperate subtropical climate and one conducted in a temperate Mediterranean climate, in Chile. Notably, in these continents, no studies were found in tropical or arid environments, which are prevalent in large areas of South America and western North America, respectively. Six field experiments were found in Africa, spanning various climate systems. One study was conducted in Egypt, northeast Africa, under a temperate Mediterranean climate. Another study took place in Nigeria, western Africa, under a tropical climate. Four studies were carried out in southern Africa—three in Botswana under an arid climate and one in Swaziland under a temperate subtropical climate. The most frequent climate evaluated was the temperate subtropical climate ($n = 9$), followed by the arid climate ($n = 8$), temperate Mediterranean climate ($n = 5$), tropical climate ($n = 1$), and continental climate ($n = 1$).

3.1.3 Main crops evaluated

Weed control treatments can affect crop yield positively or negatively depending on several factors. In our search, we identified 28 published papers (half of the total selected papers) that evaluated the treatment effects on *C. dactylon*, while evaluating the effects on crops. Overall, field crops were most frequently found, with a total of 11 species reported in 18 different papers (Table 1). Considering the total number of treatment types evaluated in these

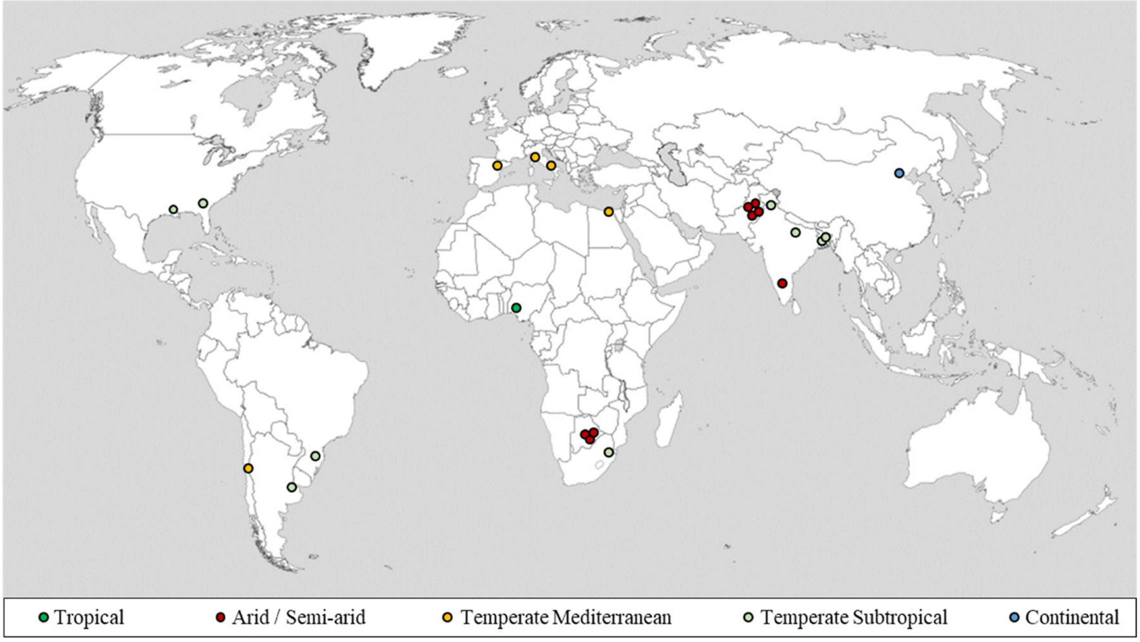


Fig. 5 Geographical distribution of the field experiments found, considering the climatic system in which they are located (Köppen climate classification).

papers, half of these were allelopathic treatments from living crops or crop residues ($n = 11$), while the rest were direct mechanical treatments ($n = 5$), classical biological control treatments excluding allelopathy ($n = 1$), and indirect treatments such as mulching ($n = 2$), tillage not perform primarily for weed control ($n = 1$), intercropping ($n = 1$), and crop competition ($n = 1$). Subsequently, six forage crops were reported in seven different papers, generally focused on allelopathic treatments as well ($n = 5$), but also focused on other treatments, such as mechanical, mulching, and thermal treatments ($n = 1$ for each treatment). Fourteen horticultural crops were considered in seven papers, which mostly evaluated allelopathic and mulching treatments ($n = 3$ for each treatment), and other treatments as well, such as classical biological control treatments ($n = 1$) and intercropping ($n = 1$). The effects on fruit species have been less studied, with only two studies found, each one focused on a different fruit species (strawberry and peach) and investigated specific treatments (cover crops and mulching, respectively).

3.2 Direct weed control methods

3.2.1 Physical weed control

Mechanical weed control In our search, we classified mechanical weed control methods as treatments that physically inhibit plant growth (e.g., hand weeding and hoe weeding). Tillage was also considered when specifically targeted the direct control of *C. dactylon* during the crop's life cycle, but not when it consisted in a general soil preparation practice indirectly affecting weed control. We found a total of nine studies that evaluated mechanical weed control treatments, all conducted since 2001. Hoe weeding was mentioned in four studies (Nadeem et al. 2013; Akter et al. 2016; Gu et al. 2019; Daramola et al. 2020), manual weeding in five studies (Abdullahi et al. 2001; Subbulakshmi et al. 2009; Thakur et al. 2012; Akter et al. 2016; Singh et al. 2021), and tillage in one study (Dalley et al. 2013). No studies were found evaluating manual cultivators, tractor hoes, brush weeders, or harrows. All the studies were carried out in open field conditions, predominantly in Asia ($n = 6$) (Subbulakshmi et al. 2009; Thakur et al. 2012; Nadeem et al. 2013; Akter et al. 2016; Gu et al. 2019; Singh et al. 2021), with additional studies in Africa (Abdullahi et al. 2001; Daramola et al. 2020) and North America (Dalley et al. 2013). These studies encompassed four different climates: subtropical temperate climate (Thakur et al. 2012; Dalley et al. 2013; Akter et al. 2016; Singh et al. 2021), arid climate (Abdullahi et al. 2001; Subbulakshmi et al. 2009; Nadeem et al. 2013), tropical savanna climate (Daramola et al. 2020), and continental climate (Gu et al. 2019). About half of the studies ($n = 5$) were carried out for periods longer than one cropping season (one study for 3 years and four studies for 2 years). In general, mechanical treatments were applied at least twice during the studies, and an increasing inhibitory effect was observed with repeated treatments over time (Abdullahi et al. 2001; Subbulakshmi et al. 2009; Thakur

Table 1 Frequency of crops considered in the different studies found and their distribution by type of experiment (lab. exp. refer to experiments in controlled laboratory settings using Petri dishes; pot exp. refer to experiments conducted in controlled conditions in growth chambers/rooms or under natural or greenhouse uncontrolled conditions; and field exp. refer to experiments conducted under real production conditions). [a]Within the same crop, summation of the type of experiments may be different from the number of papers per crop, since some authors conducted more than one type of experiment in the same paper. [b]Summation of papers for each crop may be different of the total number of papers per crop type, since some authors evaluated more than one crop in the same paper.

Crop type	Crop	Type of experiment[a]			Number of papers per crop	Number of papers per crop type[b]
		Lab. exp.	Pot exp.	Field exp.		
Field crops	Cotton (*Gossypium* spp.)	1	4	1	5	18
	Wheat (*Triticum aestivum* L.)	2	1	2	3	
	Soybean (*Glycine max* (L.) Merr.)	0	1	2	3	
	Sorghum (*Sorghum bicolor* (L.) Moench)	0	2	1	3	
	Maize (*Zea mays* L.)	0	1	1	2	
	Oat (*Avena sativa* L.)	1	1	0	2	
	Browntop millet (*Urochloa ramosa* (L.) T.Q. Nguyen)	1	1	0	2	
	Sunflower (*Helianthus annuus* L.)	0	1	1	2	
	Rice (*Oryza sativa* L.)	0	1	0	1	
	Pearl millet (*Pennisetum americanum* (L.) Leeke)	1	0	0	1	
	Foxtail millet (*Setaria italica* (L.) Beauv.)	1	0	0	1	
Forage crops	Alfalfa (*Medicago sativa* L.)	1	1	0	2	7
	Italian ryegrass (*Lolium multiflorum* Lam.)	1	1	0	2	
	Perennial ryegrass (*Lolium perenne* L.)	0	1	0	1	
	White clover (*Trifolium repens* L.)	0	1	0	1	
	Bur clover (*Medicago polymorpha* L.)	1	0	0	1	
	Sugarcane (*Saccharum* spp.)	0	0	1	1	
Horticultural crops	Lettuce (*Lactuca sativa* L.)	2	0	0	2	7
	Radish (*Raphanus sativus* L.)	1	1	0	2	
	Squash (*Cucurbita pepo* L.)	0	1	1	2	
	Broccoli (*Brassica oleracea* L.)	0	0	1	1	
	Sweet potato (*Ipomoea batatas* (L.) Lam.)	0	0	1	1	
	Jute mallow (*Corchorus olitorius* L.)	1	1	0	1	
	Beet (*Beta vulgaris* L.)	0	1	0	1	
	Cucumber (*Cucumis sativus* L.)	0	1	0	1	
	Peanut (*Arachis hypogaea* L.)	0	1	0	1	
	Bean (*Phaseolus vulgaris* L.)	0	1	0	1	
	Cowpea (*Vigna sinensis* (Torner) Savi.)	0	1	0	1	
	Okra (*Abelmoschus esculentus* L.)	0	1	0	1	
	Hot pepper (*Capsicum frutescens* L.)	0	1	0	1	
	Tomato (*Lycopersicon esculentum* Mill.)	0	1	0	1	
Fruit crops	Peach (*Prunus persica* (L.) Batsch)	0	0	1	1	2
	Strawberry (*Fragaria* × *ananassa* "Cardinal")	0	1	0	1	

et al. 2012; Dalley et al. 2013). In addition to evaluating the effectiveness of mechanical treatments in controlling *C. dactylon*, most studies also evaluated the effect of treatments on crops ($n = 7$), while two studies evaluated the effect on soil physical, chemical, and biological properties (Thakur et al. 2012; Gu et al. 2019). The evidence suggests that hoe weeding treatment is generally effective and contributes to reducing *C. dactylon* in infested fields (Table 2). The studies also indicate a high level of suppression of this weed under hand weeding treatments (with inhibition rates above 60% in most studies), which may be slightly more effective than the hoe weeding treatment under identical circumstances (e.g., the study by Akter et al. (2016)).

Overall, although manual weed control methods have demonstrated effectiveness in managing *C. dactylon*, their labor-intensive nature, high costs, and probability of weed propagation due to weed fragmentation should be carefully considered. Further research is needed to explore the potential of tillage as a direct method and investigating the long-term implications of modern mechanical treatments on weed recovery and propagation. Researching promising strategies, such as mechanical desiccation methods, is

Table 2 Results' summary regarding mechanical control treatments effects on *C. dactylon*. The efficiency results were divided into percentage levels of inhibition. Whenever studies evaluated effects over more than one season/sampling period, the results refer to the data collected in the last season/sampling period studied—with the exception of the study by Nadeem et al. (2013) which presented data combined across years (weedy check refers to a control treatment which allows weeds to grow without any intervention; n.c. means not considered; n.s. means not specified; - - - means unaffected; - - means inhibition between 1 and 20%; - means inhibition between 21 and 40%; + means inhibition between 41 and 60%; ++ means inhibition between 61 and 80%; +++ means inhibition between 81 and 100%; GC means ground cover analysis through visual assessment; DW means dry weight; B means weed biomass; D means weed density; RD means weed relative density; WAT means weeks after treatment; WAS means weeks after sowing/transplanting; and DAS means days after sowing)

Treatment	Control	Frequency	Study duration	Data collection	GC	DW	B	D	RD	Sources
Manual weeding	Weedy check	n.s.	2 years	10 WAT	++	n.c.	n.c.	n.c.	n.c.	Abdullahi et al. (2001)
	Weedy check	n.s.	2 years	n.s.	n.c.	+++	n.c.	n.c.	n.c.	
	Weedy check	2 times after sowing	≤ 1 year	60 DAS	n.c.	+++	n.c.	n.c.	n.c.	Akter et al. (2016)
	Weedy check	2 times after sowing	≤ 1 year	n.s.	n.c.	n.c.	++	++	n.c.	Singh et al. (2021)
	Chemical herbicide	2 times after sowing	≤ 1 year	n.s.	n.c.	n.c.	++	+++	n.c.	
	Weedy check	3-week intervals	2 years	12 WAT	n.c.	n.c.	++	n.c.	n.c.	Thakur et al. (2012)
	Weedy check	2 times after sowing	2 years	20 DAS	n.c.	n.c.	n.c.	n.c.	+	Subbulakshmi et al. (2009)
Hoe weeding	Weedy check	2 times after sowing	≤ 1 year	60 DAS	n.c.	++	n.c.	n.c.	n.c.	Akter et al. (2016)
	Weedy check	2 times after sowing	2 years	12 WAS	n.c.	n.c.	-	++	n.c.	Daramola et al. (2020)
	Chemical herbicide	4 times in a 10-month fallow	≤ 1 year	During fallow	n.c.	n.c.	+++	++	n.c.	Gu et al. (2019)
	Weedy check	2 times after sowing	2 years	At harvest	n.c.	n.c.	n.c.	+	n.c.	Nadeem et al. (2013)
Reduced tillage	No tillage	2 times each spring	3 years	Summer of last season	-	n.c.	n.c.	n.c.	n.c.	Dalley et al. (2013)
Conventional tillage	No tillage	4 times each spring	3 years	Summer of last season	+	n.c.	n.c.	n.c.	n.c.	

recommended considering the positive results reported by Horowitz (1996): after 7 days of exposure to open air in summer, rhizome fragments of *C. dactylon*, which had lost more than 45–50% of their initial weight, failed to sprout. Modern desiccation tillage implements such as the Kvik-up cultivator also deserve to be tested on *C. dactylon*, considering the results reported by Ringselle et al. (2020) in managing *Elymus repens* (L.) Gould, another perennial rhizomatous grass.

Thermal weed control The principle behind controlling weeds using thermal methods is based on inducing plant damage through extreme temperatures, leading to severe dehydration and subsequent death. This approach encompasses several methods, including flame burning, hot water, hot foam, solarization, microwave radiation, infrared radiation, and electrocution, among others. This search yielded five research articles that evaluated thermal weed control methods against *C. dactylon*, namely two articles that investigated microwave radiation in laboratory conditions (Kaçan et al. 2018; Aygün et al. 2019), one article that assessed steaming under greenhouse conditions (Leon and Ferreira 2008), one article that examined hot foam and hot water treatments under uncontrolled field conditions in Italy (Martelloni et al. 2021), and one article that evaluated solarization under real production conditions in North America (Johnson and Davis 2012).

Studies involving the use of microwaves under laboratory conditions have shown highly promising results. Both Kaçan et al. (2018) and Aygün et al. (2019) evaluated the effects of different levels of microwave power (minimum 1.6 kW and maximum 5.6 kW) with different forward speeds (0.1 to 0.3 m s^{-1}) on the efficacy of killing *C. dactylon* at different growth stages. These studies consistently showed that *C. dactylon* required high microwave power (between 3.2 and 5.6 kW) to achieve mortality, with the required power increasing with higher speeds and at later growth stages. Despite the increased energy requirement, both studies showed the strong capability of microwaves to cause the death of *C. dactylon*, which should be further explored. Similarly, studies involving steaming, hot water, and hot foam have also shown that *C. dactylon* can be inhibited by high-temperature sources. For example, exposure to steaming treatment at 400 °C for 0.36 s (equivalent to a steaming speed of 2 km h^{-1}) significantly affected *C. dactylon* shoot length and biomass, reducing them to 66% and 54% of untreated plants, respectively. Visual steam injury, characterized by stunting, chlorosis, and necrosis, ranged from 72 to 65% at 1 and 14 days after treatment, respectively (Leon and Ferreira 2008). Concerning the hot water and hot foam methods, the results indicate that *C. dactylon* disappeared from plots after the application of 5.00 kg m^{-2} of hot water and after 3.33 kg m^{-2} of hot foam (Martelloni et al. 2021). However, among other weeds present in the plots, *C. dactylon* was one of the first weeds to re-sprout within 7 days after the treatment intervention. Regarding solarization, the results reported by Johnson and Davis (2012) indicate that a summer solarization alone could reduce *C. dactylon* total biomass by up to 60%, while combining it with winter tillage using a peanut digger could lead to an 82% reduction compared to a non-treated control. However, the authors emphasized that using these approaches for one season was not sufficient to prevent re-infestation by survivors.

In general, although there is evidence suggesting the sensitivity of *C. dactylon* to thermal treatments, the current research is limited to laboratory and controlled field conditions, while the few studies conducted in open field settings highlight the weed persistence and reappearance after treatment. Further research should assess the long-term effects of thermal treatments in open field conditions; explore the optimal thermal frequency/intensity required to control the weed; evaluate the management, costs, and benefits of each method; explore the potential combination of thermal methods with other control strategies; and study other thermal approaches, such as flame weeding, which presented promising results in studies found during the screening process, where flame weeding was used to protect *C. dactylon* (Fontanelli et al. 2017; Martelloni et al. 2018).

3.2.2 Biological weed control

Classical biological weed control Classical biological control is the deliberate introduction of an exotic biological control agent (insect herbivores, parasitoids, or pathogens) into an area that has been infested by a pest for the purpose of permanent establishment and long-term pest control (Omkar and Kumar 2016). Our search yielded three research articles mentioning the effects of different fungi (García-Guzmán and Burdon 1997; Tilley and Walker 2002; Soesanto et al. 2021) and one article mentioning the effects of rhizobacterial isolates on *C. dactylon* (Raza et al. 2021). No articles were found mentioning the effects of insect herbivores on *C. dactylon*.

In a greenhouse study, Tilley and Walker (2002) evaluated the potential of the fungus *Curvularia intermedia* as a microbial herbicide. Although the mortality rate of *C. dactylon* was unaffected by the inoculation of *C. intermedia* in the host range study, the weed reduced its dry weight to 38% after the fungus inoculation, suggesting a significant susceptibility of *C. dactylon* in the presence of *C. intermedia*. Another greenhouse experiment conducted by García-Guzmán and Burdon (1997) evaluated the effects of the flower-infecting smut fungus *Ustilago cynodontis* on *C. dactylon*. The study reported that the fungus was capable of sterilizing the weed by replacing floral structures with a teliospore-producing fungal stroma, which forced the plant to rely entirely on vegetative growth for reproduction. The infection had no impact on seed germination or emergence, but it did reduce overall dry matter production and stolon growth rate, altered resource allocation between roots and shoots, and affected the survival of *C. dactylon* plants under crowded conditions in a naturally lit glasshouse. These findings suggest that both *Curvularia intermedia* and *Ustilago cynodontis* have negative effects on *C. dactylon* under greenhouse conditions, which deserves to be further researched. However, the results reported by Soesanto et al. (2021) in a laboratory experiment were not as promising as the previously mentioned studies. While assessing the use of alternative liquid media for the propagation of pathogenic fungi, such as *Chaetomium* sp., *Fusarium* sp., and *Curvularia lunata*, the authors evaluated the effects of those fungi on *C. dactylon*. The results indicate that the studied weed pathogenic fungi were not effective in controlling *C. dactylon*, being a weak alternative to control this weed.

Regarding the effects of rhizobacterial isolates, Raza et al. (2021) conducted laboratory and field experiments to assess the comparative effectiveness of a consortium of two different rhizobacteria (*Pseudomonas fluorescens*, strain 6K; and *Bacillus* sp., strain 6) to the management of *C. dactylon*. The laboratory experiment showed that rhizobacterial consortium significantly suppressed the seed germination percentage of *C. dactylon* by 21.3%. In field conditions, the same treatment significantly reduced the weed density by 89.3% at 45 days after sowing.

In summary, our search suggests promising results on the use of the fungi *Curvularia intermedia* and *Ustilago cynodontis*, and the rhizobacterial consortium of *Pseudomonas fluorescens* and *Bacillus* sp. against *C. dactylon*, that could be further researched, while there is a significant knowledge gap regarding the effects of insects and other microorganisms. There are research opportunities to optimize the use of these species, particularly as complementary methods to more commonly employed strategies. Although classical biological control has been adopted for many years, the number of new introductions has gradually decreased (Schwarzländer et al. 2018), and the results and perceptions of this strategy are very controversial (Cripps et al. 2011; van Lenteren 2012; Sutton et al. 2019). Therefore, additional research is needed to understand the potential of classical biological control for managing *C. dactylon*, considering the practicability of the method, resistance phenomena, and potential impacts on crops and non-target organisms.

Allelopathy The use of allelopathic organisms represents a significant approach towards achieving sustainable weed control, particularly considering the environmental challenges and the rise of herbicide resistance (Bhowmik and Inderjit 2003; Jabran et al. 2015). Allelopathy, as defined by Rice (1984), involves the stimulatory or inhibitory effects of live or dead plant (including microorganisms) on others through the release of chemical compounds into the environment. Our search yielded 28 articles directly related to the allelopathic effects of 25 plant species against *C. dactylon*, belonging to 14 families, namely Asteraceae, Anacardiaceae, Brassicaceae, Cistaceae, Euphorbiaceae, Fabaceae, Lamiaceae, Malvaceae, Moraceae, Myrtaceae, Pinaceae, Poaceae, Polygonaceae, and Rutaceae. The most studied families were Poaceae, Fabaceae, and Euphorbiaceae (Datta and Sinha-Roy 1975; Hussain 1980; Alsaadawi et al. 1990; Kalburtji and Mosjidis 1992, 1993; Al-Humaid and Warrag 1998; Koger and Bryson 2004; Koger et al. 2004; McCarty et al. 2010; Wang et al. 2011; dos Santos et al. 2014; Shahzad et al. 2016; Raza et al. 2021). *Sorghum bicolor* (L.) Moench, from the Poaceae family, was the most studied species, especially when considering real production conditions. The allelopathic effects were evaluated through various methods, such as application of plant extracts, application of soil extracts where allelopathic plants were in contact, incorporation of plant residues in soil where *C. dactylon* was grown, use of soil where allelopathic plants grew as a substrate for *C. dactylon* growth, application of root exudates, mulching, and use of allelopathic crops in crop succession. The evaluation of extracts was the most identified method (21 studies out of 28 considered at least one extract treatment). The extracts identified were mostly obtained with water ($n = 16$), but also with other solvents (e.g., methanol, ethanol, petroleum ether, and Hoagland's nutrient solution). Most studies were conducted exclusively in the laboratory ($n = 10$). Pot experiments under controlled conditions (e.g., controlled light and temperature, in growth chambers/rooms) were conducted by five studies, while pot experiments under natural or greenhouse conditions were conducted by six studies. Experiments conducted only under open field settings were pointedly less found ($n = 2$), and all of them were located in Asia, under arid and temperate subtropical climates. The remaining studies scaled up from laboratory experiments to pot experiments under controlled conditions ($n = 1$), to pot experiments under uncontrolled conditions ($n = 3$), and to open field experiments ($n = 1$). Increasing concentrations/rates of treatments were often assessed to determine the concentration/rate with the best inhibitory effects. In most studies, treatment's inhibitory effects tended to increase, with increasing concentration/rate of the treatment applied. Table 3 presents the results' summary focused on the minimum concentration/rate of the best inhibition levels found for each treatment. Under laboratory and pot experiments, with few exceptions, most of the studies evaluated germination rates, radicle/root, shoot, and whole weed growths through length and/or dry weight, while under real production conditions, the studies mostly evaluated the whole weed dry weight and/or weed density. Differently, Chen et al. (2018) evaluated the allelopathic effects of

Table 3 Results' summary regarding the effects of the allelopathic species reported in the found studies on *C. dactylon*. The efficiency results were divided into percentage levels of inhibition and correspond to the minimum concentration of the best inhibition levels found. Whenever studies evaluated effects over more than one season/sampling period, the results refer to the data collected in the last season/sampling period studied—with the exception of the study by El-Rokiek et al. (2011) which presented data combined across years (n.c. means not considered; - - - means unaffected; - - means inhibition between 1 and 20%; - means inhibition between 21 and 40%; + means inhibition between 41 and 60%; ++ means inhibition between 61 and 80%; +++ means inhibition between 81 and 100%; L means laboratory experiments; PCC means pot experiments under controlled conditions in growth chambers/rooms; PUC means pot experiments under natural or greenhouse uncontrolled conditions; F means open field experiments; G means germination or emergence; RL means radicle/root length; SL means shoot length; RDW means root dry weight; SDW means shoot dry weight; WPDW means whole plant dry weight; D means weed density; DAS means days after sowing; and DAG means days after germination)

Family	Species	Exp.	Treatment	G	RL	SL	RDW	SDW	WPDW	D	Sources
Asteraceae	*Artemisia arborescens* (Vaill.) L.	L	Methanolic extract (0.6%, w/v)	+++	+++	n.c.	n.c.	n.c.	n.c.	n.c.	Araniti et al. (2016)
			Hexane fraction (0.8%, w/v)	- -	++	n.c.	n.c.	n.c.	n.c.	n.c.	
			Chloroform fraction (0.2%, w/v)	+++	+	n.c.	n.c.	n.c.	n.c.	n.c.	
			Ethyl acetate fraction (0.2%, w/v)	+++	+	n.c.	n.c.	n.c.	n.c.	n.c.	
	Pluchea dioscoridis (L.) DC.	L	Root extract (6%, w/v)	+++	+++	+++	n.c.	n.c.	n.c.	n.c.	Fahmy et al. (2012)
			Leaf extract (2%, w/v)	+++	+++	+++	n.c.	n.c.	n.c.	n.c.	
		PUC	Mulching (7.67 t ha^{-1})	n.c.	n.c.	n.c.	+++	+++	n.c.	n.c.	
			Soil previously in contact with *P. dioscoridis* as growth medium	n.c.	n.c.	n.c.	++	++	n.c.	n.c.	
Anacardiaceae	*Mangifera indica* L.	PUC	Leaf residues in soil (10%, w/w) 70 DAS (2 seasons)	n.c.	n.c.	+	++	++	n.c.	n.c.	El-Rokiek et al. (2011)
Brassicaceae	*Brassica juncea* (L.) Czern.	F	Seed meal extract (225 L/ha) compared to weedy check	n.c.	n.c.	n.c.	n.c.	n.c.	+	- - -	Singh et al. (2021)
			Seed meal extract (225 L/ha) compared to chemical herbicide	n.c.	n.c.	n.c.	n.c.	n.c.	++	+	
Cistaceae	*Cistus ladanifer* L.	L	Flavonoid solution (12.5%, w/v)	- -	n.c.	++	n.c.	n.c.	n.c.	n.c.	Chaves and Escudero (1997)
			Remainder compounds solution (12.5%, w/v)	+	n.c.	++	n.c.	n.c.	n.c.	n.c.	
			Flavonoid + remainder compounds solution (12.5%, w/v)	-	n.c.	++	n.c.	n.c.	n.c.	n.c.	

Table 3 (continued)

Family	Species	Exp.	Treatment	G	RL	SL	RDW	SDW	WPDW	D	Sources
Euphorbiaceae	*Croton bonplandianum* Baill.	L	Leaf extract (40%, w/v)	+++	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	Datta and Sinha-Roy (1975)
			Leaf leachate (40%, w/v)	+	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
			Decaying leaf in soil (4%, w/w)	+	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
			Soil previously in contact with *C. bonplandianum* collected during the dry season as growth medium	- -	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
			Soil previously in contact with *C. bonplandianum* collected during the wet season as growth medium	-	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
	Euphorbia granulata Forssk.	L	Leaf extract (5%, w/v)	+	n.c.	n.c.	++	n.c.	n.c.	n.c.	Hussain (1980)
			Soil extract (20%, w/v)	+	n.c.	n.c.	++	n.c.	n.c.	n.c.	
			Soil previously in contact with *E. granulata* as growth medium	+	n.c.	n.c.	++	n.c.	n.c.	n.c.	
		PCC	Litter decomposition in sand (2.5%, w/w)	++	n.c.	n.c.	n.c.	n.c.	+++	n.c.	
	Euphorbia prostrata Aiton	PUC	Plant extract (6%, w/v)	++	n.c.	n.c.	++	++	n.c.	n.c.	Alsaadawi et al. (1990)
			Decaying residues in soil (0.15%, w/w)	++	n.c.	n.c.	++	+++	n.c.	n.c.	
			Soil previously in contact with *E. prostrata* as growth medium	+	n.c.	n.c.	++	++	n.c.	n.c.	
			Root exudates	- -	n.c.	n.c.	++	+	n.c.	n.c.	
Fabaceae	*Lespedeza cuneata* (Dum. Cours.) G. Don	L	Low tannin extract (10%, w/v)	- -	n.c.	- -	n.c.	n.c.	n.c.	n.c.	Kalburtji and Mosjidis (1992)
			High tannin extract (10%, w/v)	- -	n.c.	- -	n.c.	n.c.	n.c.	n.c.	
			Topsoil extract (10%, w/v)	- - -	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
			Subsoil extract (10%, w/v)	- - -	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
		PUC	Residues in soil (12 g/pot of 1890 cm^{-3})	- -	n.c.	n.c.	n.c.	- -	n.c.	n.c.	
		PUC	Root exudates	- -	-	- -	n.c.	- -	n.c.	n.c.	Kalburtji and Mosjidis (1993)
	Prosopis juliflora (Sw.) DC	L	Mature green leaf extract (6%, w/v)	+++	+++	+++	n.c.	n.c.	n.c.	n.c.	Al-Humaid and Warrag (1998)
	Tephrosia vogelii Hook. f.	L	Fresh leaf leachates (10%, w/v)	-	-	-	n.c.	n.c.	n.c.	n.c.	Wang et al. (2011)
			Leaf volatiles (0.05 g/cm^3)	-	-	+	n.c.	n.c.	n.c.	n.c.	
			Leaf litter leachates (0.5% w/v)	n.c.	++	+	n.c.	n.c.	n.c.	n.c.	
	Vigna radiata (L.) Wilczek	F	Mungbean-wheat succession compared to fallow-wheat succession (2 seasons)	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	+	Shahzad et al. (2016)

Table 3 (continued)

Family	Species	Exp.	Treatment	G	RL	SL	RDW	SDW	WPDW	D	Sources
Lamiaceae	*Nepeta meyeri* Benth.	L	Leaf essential oil (0.01%, v/v)	+	+	-	n.c.	n.c.	n.c.	n.c.	Mutlu et al. (2010, 2011)
			Leaf essential oil (0.02%, v/v)	++	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
	Rosmarinus officinalis L.	L	Fresh leaf leachates (10%, w/v)	-	+	+	n.c.	n.c.	n.c.	n.c.	Chen et al. (2013)
			Leaf volatiles (5%, w/v)	n.c.	-	+	n.c.	n.c.	n.c.	n.c.	
			Leaf litter leachates (0.5%, w/v)	n.c.	+	-	n.c.	n.c.	n.c.	n.c.	
Malvaceae	*Gossypium* sp.	F	Cotton-wheat succession compared to fallow-wheat succession (2 seasons)	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	++	Shahzad et al. (2016)
Moraceae	*Morus alba* L.	L	Leaf extract (50%, w/v)	+++	+++	+++	n.c.	n.c	n.c.	n.c.	Haq et al. (2010)
		PUC	Foliar spray (100%, w/v)	n.c.	++	++	+++	+++	n.c.	n.c.	
Myrtaceae	*Eucalyptus globulus* Labill.	PUC	Dry powdered leaf leachate (40%, w/v)	n.c.	- -	- -	- -	- -	- -	n.c.	Babu and Kandasamy (1997)
			Dry powdered leaf material in 1:1:1 sand-red soil-farmyard manure mixture (0.42%, w/w)	n.c.	- -	- -	-	-	-	n.c.	
			Fresh leaf leachate (20%, w/v)	n.c.	++	++	+++	+++	+++	n.c.	
			Fresh leaf cuttings in 1:1:1 sand-red soil-farmyard manure mixture (1.67%, w/w)	n.c.	++	+	+++	+++	+++	n.c.	
			Dry powdered leaf material in soil (10%, w/w) 70 DAS (2 seasons)	n.c.	n.c.	-	+	++	n.c.	n.c.	El-Rokiek et al. (2011)
Pinaceae	*Pinus halepensis* Mill.	PCC	Perlite substrate with fresh needles (18 g/pot of 423 cm^{-3})	n.c.	-	-	-	+	n.c.	n.c.	Nektarios et al. (2005)
			Perlite substrate with senesced needles (18 g/pot of 423 cm^{-3})	n.c.	-	-	-	+	n.c.	n.c.	
			Perlite substrate with decaying needles (18 g/pot of 423 cm^{-3})	n.c.	-	- -	- -	-	n.c.	n.c.	

Table 3 (continued)

Family	Species	Exp.	Treatment	G	RL	SL	RDW	SDW	WPDW	D	Sources
Poaceae	*Imperata cylindrica* (L.) Rauschel	L	Leaf extract (8%, w/v)	-	+	+++	n.c.	n.c.	n.c.	n.c.	Koger and Bryson (2004)
			Root extract (8%, w/v)	-	+	+++	n.c.	n.c.	n.c.	n.c.	
		PCC	Leaf residues in silica sand substrate (4%, w/w)	+++	n.c.	n.c.	+++	+++	n.c.	n.c.	Koger et al. (2004)
			Root residues in silica sand substrate (1%, w/w)	+++	n.c.	n.c.	+++	+++	n.c.	n.c.	
	Lolium perenne L.	PCC	Leaf residues in peat, perlite, and vermiculite substrate (23%, w/w)	-	n.c.	n.c.	+	- -	n.c.	n.c.	McCarty et al. (2010)
			Root residues in peat, perlite, and vermiculite substrate (12%, w/w)	- - -	n.c.	n.c.	- - -	-	n.c.	n.c.	
			Irrigation water + leaves (2%, w/v)	- - -	n.c.	n.c.	- - -	- - -	n.c.	n.c.	
			Irrigation water + roots (1%, w/v)	- - -	n.c.	n.c.	- -	- - -	n.c.	n.c.	
	Sorghum bicolor (L.) Moench	L	Plant extract (10%, w/v)	-	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	Raza et al. (2021)
			Plant extract (10%, w/v) + consortium of rhizobacterial isolates of *Pseudomonas fluorescens* strain 6K and *Bacillus* sp., strain 6 (10^6 CFU mL^{-1})	+	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	
		PUC	Planted with *C. dactylon* (5:4 ratio weed-*S. bicolor*)	n.c.	n.c.	n.c.	+	++	n.c.	n.c.	dos Santos et al. (2014)
		F	Plant extract (10%, w/v) 45 DAS	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	+++	Raza et al. (2021)
			Plant extract (10%, w/v) + consortium of rhizobacterial isolates of *Pseudomonas fluorescens* strain 6K and *Bacillus* sp., strain 6 (10^6 CFU mL^{-1}) 45 DAS	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	+++	
			Sorghum-wheat succession compared to fallow-wheat succession (2 seasons)	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	+++	Shahzad et al. (2016)
	Oryza sativa L.	F	Rice-wheat succession compared to fallow-wheat succession (2 seasons)	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	+++	Shahzad et al. (2016)

Table 3 (continued)

Family	Species	Exp.	Treatment	G	RL	SL	RDW	SDW	WPDW	D	Sources
Polygonaceae	*Polygonum aviculare* L.	PUC	Soil in contact with *P. aviculare* as growth medium	- -	n.c.	n.c.	- -	- - -	- - -	n.c.	Alsaadawi and Rice (1982)
			Soil previously in contact with *P. aviculare* as growth medium	+	n.c.	n.c.	++	++	++	n.c.	
			Leaf leachate (concentration not specified)	- -	n.c.	n.c.	n.c.	n.c.	- - -	n.c.	
			Decaying shoots in 2:1 soil-sand mixture (0.4%, w/w)	-	n.c.	n.c.	n.c.	n.c.	-	n.c.	
			Decaying roots in 2:1 soil-sand mixture (0.2%, w/w)	-	n.c.	n.c.	n.c.	n.c.	-	n.c.	
			Decaying shoots (0.4%, w/w) + decaying roots (0.2%, w/w) in 2:1 soil-sand mixture, 40 DAG	n.c.	n.c.	n.c.	+	+	+	n.c.	
			Root exudates	n.c.	n.c.	n.c.	- -	-	-	n.c.	
		L	Sodium myristate (50 ppm)	- -	-	- -	n.c.	n.c.	n.c.	n.c.	Alsaadawi et al. (1983)
			Sodium palmitate (50 ppm)	-	++	-	n.c.	n.c.	n.c.	n.c.	
			Sodium linolelaidate (50 ppm)	+	+	- -	n.c.	n.c.	n.c.	n.c.	
			Sodium oleate (50 ppm)	-	++	- -	n.c.	n.c.	n.c.	n.c.	
			Sodium stearate (50 ppm)	-	-	- -	n.c.	n.c.	n.c.	n.c.	
			Sodium arachidate (50 ppm)	- -	-	- - -	n.c.	n.c.	n.c.	n.c.	
			Sodium 11, 14-eicosadienoate (50 ppm)	- -	+	- -	n.c.	n.c.	n.c.	n.c.	
			Sodium heneicosanoate (50 ppm)	- -	+	- - -	n.c.	n.c.	n.c.	n.c.	
			Sodium behenate (50 ppm)	- - -	-	- -	n.c.	n.c.	n.c.	n.c.	
Rutaceae	*Citrus aurantium* L.	PCC	Soil previously in contact with *C. aurantium* as growth medium	++	n.c.	n.c.	n.c.	n.c.	+++	n.c.	Alsaadawi and AlRubeaa (1985)
			Senescent leaf extract (10%, w/v)	++	n.c.	n.c.	+	++	++	n.c.	
			Nonsenescent leaf extract (10%, w/v)	+	n.c.	n.c.	-	++	+	n.c.	
			Decaying senescent leaf in soil (0.6%, w/w)	+	n.c.	n.c.	+	- -	-	n.c.	
			Decaying nonsenescent leaf in soil (0.6%, w/w)	++	n.c.	n.c.	++	+	++	n.c.	

decomposing leaf litter of *Leucaena leucocephala* (Lam.) de Wit, from the Fabaceae family, on the photosynthesis of *C. dactylon* in controlled potted experiments. Their results indicated that the increase of *L. leucocephala* leaf litter contributed to decrease stomatal conductance, transpiration rate, dark respiration rate, and net photosynthetic rate of *C. dactylon*, affecting the photosynthetic traits, light adaptation ability, and physiological metabolism of the weed. According to the study, *L. leucocephala* significantly inhibited *C. dactylon*, and such inhibition of photosynthesis was mainly associated with non-stomatal limitations, through a decreased pigment content and increased accumulation of soluble sugar.

The remaining studies, summarized in Table 3, indicate that *Sorghum bicolor* (L.) Moench (sorghum), and *Oryza sativa* L. (rice), from the Poaceae family, can have very high inhibition effects (often above 80%), especially under open field conditions, resulting from allelopathic effects and/or crop competition (Koger and Bryson 2004; Koger et al. 2004; dos Santos et al. 2014; Shahzad et al. 2016; Raza et al. 2021). Species such as *Vigna radiata* (L.) Wilczek (mungbean; Fabaceae), *Brassica juncea* (L.) Czern. (mustard; Brassicaceae), and *Gossypium* sp. (cotton; Malvaceae) also presented good inhibition results under real production conditions (Shahzad et al. 2016; Singh et al. 2021). Species from the families Asteraceae, Anacardiaceae, Cistaceae, Euphorbiaceae, Lamiaceae, Moraceae, and Rutaceae showed satisfactory inhibition results under laboratory and/or pot experiments which deserve to be further researched in open field conditions (Datta and Sinha-Roy 1975; Alsaadawi and AlRubeaa 1985; Chaves and Escudero 1997; Haq et al. 2010; Mutlu et al. 2010, 2011; El-Rokiek et al. 2011; Fahmy et al. 2012; Chen et al. 2013; Araniti et al. 2016). On the contrary, *Lolium perenne* L. (perennial ryegrass; Poaceae), *Pinus halepensis* Mill. (Aleppo pine; Pinaceae), and *Polygonum aviculare* L. (prostrate knotweed; Polygonaceae) showed relatively reduced inhibitory effects in several parameters (Alsaadawi and Rice 1982; Alsaadawi et al. 1983; Nektarios et al. 2005; McCarty et al. 2010). *Eucalyptus globulus* Labill. (blue gum; Myrtaceae) showed both high (above 80%) and low (under 20%) levels of inhibition depending on the treatment and on the study (Babu and Kandasamy 1997; El-Rokiek et al. 2011).

Bioactive compounds or genes responsible for the inhibitory effects on *C. dactylon* were identified by 12 studies, with terpenoids and/or phenolic compounds (flavonoids, phenolic acids, and tannins) being the most common (Datta and Sinha-Roy 1975; Alsaadawi et al. 1983; Kalburtji and Mosjidis 1992; Chaves and Escudero 1997; Nektarios et al. 2005; Mutlu et al. 2010, 2011; El-Rokiek et al. 2011; Fahmy et al. 2012; Chen et al. 2013; dos Santos et al. 2014; Araniti et al. 2016). A significant portion of studies did not assess allelopathic effects on crops where *C. dactylon* is problematic ($n = 13$), and the impacts on soil microbiology and non-target organisms were largely overlooked.

Overall, the abundance of articles on allelopathic effects against *C. dactylon* suggests a high interest of the scientific community in this control method. However, the current knowledge is limited by the low amount of studies conducted under real field conditions, which is crucial for practical application. Some authors have highlighted the possibilities of developing herbicides from allelochemicals (Bhowmik and Inderjit 2003; Soltys et al. 2013; Farooq et al. 2020; Khamare et al. 2022), which may be a research opportunity regarding *C. dactylon*. Moreover, allelopathy has presented positive results on the management of several weed species, through intercropping, cover crops, crop rotation, mulching, and residue incorporation (Bhowmik and Inderjit 2003; Kunz et al. 2016; Sturm et al. 2018; Blaise et al. 2020; Farooq et al. 2020; Khamare et al. 2022). In this context, the current knowledge can be of great importance in informing farmers/researchers about which crops may be useful to include in a farm system infested by *C. dactylon*, which should be a focus of future research, especially to understand how these crops should be used/optimized.

Weed control using animals Crop-livestock integration plays a key role in the sustainability of farming systems as it promotes nutrient cycling, utilizes on-farm resources, and reduces external inputs (Russelle et al. 2007; Hendrickson et al. 2008; Hilimire 2011). Animals can provide additional sources of income while providing valuable ecosystem services such as soil fertility enhancement, pest control, and weed suppression (Pedersen et al. 2002; Bonaudo et al. 2014; Soares et al. 2022). Despite the potential benefits of this farming strategy, our search yielded only one article that evaluated the impact of animals on *C. dactylon*. Cosentino et al. (2020) evaluated the impact of grazing-laying hens on plant biodiversity in the ground cover of hazelnut (*Corylus* spp.) orchards in southern Italy. The study found that hens grazing had an effect on the composition of the herbaceous understory, with *C. dactylon* being one of the most consumed species. The relative abundance of this weed was reduced about 48% during grazing. These results suggest that integrating hens into fruit tree systems can be a promising alternative for controlling understory vegetation, while providing positive benefits to the overall production system. Considering these results and the limited knowledge in this area, more research is recommended to explore the use of animals, particularly herbivores, for the control of *C. dactylon* and other weeds in various agricultural environments. This research should encompass not only orchards and vineyards but also crop fields, where animals can be integrated into crop rotations to suppress weeds and enhance soil fertility before the cultivation of main crops, as experimented by Bilenky and Nair (2018).

3.3 Indirect weed control methods

3.3.1 Tillage

Tillage practices are commonly used to prepare soil for crop production by promoting soil decompaction and controlling weeds (Demjanová et al. 2009; Gruber and Claupein 2009; Brandsæter et al. 2017). During our search, we identified nine research articles that assessed the effects of different tillage practices on *C. dactylon* under open field conditions on five different continents, namely Asia (Subbulakshmi et al. 2009; Shahzad et al. 2016; Gu et al. 2019; Ul-Hassan et al. 2020), Africa (Phillips 1993; Abdullahi 2002), Europe (Valencia-Gredilla et al. 2020), North America (Johnson and Davis 2012), and South America (Guglielmini and Satorre 2004). These field experiments were conducted under different climates, including arid (Phillips 1993; Abdullahi 2002; Subbulakshmi et al. 2009; Shahzad et al. 2016; Ul-Hassan et al. 2020), subtropical temperate (Guglielmini and Satorre 2004; Johnson and Davis 2012), Mediterranean temperate (Valencia-Gredilla et al. 2020), and continental (Gu et al. 2019) climates. Except for one study (Gu et al. 2019), all experiments lasted for more than 2 years, which increases the credibility of the field results obtained. The available results suggest that tillage can significantly contribute to the control of *C. dactylon* compared to no-tillage treatments (Table 4). The results indicate that tillage with chisel or similar implements may be more effective in controlling *C. dactylon* than tillage involving the inversion of soil layers through mouldboard plowing, as higher inhibitions were observed with chisel or similar implements. However, we emphasize that this is not generally the case for other perennial weeds, for which chisel plowing may be less effective than mouldboard plowing (Gruber and Claupein 2009). Accordingly, Ul-Hassan et al. (2020), the only authors in our review who compared these two tillage treatments, found higher inhibition with mouldboard plowing than with chisel plowing. Therefore, the low inhibitions reported in other studies regarding tillage treatments involving the soil layer inversion may be attributed to variables specific to each study (e.g., edaphoclimatic differences, weed infestation level, and tillage depth), which make it difficult to compare results between studies. In addition to the type of equipment, the results also suggest that the frequency and timing of tillage can influence weed control, although this may be dependent on several factors such as field conditions and tillage implements. For instance, double mouldboard plowing was found to inhibit *C. dactylon* more than a single mouldboard plowing (Abdullahi 2002), and a mouldboard plow with tine cultivation in winter and spring inhibited *C. dactylon* more effectively than a double spring mouldboard plow with tine cultivation (Phillips 1993). Combining tillage with other practices, such as the use of cover crops, can enhance the inhibition of *C. dactylon* (Valencia-Gredilla et al. 2020), and further research in this area is warranted since this combination may help mitigate several issues associated with tillage, including soil erosion. Despite the inhibition results achieved with tillage treatments, it is important to consider that these treatments can contribute to the spread and dispersal of weed structures over the field. Guglielmini and Satorre (2004) quantified the effect of non-inversion tillage on dispersal, establishment, and colonization of *C. dactylon* (data not shown). The authors conducted two field experiments in different locations, both of which involved chisel plowed (30 cm deep), followed by two passes of a disk and straight-tined harrow (8 cm deep). According to the study, the tools used for non-inversion tillage dispersed vegetative structures of *C. dactylon* similarly in both experiments. The chisel plow first dragged patches in reduced fragments, and then, the disk and straight-tined harrow cut them into smaller vegetative units, dispersing propagules over the area. The overall dispersal highly depended on the original patch biomass, as higher patch biomass leads to a greater contact between *C. dactylon* vegetative structures and tillage tools, resulting in increased dispersal. Consequently, it is suggested that adopting no tillage or direct drill–cropping systems could greatly reduce the dispersal ability of the weed in the field. As for the establishment and colonization of *C. dactylon*, which was assessed in only one location, the authors reported poor establishment due to the desiccation of aboveground vegetative units, with newly established patches originating mainly from partially buried vegetative structures.

To sum up, tillage can be an effective strategy for *C. dactylon* control, but careful selection of equipment, frequency, and timing is crucial, considering that certain practices can contribute to weed dispersal. To mitigate these side effects and promote sustainable weed control, future research should explore the integration of tillage with other control methods, such as cover crops, considering the positive outcomes of these combined treatments in controlling other perennial rhizomatous grasses (Ringselle et al. 2018).

3.3.2 Mulching

Mulching is widely used management practice that helps conserve soil and water, while providing stable habitats for plant growth, by leaving crop residues or other materials on the soil surface (Derpsch 2003; Jordán et al. 2011). This practice has been shown to reduce weed pressure by physically impeding weed growth, while improving several soil properties (Bajorienė et al. 2013; Gu et al. 2016; Prosdocimi et al. 2016).

Our search identified eight research articles that focused on the application of mulch against *C. dactylon*. Seven of these studies were exclusively field experiments, while one study conducted both laboratory and pot experiments under

Table 4 Results' summary regarding tillage treatments on *C. dactylon*. The efficiency results were divided into percentage levels of inhibition. Whenever studies evaluated effects over more than one season/sampling period, the results refer to the data collected in the last season/sampling period studied—with the exception of the study by Johnson and Davis (2012) which presented data combined across years (n.c. means not considered; - - - means unaffected; - - means inhibition between 1 and 20%; - means inhibition between 21 and 40%; + means inhibition between 41 and 60%; ++ means inhibition between 61 and 80%; +++ means inhibition between 81 and 100%; GC means ground cover analysis through visual assessment; B means weed biomass; DW means weed dry weight; F means weed frequency; D means weed density; and RD means weed relative density).

Treatment	Control	Study duration	GC	B	DW	F	D	RD	Sources
Winter and spring mouldboard plow without tine cultivation	Single plow in spring	3 years	n.c.	n.c.	-	n.c.	n.c.	n.c.	Phillips (1993)
Double spring mouldboard plow without tine cultivation	Single plow in spring	3 years	n.c.	n.c.	-	n.c.	n.c.	n.c.	
Winter and spring mouldboard plow with tine cultivation	Single plow in spring	3 years	n.c.	n.c.	+	n.c.	n.c.	n.c.	
Double spring mouldboard plow with tine cultivation	Single plow in spring	3 years	n.c.	n.c.	-	n.c.	n.c.	n.c.	
1 mouldboard plowing/disk plowing followed by a disk harrow	No tillage	2 years	n.c.	n.c.	n.c.	n.c.	n.c.	++	Subbulakshmi et al. (2009)
Spring single mouldboard plowing	No tillage	2 years	- -	n.c.	n.c.	n.c.	n.c.	n.c.	Abdullahi (2002)
Spring double mouldboard plowing	No tillage	2 years	- -	n.c.	n.c.	n.c.	n.c.	n.c.	
Winter single mouldboard plowing	No tillage	2 years	- -	n.c.	n.c.	n.c.	n.c.	n.c.	
Winter double mouldboard plowing	No tillage	2 years	-	n.c.	n.c.	n.c.	n.c.	n.c.	
Mouldboard plow and 2 cultivations	3 cultivations with a cultivator	2 years	n.c.	n.c.	+	n.c.	n.c.	n.c.	Ul-Hassan et al. (2020)
Chisel plow and 2 cultivations	3 cultivations with a cultivator	2 years	n.c.	n.c.	-	n.c.	n.c.	n.c.	
2 cultivations with a tractor-mounted cultivator (20 cm)	No tillage	2 years	n.c.	n.c.	n.c.	n.c.	+++	n.c.	Shahzad et al. (2016)
2 cultivations with a tractor-mounted chisel plow (45 cm) and 2 cultivations with a tractor-mounted cultivator (20 cm)	No tillage	2 years	n.c.	n.c.	n.c.	n.c.	+++	n.c.	
2 cultivations with a tractor-mounted cultivator (20 cm) and a manual bed maker with soil layers inversion	No tillage	2 years	n.c.	n.c.	n.c.	n.c.	+++	n.c.	
Summer peanut digger	No tillage	2 years	n.c.	++	n.c.	n.c.	n.c.	n.c.	Johnson and Davis (2012)
Winter peanut digger	No tillage	2 years	n.c.	++	n.c.	n.c.	n.c.	n.c.	
Summer peanut digger followed by winter peanut digger	No tillage	2 years	n.c.	++	n.c.	n.c.	n.c.	n.c.	
Tillage of the topsoil layer to 20–30 cm with a spade	Chemical herbicide	≤ 1 year	n.c.	+++	n.c.	n.c.	+++	n.c.	Gu et al. (2019)
Chisel plow (20 cm) and spontaneous vegetation growing	Compared with itself, before and after the experiment	2.5 years	+++	n.c.	n.c.	+	n.c.	n.c.	Valencia-Gredilla et al. (2020)
Chisel plow (20 cm) and barley cover crop	Compared with itself, before and after the experiment	2.5 years	+++	n.c.	n.c.	++	n.c.	n.c.	
No tillage spontaneous vegetation ground cover managed by shredding	Compared with itself, before and after the experiment	2.5 years	- - -	n.c.	n.c.	- - -	n.c.	n.c.	

greenhouse conditions (Fahmy et al. 2012). The field experiments were conducted in four different continents, namely Africa (Abul-Soud et al. 2010), Asia (Thakur et al. 2012; Nadeem et al. 2013; Hossain et al. 2021), North America (Dalley et al. 2013), and South America (Ormeño-Núñez et al. 2008; Grisa et al. 2019). Among the studies conducted under real production conditions, four were conducted under the subtropical temperate climate (Thakur et al. 2012; Dalley et al. 2013; Grisa et al. 2019; Hossain et al. 2021), two under the Mediterranean climate (Ormeño-Núñez et al. 2008; Abul-Soud et al. 2010), and one under the arid climate (Nadeem et al. 2013). Regarding the type of mulching material applied, most of the studies examined how organic mulches affected *C. dactylon* growth ($n = 6$), while one study evaluated the effects of both organic and plastic mulches, and another study focused only on plastic mulches. The studies that assessed plastic mulching considered various plastic thicknesses (50 μm and 100 μm) and color types, such as black and white (Abul-Soud et al. 2010; Thakur et al. 2012). Plastic mulching proved to be very effective in inhibiting the growth of *C. dactylon* (Table 5). However, there were differences in inhibition between black and white plastics, with black plastics showing higher levels of inhibition compared to white plastics (nearly 100% to 79% of inhibition, respectively). This difference is likely due to the lack of penetration of photosynthetically active radiation in the black plastics. Since white plastics allow the passage of photosynthetically active radiation, it is understandable that this radiation would stimulate weed growth over time. Regarding the studies that evaluated organic mulching, the overall results also suggest high inhibition rates (Table 5) provided by the few tested species (rice, wheat, rye, pearl millet, mungbean, mustard, and sugarcane). However, the inhibition rates differ significantly between studies and treatments. Two studies found that organic mulching was totally ineffective against *C. dactylon* (Dalley et al. 2013; Hossain et al. 2021). Nonetheless, the remaining studies demonstrated high inhibition rates, including a case where high inhibitions were observed even when the amount of mulching applied decreased over time (Grisa et al. 2019). Another study found that there is a trend for the inhibitory effect to increase with increasing amounts of mulching applied, indicating that thicker organic mulch layers tend to provide better control of *C. dactylon*, by making it difficult for the weed to emerge at the surface (Thakur et al. 2012).

Overall, both plastic and organic mulching offer potential strategies for managing *C. dactylon*. However, the number of studies focusing on plastic mulching is limited, requiring further research to better understand its benefits, economic feasibility, and environmental impacts. For organic mulching, the results are more diverse due to the variety of materials, application rates, and other factors involved such as the form of application (some studies applied undetermined amounts, while other studies assessed the accumulation of organic mulching at specific rates). Future investigations should encompass a wider range of organic mulch sources and application rates, while considering the use of allelopathic materials to inhibit *C. dactylon* growth—as conducted by Fahmy et al. (2012), who applied the residues of *Pluchea dioscoridis* (L.) DC. to control *C. dactylon* (cf. Table 3).

3.3.3 Cover crops

Cover crops are crops that replace bare fallow during winter period and are plowed as green manure before sowing the next main crop (Poeplau and Don 2015). These crops can also be living mulches, planted either before or with the main crop and maintained as a living ground cover throughout the growing season (Hartwig and Ammon 2002). This farming practice provides several ecosystem services, such as soil conservation and weed suppression (Blanco-Canqui et al. 2015; Florence et al. 2019).

Our search yielded three studies reporting the use of cover crops against weeds, where *C. dactylon* is mentioned as a dominant or relevant weed. One study was conducted under controlled conditions in a pot experiment (Whitworth 1996), while the other two were field studies conducted in Europe (Valencia-Gredilla et al. 2020) and Asia (Ul-Hassan et al. 2020). Whitworth (1996) evaluated the effects of cover crops incorporated into the soil on the growth of *C. dactylon*. The weed was sown in pots where different cover crops (crimson, clover wheat, and rye) had previously been grown separately for approximately 5 months and then incorporated into the soil. The study found no statistical differences between *C. dactylon* grown in pots with cover crops incorporated and those grown in control pots without cover crops incorporated. Under real production conditions, Ul-Hassan et al. (2020) evaluated a wheat system followed by cluster beans (*Cyamopsis tetragonoloba* (L.) Taub. (Guar)) as green manure. Compared to a control treatment of wheat followed by fallow, the treatment with wheat followed by cluster beans as green manure exhibited slightly less *C. dactylon* biomass (about 6% inhibition) than the wheat control treatment followed by fallow. This suggests that a succession of cover crops may be a slightly better alternative to suppress the weed compared to fallow. In Europe, Valencia-Gredilla et al. (2020) assessed the effects of different ground cover strategies in the inter-rows of a vineyard over three growing seasons, to manage *C. dactylon* population dynamics, specifically evaluating changes in coverage and frequency. The authors compared two tilled treatments, one with spontaneous vegetation and the other with a barley (*Hordeum vulgare* L.) cover crop seeded, against two no-tillage treatments. At the end of the experiment, the barley cover crop treatment significantly reduced *C. dactylon* coverage and frequency by 93.9% and 73.3%, respectively, making it the most effective

Table 5 Results' summary regarding the plastic and organic mulching effects on *C. dactylon*. The efficiency results were divided into percentage levels of inhibition. Whenever studies evaluated effects over more than one season/sampling period, the results refer to the data collected in the last season/sampling period studied—with the exception of the study by Nadeem et al. (2013) which presented data combined across years (weedy check refers to a control treatment which allows weeds to grow without any intervention; n.c. means not considered; - - - means unaffected; - - means inhibition between 1 and 20%; - means inhibition between 21 and 40%; + means inhibition between 41 and 60%; ++ means inhibition between 61 and 80%; +++ means inhibition between 81 and 100%; GC means ground cover analysis through visual assessment; DW means weed dry weight; B means weed biomass; D means weed density; SSB means soil seed bank; WATr means weeks after transplanting; and WAT means weeks after treatment)

Treatment	Material	Control	Study duration	Data collection	GC	DW	B	D	SSB	Sources
Plastic mulch	Black polyethylene 50-µm sheet	Bare soil	2 years	8 WATr	n.c.	n.c.	+++	n.c.	n.c.	Abul-Soud et al. (2010)
	Black polyethylene 100-µm sheet	Weedy check	2 years	12 WAT	n.c.	n.c.	+++	n.c.	n.c.	Thakur et al. (2012)
	White polyethylene 100-µm sheet	Weedy check	2 years	12 WAT	n.c.	n.c.	++	n.c.	n.c.	
Organic mulch	Rice straw mulch (10.5 t ha^{-1})	Weedy check	2 years	12 WAT	n.c.	n.c.	++	n.c.	n.c.	Thakur et al. (2012)
	Rice straw mulch (15.5 t ha^{-1})	Weedy check	2 years	12 WAT	n.c.	n.c.	+++	n.c.	n.c.	
	Wheat straw mulch (6 t ha^{-1})	Weedy check	2 years	At harvest	n.c.	n.c.	n.c.	+	n.c.	Nadeem et al. (2013)
	Mowed foliage of rye grown in between grapevine rows stacked in the rows making mulching (amounts not specified)	Mowed rye left in between grapevine rows where it was grown	≤ 1 year	16 WAT	n.c.	+++	n.c.	n.c.	n.c.	Ormeño-Núñez et al. (2008)
		Chemical and mechanical interventions, without rye residues	≤ 1 year	16 WAT	n.c.	+++	n.c.	n.c.	n.c.	
	Pearl millet mulch (whole plant; 23.5 in the 1st year + 8.8 kg ha^{-1} in the 2nd year)	Weedy check	2 years	15 WATr	n.c.	n.c.	n.c.	+++	n.c.	Grisa et al. (2019)
	Pearl millet mulch (ground milled plant; 23.5 in the 1st year + 8.8 kg ha^{-1} in the 2nd year)	Weedy check	2 years	15 WATr	n.c.	n.c.	n.c.	+++	n.c.	
	50% standing mulch from previous crops in rotation (wheat, mungbean, mustard, monsoon rice, and winter rice; amounts not specified)	Rotation without mulching	2 years	After 2 years of rotation	n.c.	n.c.	n.c.	n.c.	- - -	Hossain et al. (2021)
	Sugarcane residues left in the field and repositioned (amounts not specified)	Residues removed	3 years	Summer of last season	- - -	n.c.	n.c.	n.c.	n.c.	Dalley et al. (2013)

treatment in the study. The tilled soil with growing spontaneous vegetation also inhibited coverage and frequency by 82.6% and 52%, respectively (cf. Table 4). Compared to tillage alone, tillage and barley together had a higher coverage inhibition (+11.3%) and a higher frequency inhibition (+21.3%), suggesting that barley cover crop may enhance the effects of tillage practice.

In summary, the reviewed studies suggest that cover crops can play a role in controlling *C. dactylon*, although the efficacy may vary depending on the specific cover crop used. More research is needed to evaluate the performance of different cover crops in diverse climatic regions and to explore their potential when integrated with other weed control methods. Given that cover crops offer multiple ecosystem services, their effectiveness in controlling *C. dactylon* deserves further investigation.

3.3.4 Crop rotation and crop succession

Crop rotation is a farming practice that involves growing different crops in recurrent succession and in definite sequence on the same field, as opposed to the continuous cultivation of the same crop (monoculture) (Sumner 2001). Weed management in monoculture systems can be challenging, since it exposes weeds to the same set of ecological and agronomic conditions, leading to increased weed resistance over time (Weisberger et al. 2019). Diversified and long crop rotations can be a potential alternative to disrupt weed population dynamics and contribute to reducing weed density (Anderson 2010).

Our search yielded one article mentioning the effects of crop rotations in *C. dactylon* (Hossain et al. 2021) and three articles applying crop successions against the weed under study (Subbulakshmi et al. 2009; Shahzad et al. 2016; Ul-Hassan et al. 2020). All studies were conducted under open field conditions in Asia.

Regarding crop rotations, a comparison between the effects of two different crop rotations in *C. dactylon* soil seed bank was conducted by Hossain et al. (2021). The authors conducted two field studies under wheat-mungbean-winter rice rotation and a less diversified rotation with monsoon rice-mustard-winter rice, over two growing seasons. After the field experiment, the soil seed bank of *C. dactylon* was evaluated at three different soil depths (0 to 5 cm; 5 to 10 cm; and 10 to 15 cm) in a shade-house experiment. On average, the rotation with wheat-mungbean-winter rice had a smaller *C. dactylon* soil seed bank compared to the less diverse monsoon rice-mustard-winter rice rotation (101 vs 165 seeds m^{-2}). This suggests that diversified rotations may have a negative impact on *C. dactylon* compared to less diversified rotations. The authors also emphasized that the crop rotation with wheat-mungbean-winter rice increased weed species diversity compared to the less diverse rotation, which may contribute to a less competitive weed community and overall farm sustainability (Storkey and Neve 2018).

Shahzad et al. (2016) evaluated the allelopathic effects of different crop successions combined with tillage practices on *C. dactylon*. The authors evaluated the following successions: rice followed by wheat, cotton followed by wheat, mungbean followed by wheat, and sorghum followed by wheat. As previously reported (Table 3), although the mungbean and cotton successions were not as effective in controlling *C. dactylon*, the cropping systems that included two species from the Poaceae family (rice and sorghum) had no *C. dactylon* plants during both years of the study. This suggests that incorporating allelopathic species in crop successions may help to control *C. dactylon*. Another study on crop successions evaluated the weed flora shift in a maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) succession during two cropping seasons (Subbulakshmi et al. 2009). The results suggested several changes in the weed flora composition, leading to an overall reduction in weed species. However, the relative density of *C. dactylon* increased during the experiment, particularly under zero tillage treatment, which greatly favored its growth. The authors emphasized that crop rotation plays an important part in controlling the composition and density of weed flora, especially in conventional tillage systems. Ul-Hassan et al. (2020) experimented a succession of wheat followed by cluster bean cover crop, during two growing seasons. As mentioned in the previous section, compared to a control treatment with wheat followed by fallow, the succession with green manure contributed to a slight reduction in *C. dactylon* biomass.

The results suggest that crop successions or rotations can help suppress *C. dactylon*. However, the results are limited to the Asian continent, arable crops, and mostly short- or medium-term successions. Future research should explore other regions and focus on long and diverse rotations rather than short- or medium-duration experiments. Additionally, identifying and considering crops with allelopathic effects, such as rice and sorghum, or crops that compete with *C. dactylon* for ecological resources would be beneficial in future research endeavors.

3.3.5 Intercropping

Intercropping can effectively suppress weeds by optimizing the use of ecological resources by the existing crops. In monocropping systems, crops often fail to use all available natural resources, such as light, water, nutrients, and space, leaving these underutilized resources available to weeds to grow and compete with crops with identical resource requirements. On the other hand, when intercropping crops with complementary needs (crops that will compete little or nothing with each other), the available ecological resources will be scarce to weeds' growth, leading to its suppression (Mousavi and Eskandari 2011).

In the course of our search, two studies were found evaluating such approach as a management treatment to control several weeds, including *C. dactylon* (Ossom 2010; Ul-Hassan et al. 2020). The study conducted by Ul-Hassan et al. (2020) in Pakistan, Asia, evaluated the effects of different tillage practices combined with the following cropping systems: (i) wheat monoculture followed by fallow as a control treatment; (ii) intercropping of wheat and brassica followed by fallow; (iii) intercropping of wheat and chickpea followed by fallow; and (iv) wheat followed by cluster bean, as green manure. Among these cropping systems, the control treatment (wheat monoculture followed by fallow) resulted in the highest biomass of *C. dactylon*. In contrast, the intercropping system of wheat and brassica exhibited the lowest biomass of *C. dactylon* (about 20% inhibition), followed by wheat and chickpea intercropping system (about 12% inhibition). In Swaziland, southern Africa, Ossom (2010) assessed the relative abundance of *C. dactylon* under different intercropping systems of maize and sweet potato, evaluating five different cropping variations during one growing season, namely (i) maize monoculture (40,000 plants/ha), (ii) sweet potato monoculture (16,666 plants/ha), (iii) sweet potato monoculture (33,333 plants/ha), (iv) maize (40,000 plants/ha) intercropped with sweet potato (16,666 plants/ha), and (v) maize (40,000 plants/ha) intercropped with sweet potato (33,333 plants/ha). The results showed that intercropping maize with sweet potato at both low and high densities resulted in a relative abundance of *C. dactylon* of 20.4% and 15.7%, respectively. Comparatively, the relative abundances of *C. dactylon* in the maize monoculture and low-density sweet potato were similar (16.4% and 22.9%, respectively), while the denser sweet potato system alone showed the highest relative abundance of *C. dactylon* (43.6%) among all treatments. Intercropping maize with sweet potato at both low and high densities reduced the relative abundance of *C. dactylon* by 53% and 64%, respectively, compared to the high-density sweet potato monoculture. These results suggest that intercropping maize with sweet potato can reduce the relative abundance of *C. dactylon*, compared to high-density sweet potato monoculture, while maintaining similar abundances as maize monoculture.

Future studies should consider optimal crop density combinations that not only address *C. dactylon* control but also take into account the economic factors, farmer and market requirements, environmental conditions, and crop complementarity.

3.3.6 Crop competition

An alternative approach to improve the use of natural resources by crops is to narrow the spacing between rows and increase crop density without compromising crop yield. This increase in density results in enhanced crop competition against weeds (Boerboom and Young 1995; Datta et al. 2017).

Two studies have evaluated this method against *C. dactylon*, namely a study focused on evaluating soybean (*Glycine max* L.) row spacing effects on weed population dynamics, in Nigeria, West Africa (Daramola et al. 2020); and a study simulating the effects of light competition on *C. dactylon* spatial growth, taking into account previous soil cultivation effects (Guglielmini and Satorre 2004). Daramola et al. (2020) evaluated the effects of three different soybean row spacing (50, 75, and 100 cm) on *C. dactylon* density and biomass during two growing seasons. The treatment with the highest crop density and consequently the strongest crop competition (50 cm of row spacing) reduced both *C. dactylon* density and biomass with subsequently higher soybean dry matter, seed yield, revenue, and marginal returns compared to 75 and 100 cm row spacing. The density and biomass of *C. dactylon* increased as crop density decreased in both growing seasons, suggesting that crop competition was effective in controlling *C. dactylon* under the studied conditions. These results are consistent with the results of Guglielmini and Satorre (2004), who suggest that crop competition may contribute to *C. dactylon* control. The authors quantified the effect of non-inversion tillage on dispersal, establishment, and colonization of *C. dactylon* in experimental fields in South America. Following the experimental work, a simple model was proposed considering soil cultivation effects and light availability on spatial growth of *C. dactylon* patches, under two environmental conditions without other constraints, namely sunny conditions, considering a full daylight environment, and shaded conditions, considering an environment with 85–87% shading. The results indicated that, under the studied conditions and based on the simulation, the total area invaded by *C. dactylon* in a situation without crop competition and under full solar radiation would be 180 m^2 and 109 m^2 under high shading condition, out of 900 m^2 in the total field. The authors suggest that utilizing crop competition for light could create unsuitable habitats limiting weed colonization.

Crop competition shows promise as a strategy for managing *C. dactylon*. However, our understanding is currently based on a limited number of studies and specific crops. Additional research is needed to investigate the advantages and constraints of adjusting row spacing and crop density, taking into account crop-specific needs, regional variations, and the economic and practical considerations for farmers.

4 Knowledge gaps and further research

Based on this systematic review, the following knowledge gaps were identified, leading to specific recommendations for future research:

1. More than half of the knowledge is limited to experimental model system conditions (57%). More research

under real production conditions is recommended to understand the potential of treatments in field settings and ensure that this knowledge is useful to farmers.

2. Most of the field experiments have taken place on the Asian continent, under temperate subtropical and arid climates. Further research is recommended on other continents and climate systems where *C. dactylon* is also often a problematic weed.
3. Only 50% of the studies evaluated the effect of treatments on weeds and crops simultaneously. Future research should consider crop productivity as a key focus, as it is a primary goal in agroecosystems.
4. Most research on mechanical and thermal treatments has been conducted in the last decade. There is a clear need to optimize treatments and understand their long-term effects on *C. dactylon*—e.g., evaluating modern types of mechanical treatments and mechanical tools/implements that can be applied by farmers (e.g., the Kvik-up cultivator); and optimizing thermal treatments already studied under controlled conditions and experimenting untested treatments, such as flame weeding.
5. Studies focused on allelopathy stood out significantly throughout the review process (50% of the papers found focus on allelopathy). However, only a minority of studies on allelopathy consider real production scenarios. More research should be conducted to understand in detail how allelopathic species can be used/optimized to effectively control *C. dactylon*.
6. Animal weed control shows promise as a farming strategy, but only one study was found evaluating such practices, in an orchard with laying hens. More research is recommended that focused on different animal species, namely herbivores, and in other farming systems, such as crop fields.
7. Among indirect treatments, tillage has been the most studied over time. However, considering the side effects of intensive and frequent tillage and the possible spread of weeds throughout the field by some implements, more research is recommended to mitigate these effects by combining tillage treatments with other agricultural practices, such as the use of cover crops.
8. Organic mulching treatments showed high inhibition values in several cases, but the inhibition rates differed significantly between studies and treatments. Future research should cover a wider range of organic mulch sources and identify optimal application rates for each material, while considering the use of allelopathic species to inhibit *C. dactylon* growth.
9. Crop rotation, crop succession, intercropping, and crop competition have been more explored in the past two decades, but the studies are still scarce (less than 5 studies per type of treatment). More research should be conducted to evaluate these methods in the future, considering that these practices can contribute to *C. dactylon* control, especially when combined with other control methods.

5 Conclusions

Cynodon dactylon is one of the world's worst weeds, affecting many crops, in different countries and climate systems. Its high dispersal ability, high establishment ability, and high tolerance to chronic disturbance make it one of the most difficult weeds to control. In the past decades, the development of chemical herbicide-resistant weeds has threatened the productivity of farming systems which rely on herbicide inputs to control weeds, while contributing to several environmental problems. Initiatives such as the European Green Deal have emerged to address these sustainability concerns, which require further research. Within this context, this review assessed the most commonly studied alternative control methods of *C. dactylon* published in 56 research articles, over the past 50 years.

The review findings indicate that several direct and indirect weed control methods have shown high potential to control *C. dactylon* in specific regions and climates around the world. Allelopathy and mechanical treatments have been the most studied and have shown positive results in the control of this weed. However, in general, there is a great need to understand and deepen the knowledge of many treatments in different production contexts. Modern techniques and integrated approaches may pave the way for effective management of *C. dactylon* across diverse agricultural systems, but more research is needed.

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