



Eco-biology, impact, and management of *Sorghum halepense* (L.) Pers.

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Abstract *Sorghum halepense* (L.) Pers. is ranked among the worst and extensively disseminated weed species. It is emerging as a potential menace for agroecosystems in 53 different countries across the world. This weed is adapted to warmer regions and is native to Mediterranean areas of Africa, Asia, and Europe. In the mid-1900s, cultivation of this weed species as a potential forage crop resulted in its escape from crop fields and invasion of agricultural and natural areas, but in some European countries, it has been introduced deliberately (e.g., as contamination of seeds and soil). *S. halepense* interferes with

economically important agronomic and horticultural crops and cause 57–88% yield losses. Herbicide tolerance, diverse propagation mechanisms, rapid development, and strong competitiveness are key attributes in its invasion. Conventional management approaches are limited in their scope to control this weed due to its rapid vegetative growth and increasing herbicidal tolerance. Integration of chemical methods with cultural or mechanical approaches is important for restricting its future spread to non-infested areas. This review provides insights into the invasion mechanisms of *S. halepense*, which will help in its

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management. A better understanding of ecobiological aspects, survival mechanisms, and genetic variabilities of *S. halepense*, within a wide range of environmental conditions, will assist in designing more effective management strategies for this serious invasive weed. Collaborative research between the various countries impacted by this weed will assist in developing efficient, sustainable, and economical approaches to restrict its invasion in new areas.

Keywords Johnson grass · Impact · Competition · Allelopathy · Weed management

Introduction

Sorghum halepense (Pers.) L. (Johnsongrass), in the Poaceae family, is a C₄ perennial graminoid plant species and is among world's most persistent weeds (Holm et al. 1997). It is distributed over one-third of the total global area, causing significant losses to agriculture and natural biodiversity in Asia, Africa, America, and Europe (Chirita et al. 2007). *S. halepense* is ranked as the world's sixth worst weed, infesting 30 different crops in 53 countries, and is widely naturalized over millions of hectares globally (Valverde and Gressel 2006). Initially, it was introduced as a perennial forage crop; however, its invasive and persistent nature has caused it to become troublesome to agricultural production (Hoffman and Buhler 2002; Binimelis et al. 2009).

Sorghum halepense is well known for its damaging impacts on the growth and development of neighboring plants through its strong competitive abilities and allelopathic potential (Novak et al. 2009; Huang et al. 2015). It has been widely reported in cropped areas, causing severe yield losses in economically important crops including wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), vegetables, and fruits (Mitskas et al. 2003; Uludag et al. 2007; Uremis et al. 2009). It acts as an alternative host to several insects, pathogens, and nematodes, which significantly affect crop production (Vega et al. 1995). In addition, grazing on *S. halepense* exerts a harmful effect on cattle, sheep, and horses during frost and drought, when the weed has a high cyanide content (Henderson 2001).

Diverse modes of propagation, fast-growing nature, crop mimicry, and adaptation to extreme climatic variabilities allow *S. halepense* to thrive in varying environments and ecological niches (Mihovsky and Pachev 2012; Vila-Aiub et al. 2013). These characteristics in the biology of *S. halepense* have raised its status as a difficult-to-control weed and also affects the of intercultural operations efficacy for controlling *S. halepense* in different crops (Dalley and Richard 2008; Heap 2014). Chemical control of this weed species has become challenging due to the evolution of herbicide resistance, particularly against glyphosate (Rosales-Robels et al. 1999; Johnson and Norsworthy 2014). Despite continued use of post-emergence (POST) control measures, *S. halepense* has proved troublesome in extensive cropping systems across the world (Acciaresi and Chidichimo 2005; Johnson and Norsworthy 2014). Evolutionary changes within the species, resistance to herbicides, and tolerance against cultivation practices are thought to have fostered its widespread distribution within an agroecosystem (Clements and DiTommaso 2011).

Information on the biology, ecology, and agricultural impact of a weed species are necessary to increase the sustainability of control strategies (Chauhan 2012; Chauhan and Johnson 2010). Alternation in crop management practices, improved mechanical approaches, diverse chemical-based techniques, biological agents, allelopathy, and their integration, are possible options for the control of this invasive weed in cropping systems (Chauhan 2012). This review summarizes the current state of information on the biology and ecology, invasion history and current distribution of *S. halepense*, its impact on agriculture and management options. The review identified potential research gaps and complexities in the reproductive biology, interference, invasion, and resistance mechanism of this weed, to reform deficiencies in the current management approaches.

Global distribution

Sorghum halepense is native to Mediterranean regions of Africa, Asia, and Europe and is a top-ranked weed in many tropical and subtropical areas in the world (McWhorter 1989; Holm et al. 1997). It is naturalized in Africa, Europe, North America, and south-western Asia, as well as in Argentina, Brazil, and northern

Australia (Table 1; Groves 1991). This weed species has been reported as most problematic weed in many countries across Asia, including Afghanistan, Bangladesh, China, India, Indonesian, Iran, Israel, Japan, and Pakistan (Holm et al. 1997). In the 1800s, it was introduced from Turkey to South Carolina, and Argentina as a potential forage crop and pasture grass (Anderson 1999). Unfortunately, it escaped from cultivation and has become the most invasive plant species in Southeast America, Central California, and New Mexico (Mcwhorter 1989). By 1900, its utilization for agricultural production was restricted due to its increasing invasiveness and continuous spread as an invasive weed (Binimelis et al. 2009). It has been documented as a serious invasive weed of numerous important crops in 22 of 50 states of United States; ranked as the 18th most troublesome and noxious weed of soybean in the US southern states (Gressel 2005; Webster and Nichols 2012). This weed is now invading ecosystems grassland (non-agricultural) and is listed a major invasive species of natural areas in 16 states (Quinn et al. 2013). Evidence from the genetic analyses indicated two geographically distant introductions of divergent genotypes spreading across the US in less than 200 years (Sezen et al. 2016). This genotyping provided the evidence for a habitat switch

from agricultural to non-agricultural systems, and may also contributed in the ubiquity and aggressiveness of *S. halepense* in US.

In the last decade, researchers reported the spread of this serious invasive weed in agricultural habitats in Europe (Weber and Gut 2005). *S. halepense* is widely established as a serious weed in south-eastern and southern European countries, and is frequently found in agricultural fields of Austria and Slovenia (Weber and Gut 2005). It is adapted to warmer regions, indicating the influence of climatic change on its possible spread (Novak et al. 2009). A recent study has revealed that *S. halepense* habitat affiliation seems to have changed, and its distribution has increased to other areas of central Europe (Follak and Essl 2013). The majority of the grain maize and oil-pumpkin areas (*Cucurbita pepo* L.) of southern Austria are not currently invaded by *S. halepense* (Follak and Essl 2013). However, it is likely that, as oil-pumpkin and maize areas have expanded in recent years, further spread of *S. halepense* is possible in southern Austrian fields. Using a niche-based habitat modeling approach, under moderate climatic change scenarios temperatures will rise so that all the main agricultural areas of Europe will become ecologically suitable for *S. halepense* by 2050 (Kleinbauer et al. 2010).

Table 1 Introduced and native countries of *Sorghum halepense* in different continents

Continent/region	Countries	Status
Asia	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, India, Iran, Iraq, Israel, Jordan, Kazakhstan, Kyrgyzstan, Lebanon, Oman, Pakistan, Saudi Arabia, Syria, Turkey, Turkmenistan, Uzbekistan	Native
	China, Indonesia, Japan, Korea, Nepal, Philippines, Sri Lanka, Taiwan, Tajikistan, Thailand	Introduced
Africa	Benin, Malawi	Unknown
	Morocco, Mozambique, Namibia, Senegal, South Africa, Swaziland, Tanzania	Introduced
	Egypt, Libya	Native
North America	Canada, Mexico, USA	Introduced
Central America and the Caribbean	Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Honduras, Jamaica, Nicaragua, Panama, Puerto Rico	Introduced
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, French Guiana, Paraguay, Peru, Uruguay, Venezuela	Introduced
Europe	Albania, Austria, Bosnia-Herzegovina, Bulgaria, Denmark, France, Hungary, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Russia, Spain, Switzerland, UK, Ukraine	Introduced
	Croatia, Greece	Unknown
	Southern Russia, Serbia	Native
Oceania	Australia, Cook Islands, Fiji, Guam, Marshall Islands, New Caledonia, New Zealand, Palau, New Guinea, Pitcairn Island, Samoa, Solomon Island, Tonga, Vanuatu, Wallis and Futuna Islands	Introduced

In Australia, *S. halepense* is reported as an invasive weed in crops and pastures, occurring mainly in temperate to tropical regions (Parsons and Cuthbertson 2001; Jacobs et al. 2008). In 1871, *S. halepense* was first grown as a potential fodder plant at the Adelaide botanical gardens, South Australia, and first naturalized in New South Wales during the year 1883 (Parsons and Cuthbertson 2001). During the last quarter of a century, it has become a severe environmental threat in some parts of Australia, where it is associated with summer cropping systems and increased summer rainfall. In high rainfall regions, it has invaded arable lands and covered whole paddocks in dryland and irrigated areas of New South Wales, Victoria, Queensland, Western and South Australia (Parsons and Cuthbertson 2001; Sharp and Simon 2002). In recent years, it has spread into previously non-infested parts of the Northern Territory, Tasmania, and the Australian Capital Territory (Navie 2004).

Investigations regarding the invasion history of this alien weed species can provide valuable insights into the spatiotemporal patterns and spread dynamics of this weed species, which will assist in identifying the underlying invasion mechanisms and provide evidence for the potential spread of this weed in the future (Essl et al. 2009; Bajwa et al. 2016). In particular, in developing strategies to restrict the future spread of *S. halepense*, it is prerequisite to consider how the weed is spread. Transport of seeds and rhizomes from field to field should be avoided by cleaning machinery and harvesting equipment. Small infestations should be eradicated mechanically by discarding *S. halepense* plants together with its rhizomes, and this practice needs to be repeated over several years to prevent rhizome-fragments' re-sprouting.

Eco-biological prospects

Morphological attributes

Sorghum halepense, a cosmopolitan perennial grass species in the Poaceae family, has numerous erect stems arising from extensively creeping rhizomes, which have fibrous roots at the nodes (Felger 2000). The leaf blades are glabrous, large, and flat with a prominent whitish midvein at maturity, and a ribbed sheath with smooth, overlapping margins.

Inflorescences of *S. halepense* are open, and the terminal panicles are usually large and densely flowered, with flowers opening from the base to the top in an ascending pattern. The fertile spikelets are appressed-silky, awned, ovate, and 4.5–6 mm long, occurring in pairs on short branches, and producing a long, oval, reddish brown seeds (Felger 2000). *S. halepense* is tetraploid ($2n = 40$), which means it is able to cross with annual sorghum ($2n = 20$) (Hoffman and Buhler 2002). It can easily form hybrids with other *Sorghum* species, particularly with *S. bicolor* (Anderson 1999). Therefore, it is believed that *S. halepense* ecotypes are widely distributed across the world, with differing ecological, morphological, physiological, phenological, and genetic characteristics (Anderson 1999; Essl et al. 2009). The ability to hybridize with other sorghum species might be a key invasive attribute of this serious weed, which help *S. halepense* to develop ecotypes that are more tolerant to extreme climatic conditions, and resistant to different herbicides; need to be investigated.

Habitat and climatic requirements

Sorghum halepense is well adapted to warm, humid, rainfed regions of the subtropics, preferably semi-arid and sub-humid climates (Newman 1993). The emergence of new ecotypes enables it to extend its habitat in tropical and temperate climates between the latitudes 55°N–45°S. *S. halepense* possesses the ability to survive under drought, while also tending to be more productive during the rainy season (Hutchison 2011). Maximum growth of *S. halepense* in temperate zones was observed at 32 °C after 12 weeks, and minimum growth was observed at 40 °C (McWhorter and Jordan 1976a). It usually requires an annual rainfall of 500–700 mm, and day temperatures of 27–32 °C for optimal growth (Hutchison 2011). However, newly emerged ecotypes of *S. halepense* have become increasingly tolerant of cold conditions, demonstrating an ability to survive at temperatures as low as –10 °C (CDFA 2002). Rhizomes of *S. halepense* near the soil surface can hardly survive for more than three days at high temperatures between 50 and 60 °C (CDFA 2002). It can grow on a wide range of soil types; but grows best on porous, fertile lowlands, and is least adapted to poorly drained clayey soils (Uva et al. 1997). Rhizomes of *S. halepense* penetrate more deeply into

light textured soils; up to 7–12 cm in sandy loam soil, compared with 5–7 cm in clayey soil (Warwick and Black 1983). It is mostly associated with moist sites, such as along irrigation canals, cultivated fields, field edges, orchards, and pastures (Holm et al. 1997; Chambers and Hawkins 2002). In Arizona, it has been reported as a riparian weed in the Sonoran Desert, although it prefers moist sites in urban areas (Martin 2002). The ability of *S. halepense* to survive in diverse ecological habitats poses a significant threat to agronomic and horticultural crops across the globe.

Reproductive biology

Sorghum halepense reproduces through seeds and rhizomes (Uddin et al. 2010; Mihovsky and Pachev 2012). It reproduces freely from seed in moist areas, usually overwinters as rhizomes or seeds, and can rapidly colonize a wide range of habitats within different agroecosystems (Martin 2002). *S. halepense* is primarily self-pollinated, however, some wind-pollination may occur when plants are spread far apart (Warwick and Black 1983). The seeds usually germinate slightly after the rhizome sprout, and require temperatures to be approximately 10 °C higher than is required for rhizomes to sprout (Newman 1993). Seed production has the greatest potential for the establishment and spread of *S. halepense* (Keeley and Thullen 1979), and timely control measures throughout the season are needed to prevent its seed production. Sexual and asexual reproduction in *S. halepense* occurs simultaneously; however, asexual reproduction through rhizomes has received more attention (Barroso et al. 2016). In an established *S. halepense* population, most of the plant growth is associated with asexual regeneration through rhizomes as the primary mean of its dispersal in the field (Holm et al. 1997; Mitskas et al. 2003).

Multiple dormant genes control rhizome expression in this weed species, showing different rhizome formations in *S. halepense* and its ecotypes (Yim and Bayer 1997). A single plant of *S. halepense* has the potential to produce 60–90 rhizomes per m⁻² per growing season in cropland and wasteland sites, and is capable of producing 94–229 nodes and up to 5200 internodes after 10 and 18 weeks of growth, respectively (McWhorter and Jordan 1976b). Rhizomes of *S. halepense* possess the ability to withstand frequent desiccation, and produce longer

fragments which are more tolerant than shorter ones (McWhorter and Jordan 1976b). Apical dominance in terminal buds allows rhizomes to regenerate easily once chopped into fragments during cultivation, initiating sprouting of axillary buds located at nodes on the rhizomes (Warwick and Black 1983; Holm et al. 1997). Scientists have reported that above-ground parts of *S. halepense* are susceptible to frost and freezing damage in fall and early winter, but rhizomes generally survive at deep soil burial depth to which freezing temperatures cannot penetrate (Anderson 1999). Stout stems and seedheads of *S. halepense* can withstand cold climates (Uva et al. 1997). As mentioned previously, rhizomes have the ability to resist frequent desiccation, which might be the possible reason, which limit the success of contact herbicides, creating an obstacle to chemical management of *S. halepense*.

Seed dormancy and germination

Seed dormancy is recognized as a key factor in the persistence and successful establishment of *S. halepense* in cropping systems (Arnold et al. 1992; Mohammadi et al. 2013). Freshly harvested seeds are highly dormant, and can remain viable for 25 years (Egley and Chandler 1978). The seeds are not capable of germinating during the season they are produced, although they germinate readily in the subsequent season as their after-ripening period lasts for 4–5 months (Holm et al. 1997). Seeds usually remain dormant when dispersed, but seed dormancy may vary between *S. halepense* ecotypes (Monaghan 1979). It is hypothesized that mechanical dormancy exists in the seeds, as the seed coat contains tannins which ultimately reduce water permeability (Bennett 1973). Additionally, glumes attached to after-ripened seeds are associated with residual dormancy. Removal of these glumes, covering 20–40% of *S. halepense* seeds, can release 95% seeds from dormancy (Holm et al. 1997). Also, dormancy can be overcome by the stimulatory effect of alternating temperature regimes, particularly 30/20 °C (Arnold et al. 1992). Hamada et al. (1993) reported chemical-type seed dormancy in *S. halepense*, due to chemical substances present outside or inside the embryo that inhibit seed germination. During summer, seed exposure to high temperature and light regimes was effective in breaking seed dormancy in *S. halepense* (Podrug et al. 2014).

Treatment of seeds with sulfuric acid (H_2SO_4), and seed immersion in water, have also been shown to break seed dormancy in this species (Dikic et al. 2011, 2014; Podrug et al. 2014). Moreover, pre-treatment of seeds with H_2SO_4 , or glume removal along with distilled water, was more effective in breaking dormancy than potassium nitrate (KNO_3) treatment (Mohammadi et al. 2013). More research is required on seed dormancy and longevity patterns that enable *S. halepense* to adapt to various environmental conditions, so as to understand the weediness potential of this species, and also to design appropriate management strategies.

Seed germination responses of *S. halepense* were reported to be directly influenced by temperature and light availability (Shou-hui et al. 2008; Krenchinski et al. 2015). Seeds germinate best at an alternating day-night temperature of 35/25 °C (Shou-hui et al. 2008), with an optimum temperature range of 25–30 °C (Yazlik and Uremis 2015). It was observed that germination was enhanced at 30–40 °C when seeds of *S. halepense* were allowed to germinate under light conditions (Podrug et al. 2014). Studies of seedling emergence in *S. halepense* have demonstrated tolerance to deep burial depth (Benvenuti et al. 2001; Podrug et al. 2014). Soil depths of 0–4 cm were ideal for *S. halepense* emergence; with maximum emergence of seeds placed at 1 cm, gradually decreasing with increased burial depth (Toth and Lehoczky 2005; Shou-hui et al. 2008; Podrug et al. 2014). About 5% of seedlings emerged from the burial depth of 10 cm, but no emergence occurred from seeds buried at more than 10 cm due to depth-imposed dormancy; a survival strategy allowing seed bank perpetuation (Benvenuti et al. 2001). However, in other studies, about 25% of seed germinated from the depth of 15 cm, and 58% emerged from 10 cm (Toth and Lehoczky 2005; Concenco et al. 2012). In another study, *S. halepense*, despite its small seeds, was able to emerge from deep burial depths of 20 and 25 cm, with a germination percentage of 30 and 6%, respectively (Toth and Lehoczky 2005). Seed age of *S. halepense* was not found to influence germination; with old seed having a higher germination percentage as compared to new seed (Dikic et al. 2011; Podrug et al. 2014). The varying responses of this weed towards environmental factors are considered to be key elements in its successful adaptation and spread within diverse agricultural and natural ecosystems.

Seed longevity

Seeds of *S. halepense* remain viable for up to 2 years when buried at 22-cm soil depth (Concenco et al. 2012). However, Looker (1981) recorded seed viability up to 50% even after 5 years of burial. Moreover, seeds stayed viable after passing through the digestive tract of cattle (Rahimi et al. 2016), and also after 7 years of dry storage (Holm et al. 1997). Through regeneration from rhizomes, *S. halepense* can survive extreme temperatures, as its rhizomes can easily reach protected depths of 20 cm or more. Investigation into seed viability at different burial depths, and seed bank dynamics under diverse environmental scenarios, is required to limit the further spread of *S. halepense* in the tropics and sub-tropics. Appropriate measures should be applied in a timely manner in order to minimize its vegetative reproduction and seed dispersal. Furthermore, manipulation of agronomic practices should be considered in order to destroy its dormant fragments as well as to manage the seed bank at different seed burial depths.

Rhizome sprouting

Plants emerged from rhizomes are more competitive and problematic as compared to seedlings, due to earlier emergence and more rapid growth (Mitskas et al. 2003). The minimum, optimum and maximum temperatures for emergence of *S. halepense* rhizomes are 20, 25–30, and 40 °C, respectively (Yazlik and Uremis 2015). It has been reported that high temperatures suppress the vegetative propagules of *S. halepense*, and negatively influence rhizome sprouting (Podrug et al. 2014). Its rhizomes usually respond to increasing temperature, with 14% sprouting at 15 °C, increasing up to 82 and 92% at 23 and 30 °C, respectively (Warwick and Black 1983). Balanced light duration of 12 h light and 12 h darkness produced maximum shoot length (71 mm) and increased the sprout production ratio by 57% as compared to darkness (Yazlik and Uremis 2015).

Dispersal mechanisms

Seeds usually disperse through infructescence shatter (dropped near to parent plants), and may achieve long-distance dispersal through water, wind, animal ingestion, grain and hay contamination, or attachment to

animal fur and farm equipment (Holm et al. 1997). Most ecologists believe that seeds of *S. halepense* are capable of surviving partial digestion by birds, which permits long distance seed dispersion, helping to colonize new environments (Holm et al. 1997). In addition, contamination of crop seeds with *S. halepense* seed is another effective distance dispersal mechanism. From a source population, maize harvesters can disperse *S. halepense* seeds up to 50 m (Ghersa et al. 1993). However, *S. halepense* can also regenerate from chopped fragments of rhizomes (see chapter 3.3.) (Warwick and Black 1983; Holm et al. 1997). These fragments can be easily moved through becoming attached to vehicles, machinery, humans and animals, and can also be transported by flowing water. Furthermore, use of *S. halepense* for forage encourages its further spread in numerous agroecological zones (Chambers and Hawkins 2002). In agroecosystems, extensive crop monoculture, and widespread ineffective use of herbicides, are considered to be the main reasons for the expansion of *S. halepense* (Novak et al. 2009). However, its expansion in cooler regions seems to be limited due to climatic constraints, partly due to its frost sensitivity and high thermal growth optimum.

Ecological impact

Sorghum halepense, a globally invasive allelopathic-grass species, resists displacement when established due to its high N-demands and strong allelopathic potential, which significantly affects the biogeochemistry of the invaded area soil (Holm et al. 1991; Bais et al. 2006; Rout et al. 2013). These species has competitive advantage over native species, particularly in systems in which invading species already become well established (Rout et al. 2013).

Displacing natural flora

Dense monocultures and strong allelopathic potential of this weed species has been reported to create significant impact in displacing native flora under natural landscapes (Rout and Callaway 2009; Rout et al. 2013). As stated earlier, rhizomes growth continues throughout the year and ramets erupts in the spring, which contributes to dense clonal monocultures. In natural habitat, the consumption of plant material of this

weed is minimal as its leaves contain cyanide in the dhurrin, which is toxic to herbivores when crushed (Nielsen and Moller 1999). In addition, sorgoleone and its derivatives are continuously exuded from the root hairs (Czarnota et al. 2003a, b). *S. halepense* exposure to freezing temperature results in plant senescence at which culms fall, leaving a thick and dense mat of litter on the soil surface (Mcwhorter 1981). Most of the water-soluble chemicals and nutrients leaches into the surrounding soils in areas receiving high rainfall; however, water-insoluble phenolic, referred as allelochemicals, usually released from the plant after decomposition (Weston et al. 1989).

Dhurrin influences the plant growth through causing cyanide toxicity (Halkier and Moller 1989). Cyanide inhibits the mitochondrial cytochrome oxidase, which blocks the electron transport chain and hinders the oxygen metabolism at cellular level. In addition to this, several derivatives of dhurrin (e.g., p-hydroxy benzoic acid) has also been identified as phytotoxic (Weston et al. 1989). Despite persistence for months in the soil, sorgoleone also targets the respiratory pathways and inhibits photosynthesis, enzymes synthesis, mitochondrial respiration, solute and nutrient uptake in the plants (Rimando et al. 1998; Meazza et al. 2002; Czarnota et al. 2001; Hejl and Koster 2004; Weidenhamer et al. 2009). Recently, Rout et al. (2013) reported that native little bluestem (*Schizachyrium scoparium*) treated with leachates of invasive *S. halepense* significantly reduced the plant biomass and produced few inflorescence. Unfortunately, limited information is available in term of relationship between the growth stage and their chemical properties on the invasion mechanism and persistence of *S. halepense* under natural landscape.

Altering soil biogeochemistry

Bais et al. (2006) reported that *S. halepense* is a successful invader with high N-demands, causing significant impact on the biogeochemistry of invaded soils. However, Rout (2005) reported that this weed can established and expanded rapidly across the southern portion of USA, even in exceptionally N-poor soils. It seems self-contradictory that this highly productive grass species can persist and expand in N-poor soils. Comparison with large above-ground biomass and high abundance suggested that *S. halepense* possess the ability to alter the N-availability

and N-cycling in invaded areas (Rout 2005). This dramatic differences between the native and invaded prairie hypothesized that this invasive grass may harbor N₂-fixing bacteria (Rout and Callaway 2009). Nitrogenase activity of the isolated bacteria showed their capability to fixing N₂, which was carried out in the rhizomes and roots of this plant. In addition, several closely matching bacterial isolates, such as plant growth-promoting bacteria, were also involved in enhancing the *S. halepense* ability to invade and persist through changing the fundamental ecosystem properties through altering the soil biogeochemistry. More investigations on the plant-microbial mutualism will help in understanding the invasive mechanism of *S. halepense* and its competitive advantage over native plant communities.

Impact on agriculture

Competition with crops

Sorghum halepense has been reported on a very large-scale, occurring in many field crops (e.g., cotton, maize, wheat, and vegetables) across multiple continents (Gunes et al. 2008). Early sprouting and rapid growth of its rhizomes enables *S. halepense* to expand and cover large spaces, displacing desired on-site plants (Holm et al. 1997). This ultimately results in higher photosynthetic activity due to increased surface area, enabling it to compete more efficiently with neighboring seedlings of desired crops. In addition, the extensive and deep network of rhizomes and roots utilizes available nutrients and water from the soil, which are thus unavailable to crops (Newman 1993). As well as through limiting moisture and nutrient availability, release of toxic allelochemicals by *S. halepense* diminishes the ability of neighboring crop plants to establish, and decreases their yield potential (Mitskas et al. 2003; Gunes et al. 2008; Novak et al. 2009). Under water stress conditions, its rhizomes are more adaptable and competitive than crops because of its ability to increase root biomass and length, which helps in water extraction and attaining a high growth rate (Acciaresi and Guiamet 2010). Season-long competition of *S. halepense* at a high density can reduce the average yield potential of cotton (70%), maize (88–100%), sugarcane (up to 69%) and soyabean (59–88%) (Williams and Hayes

1984; Bridges and Chandler 1987a; Mitskas et al. 2003; Dalley and Richard 2008; Barroso et al. 2016). In Central Europe, *S. halepense* is predominantly found in maize and oil-pumpkin, putting 17,635 and 6160 ha cultivated areas, respectively, at risk during the last 10 years (Follak and Essl 2013). In 1991, *S. halepense* was reported in 90% of cotton and soybean fields, reducing the average annual value by 5.8 and 23.7 million dollars, respectively, in Arkansas, Louisiana, and Mississippi (McWhorter 1993). Previously, inadequate research has been conducted regarding the competitive potential of this weed, and its critical period of competition against different major agronomic crops. Further studies on crop interference will help in designing appropriate management strategies to combat the impact of *S. halepense*.

Allelopathic interference

Several researchers have documented the presence of phenolic compounds and flavonoids in different parts of *S. halepense*, able to induce significant phytotoxic effects through inhibiting photosystem II (PSII) (Czarnota et al. 2003a, b; Kagan et al. 2003; Huang et al. 2010). Leaves and rhizomes of *S. halepense* contain allelochemicals, such as aliphatic acid, chlorogenic acid, dhurrin, prunasin, p-coumaric acid, p-hydroxybenzoic acid, p-hydroxybenzyl alcohol, p-hydroxybenzaldehyde, phloroglucinol, sorgoleone, and taxiphyllin (Czarnota et al. 2003a, b). Every part of the plant contains major phytochemicals, such as, valinic acid, gallic acid, 4-hydroxy benzoic acid, sorgoleone, and dihydrosorgoleone (Butnariu and Coradini 2012; Nouri et al. 2012). Eight different allelopathic compounds, including p-hydroxybenzadehyde, triclin, p-hydroxybenzoic acid, (E)-p-hydroxycinnamic, luteolin, apigenin, salcolin A, and salcolin B were isolated from the aerial portion of *S. halepense* (Huang et al. 2010). In addition, its roots secrete a prolonged chain poisonous hydrocinon named “sorghuleon” which restricts the rootlet growth of several plants (Hesammi 2011).

Fresh and decayed portions of rhizomes and leaves of *S. halepense* have been reported to contain varying amounts of water-soluble allelochemicals, which inhibit the germination and seedling development of numerous crop types (Asgharipour and Armin 2010; Kalinova et al. 2012; Nouri et al. 2012; Golubinova and Ilieva 2014; Bibak and Jalali 2015). For example,

S. halepense aqueous extracts (0.1 g ml⁻¹) negatively affected the germination rate and seedling growth of wheat, maize, and cotton at 3 days after treatment (DAT; Huang et al. 2008). The effect of allelopathic extracts on the tested crop species significantly increased the mean germination time and decreased the seedling vigour; however, the effect was concentration dependent (Kalinova et al. 2012; Golubinova and Ilieva 2014). Research has identified and isolated allelochemicals considered responsible for the successful invasion of this weed (Huang et al. 2015). Limited studies have been conducted to evaluate its allelopathic potential in different agronomic and horticultural crops. Further studies on the exudation of allelochemicals at different growth stages, and their interaction with different weeds and crop species, are pre-requisite for effective management of *S. halepense*.

Livestock poisoning

In periods of drought and frost, *S. halepense* is widely used as a fodder plant, causing poisoning in cattle due to its cyanic content (Henderson 2001). Damage to *S. halepense* plant cells by chewing, frost, or wilting releases enzymes that break down dhurrin to produce hydrocyanic acids (e.g., prussic acid), which when ingested by grazing animals, prevents cellular oxygen uptake from the blood (Nellis 1997). In Australia and the USA, prussic acid poisoning is well known to occur in cattle feeding on *S. halepense* (Parsons and Cuthbertson 2001). Plants at a juvenile stage, growing in high nitrogen and low phosphorus conditions, are likely to have high levels of toxicity (Nellis 1997). Under such circumstances, grazing of *S. halepense* is associated with major livestock diseases, including neuropathy, teratogenesis, photosensitization, nitrate intoxication, and acute cyanide poisoning in horses (Gaskill 2013). However, major risks of cyanide and nitrate poisoning are associated with this weed in cattle and sheep, which limits the possibilities for weed management through grazing, particularly in rangelands. The mechanism through which *S. halepense* causes these problems is not well understood, and does not have a specific treatment. Minimizing exposure to *S. halepense* through controlling these plants is important for reducing livestock toxicity risks from hay and pastures.

Alternative host to plant pathogens

The presence of *S. halepense* in crop fields can negatively impact crop production, particularly in maize and sorghum, as it serves as a host to several species of damaging insect pests (Vega et al. 1995). It is an important reservoir for the vector-transmitted maize dwarf mosaic virus, and *S. halepense* is closely linked with this virus in Europe (Achon and Sobrepere 2001). This virus was commonly found in areas where *S. halepense* is widespread in maize plants, particularly in northern Italy and Serbia (Vrbnicanin et al. 2009). It also hosts other viruses, causing Goss's wilt of maize (*Clavibacter michiganensis* Subsp. *nebraskensis*), rice stripe disease (*Gonatophragmium* spp.), wheat dwarf virus (*Mastrevirus* spp.), sugarbeet yellow virus (*Polyomyxa betae*), maize chlorotic mottle virus (*Machlomovirus* spp.) and wheat streak mosaic (*Emaravirus* spp.) (Warwick and Black 1983; Ikley et al. 2015; Achon et al. 2016; Parizipour et al. 2016). Several fungal pathogens, including leaf spot disease (*Cercospora sorghi*), sorghum leaf spot (*Helminthosporium sorghicola*), leaf blight (*Helminthosporium turcicum*), downy mildew (*Sclerophthora macrospora*), loose kernel smut (*Sphacelotheca cruenta*), and covered kernel smut (*S. sorghi*), can complete their life cycle on *S. halepense* in the absence of crop plants (Warwick and Black 1983; Holm et al. 1997). It also acts as an alternative host for several insect pests, most notably sorghum midge (*Contarinia sorghicola*), leaf hopper (*Graminella nigrifrons*), corn leaf aphid (*Rhopalosiphum maidis*), sorghum midge (*Contarinia sorghicola*), and wheat aphid (*Schizaphis graminum*) (Caballero et al. 2001). In addition to this, *S. halepense* is an important host of Asian corn borer (*Ostrinia furnacalis* Guenee), short-horn grasshopper (*Oxya hyla hyla*), and many nematode species such as *Paratylenchus* spp., *Rotylenchulus* spp., *Trichodorus* spp., *Hemicycliophora* spp., *Xiphinema* spp., and *Meloidogyne* spp. (Schreiner et al. 1990; Parsons and Cuthbertson 2001; Vega et al. 1995; Ghosh et al. 2014). Uncontrolled growth of *S. halepense* will increase the invasiveness and establishment of plant pathogens in an agroecosystem. Therefore, off-season growth of this weed should be managed through cultural and mechanical operations, to prevent the incidence of serious pests in crops. In addition, border plantation of this weed around the crop field will help in preventing the entry of insects, pathogens, and nematodes in the main crop field.

Potential management constraints

Crop mimicry

Taxa in the genus *Sorghum* are usually self-pollinated, but there is no barrier to the cross fertilization of species, which can out-cross (Tarr 1962). Therefore, *S. halepense* has been confused with Sudangrass (*Sorghum sudanense* (Piper) Stapf), annual grain sorghum, and maize cultivated for grain and forage purposes in Arizona (Guertin 2001). In northern, south-eastern, south-central and western USA, *S. halepense* can hardly be distinguished from annual grass shattercane (*Sorghum bicolor* ssp. *bicolor*) at the same developmental stages (Uva et al. 1997). It is also difficult to differentiate from Mexican gamagrass (*Tripsacum lanceolatum*) at the vegetative phase, because both these grasses have wide green leaves with a white midvein. Moreover, both grasses are too variable in terms of ligules, inflorescences, and other reproductive portions (Kearney and Peebles 1960). *S. halepense* has also been confused with panic grass (*Panicum bulbosum* Kunth), and can only be distinguished by its short knotty rhizomes and bulbous swelling of its culms (Snyder 1992). Columbus grass (*Sorghum almum*) has become established throughout coastal Queensland, parts of New South Wales and the Northern Territory of Australia (Parsons and Cuthbertson 2001). This rhizomatous derivative of a cross between *S. bicolor* and *S. halepense* is hard to distinguish from *S. halepense*. Columbus grass has been declared a noxious weed in New South Wales due to the similar appearance of seeds of the two species, and no seeds are allowed in traded sorghum grains.

Herbicide resistance

Repeated application of these herbicides has resulted in the evolution of resistance to each of these mechanisms of action (MOA) in *S. halepense*. It has been reported resistant to recommended doses of nicosulfuron, foramsulfuron, primisulfuron-methyl, clethodin, fluazifop, glyphosate, and imazethapyr in the USA, Chile, Mexico, and Venezuela (Heap 2014; Johnson et al. 2014a). Since 1990, commercialization of glyphosate-tolerant (GT) crops has provided farmers with another option for the control of many grassy and broadleaved weeds, including *S. halepense* (Landry et al. 2016). Unfortunately, excessive use of

a single herbicide mode of action for a long time led to weed biotypes resistant to this herbicide (Green and Owen 2011). In 2007, it was reported that glyphosate was no longer effective on *S. halepense* populations in a soybean field near Arkansas (Norsworthy et al. 2008; Rair et al. 2011). Afterward, glyphosate-resistant (GR) *S. halepense* biotypes were reported in Argentina, Mississippi, and Louisiana (Valverde and Gressel 2006; Binimelis et al. 2009; Heap 2014). The glyphosate dose recommended to kill 50% of the suspected GR biotypes increased from 3.5 to 10.5-fold in the soybean fields (Vila-Aiub et al. 2007). In dose-response studies, the resistant biotype was 5–7 fold less sensitive to glyphosate than the susceptible biotype with a similar absorption rate (Rair et al. 2011).

It is suspected that *S. halepense* accessions resistant to ACCase-, ALS-inhibiting, and dinotroanaline herbicides exist in Arkansas and surrounding states, particularly in cotton and soybean fields (Smeda et al. 1997; Burke et al. 2006; Heap 2014). Two accessions of *S. halepense* from Venezuela were confirmed to be resistant against several sulfonylurea, pyrimidinyl(thio)benzoate, imidazolinone, and triazolopyrimidine herbicides, including nicosulfuron, iodosulfuron, penoxsulam, imazapyr, imazethapyr, and pyribenzozim (Ortiz et al. 2014). Afterward, ACCase resistant *S. halepense* populations were confirmed in other parts of the United States and Israel (Burke et al. 2006; Heap 2014). In Europe, only a single case has been reported regarding herbicide resistance of *S. halepense*, in a cotton field with no information about the resistance mechanism (Kaloumenos and Eleftherohorinos 2009). Farmers in Italy have reported that *S. halepense* populations were poorly controlled by ACCase herbicides in cropping systems based on broadleaved crops, i.e., cotton, soybean, watermelon, and tomato (Scarabel et al. 2014). Once a *S. halepense* population escapes POST herbicide treatment in dicotyledonous crops, it will produce rhizomes in the following years that cannot be controlled through any PRE or POST herbicides (Scarabel et al. 2014).

Management

Cultural approaches

A study conducted by Vidotto et al. (2016) reported that early sowing time demonstrated low frequency of

crop encounter with *S. halepense* in maize and cotton. Under a moderate infestation, crop rotation alters the desired physical environment of *S. halepense* and reduces its seed and rhizomes production substantially (Uremis et al. 2009). Including Brassicaceae species in crop rotation, or as cover crops, will eliminate or reduce the need for herbicide in *S. halepense* control (Uremis et al. 2009; Bangarwa and Norsworthy 2014). For example, cultivation of three Brassicaceae species as cover crops marginally controlled *S. halepense* up to 46% at 2 weeks after tomato transplanting; however, control efficacy declined to <20% at 4 weeks after tomato transplant (Bangarwa and Norsworthy 2014). The adoption of weed control methods will depend upon farm attributes and constraints, such as availability of labor and money, access to technical means, as well as socio-environmental features, limiting the range of feasible agronomic operations. Based on agroecological principles, diversification in the cropping systems, that is, crop sequence and their associated agronomic practices, are key elements for long-term weed management in resource-constrained situations.

Mechanical approaches

Sorghum halepense can be controlled through hand pulling in cases of low infestation, and hoeing can be used during the early crop stages when seedlings are 2–3 weeks old (Newman 1993). Similarly, repeated mowing assists in preventing seed formation, rhizome production, and shoot regrowth, which ultimately reduces the vigor of established plant stands (Newman 1993; Uva et al. 1997). Development of *S. halepense* rhizomes could be prevented by exposing and destroying rhizomes through summer fallowing and frequent tillage (Warwick and Black 1983). At heavily infested sites, tilling the field six times at 2-week intervals reduced *S. halepense* rhizome production by 90% (McWhorter 1973). During summer, superficial tillage affected the emergence of *S. halepense*, with 15% seedling emergence from a 10-cm burial depth (Loddo et al. 2016). Furthermore, collection of rhizome fragments after mechanical tillage helped reduce *S. halepense* reinfestation in an organic red pepper (*Capsicum annuum* L.) cultivation system of Turkey (Arpaci et al. 2016). Conversely, a recent study reported that tillage is not suitable for *S. halepense* control, as plowing increases rhizome spread and intensifies the

problem if contaminated machinery is used in non-invaded areas (Kashif et al. 2015). A single mechanical control measure rarely provides adequate *S. halepense* control. However, integration of a diverse approach, combining tillage with a range of other control methods, will provide sufficient control of *S. halepense* and may prevent its establishment in new areas.

Chemical approaches

Herbicide-susceptible biotypes

The ineffectiveness of non-chemical approaches has forced farmers to employ herbicides for the control of *S. halepense* in cropped areas (McWhorter 1989). Different PRE and POST herbicides are applied to attain control of *S. halepense* populations in field crops (Table 2). Use of commercially available PRE herbicides, particularly for soybean and maize, with different modes of actions (e.g., s-metolachlor, pendimethalin, flufenacet, and clomazone) were reported to be effective in controlling *S. halepense* seedlings, not regrowth from rhizomes (Scarabel et al. 2014). Since their introduction in the 1980s, POST herbicides, mainly acetyl-coenzyme-A carboxylase (ACCase) and acetolactate synthase (ALS)-inhibitors, have showed a high efficacy against both the seedlings and rhizomes of *S. halepense* (Johnson et al. 2014b; Johnson and Norsworthy 2014; Scarabel et al. 2014). Among these herbicide groups, sulfonyleureas, aryloxyphenoxypropionates (FOPs), and cyclohexanediones (DIMs) are widely applied for control of *S. halepense* in maize, soybean, cotton, and other dicotyledonous crops (Bridges and Chandler 1987b; Corkern et al. 1998; Sarpe et al. 2000; Smeda et al. 2000; Kaloumenos and Eleftherohorinos 2009).

For example, PRE, early post (EPOST), and late post-emergence (LPOST) applications of acetochlor, alachlor, metolachlor, dimetenamid, rimsulfuron (either alone or in combination with atrazine and dicamba), and nicosulfuron in combination for the reliable control (91–97%) of *S. halepense* in maize (Damalas and Eleftherohorinos 2001; Baghestani et al. 2007; Markovic et al. 2008; Barroso et al. 2016). Similarly, numerous POST herbicides (i.e., clethodim, glyphosate, fluazifop-p, haloxyfop, and quizalofop-p) have been reported to provide efficient and timely control of *S. halepense* up to 95% in glyphosate-tolerant (GT) soybean, with no significant crop injury

Table 2 Recommended doses of herbicides for the chemical control of *S. halepense*

Herbicide group(s)	Herbicide	Dose (a. i. ha ⁻¹)	Crop	References
ACCcase-inhibitors	Clethodim	0.035–0.07	–	Rosales-Robels et al. (1999)
DHPase + ALS-inhibitors	Asulam + trifloxysulfuron	1.8 + 0.016	Sugarcane	Dalley and Richard (2008)
ACCcase-inhibitors	Clethodim	0.21	–	Johnson et al. (2014a)
ACCcase-inhibitors	Clethodim	0.179	Soybean	McKinley et al. (1999)
ACCcase-inhibitors	Fluazifop-p	0.105	–	Rosales-Robels et al. (1999)
ACCcase-inhibitors	Fluazifop-p	0.20	Soybean	McKinley et al. 1999
ACCcase-inhibitors	Quizalofop-p	0.056	Soybean	McKinley et al. (1999)
ACCcase-inhibitors	Fluazifop-p	0.68	–	Johnson et al. (2014a)
EPSP synthase inhibitors	Glyphosate <i>fb</i> Glyphosate	0.56 <i>fb</i> 0.56	Sugarcane	Griffin et al. (2006)
EPSP synthase inhibitors	Glyphosate	0.42	–	Johnson et al. (2014a)
ALS-inhibitors	Imazethapyr	0.40	–	Johnson et al. (2014a)
ALS-inhibitors	Nicosulfuron	0.06–0.08	Maize	Baghestani et al. (2007)
4-HPPD and ALS-inhibitors	Isoxaflutole + Nicosulfuron	0.9 + 0.5	Maize	Markovic et al. (2008)
VLCFAs + 4-PHHD inhibitors	Acetochlor + Isoxaflutole	1.6 + 0.02	Maize	Markovic et al. (2008)
ALS-inhibitors	Rimsulfuron	0.010	Maize	Damalas and Eleftherohorinos (2001)
ALS-inhibitors	Thifensulfuron-methyl + Rimsulfuron	0.006 + 0.012	Maize	Markovic et al. (2008)
4-HPPD and ALS-inhibitors	Isoxaflutole + Rimsulfuron	0.07 + 0.025	Maize	Markovic et al. (2008)
ALS-inhibitors	Rimsulfuron	0.012	Maize	Barroso et al. (2016)
ALS + PSII-inhibitors	Rimsulfuron + atrazine	0.01 + 1	Maize	Damalas and Eleftherohorinos (2001)
ALS + IAA-inhibitors	Rimsulfuron + dicamba	0.01 + 0.28	Maize	Damalas and Eleftherohorinos (2001)
Glutamine synthase inhibitors	Glufosinate	0.74	–	Johnson and Norsworthy (2014)
EPSP synthase inhibitors	Glyphosate <i>fb</i> Glyphosate	1.47 <i>fb</i> 1.47	–	Sarpe et al. (2000)

(Griffin et al. 2006). POST-treated asulam combined with trifloxysulfuron efficiently controlled rhizomatous *S. halepense*, and showed 12% increase in sugarcane yield as compared to asulam alone (Dalley and Richard 2008).

Despite the information available on the ecophysiological aspects of this weed, limited studies have been conducted on the chemical control of this weed, particularly with reduced herbicide doses (Acciaresi and Chidichimo 2005). Two decades ago, plentiful research on the chemical management of *S. halepense* in different cropping systems across the world was conducted (Johnson and Frans 1991; Rosales-Robels et al. 1999). With the passage of time, information available on the chemical control of this weed is getting outdated and impracticable. Increasing

invasiveness, evolving genetic diversity, and multiple herbicide resistance necessitates evaluation of alternative chemical options to control *S. halepense* in the native and introduced areas.

Herbicide-resistant biotypes

Recently, different PRE and POST herbicides were reported to effectively control a sulfonylurea-resistant accession of *S. halepense* (Table 3; Ortiz et al. 2014). The introduction of glufosinate-tolerant crops has provided farmers with alternatives for the control of this weed without any crop injury e.g. glufosinate, s-metolachlor, pendimethalin, flufenacet, and clomazone (Johnson and Norsworthy 2014; Scarabel et al. 2014; Johnson et al. 2014b; Landry et al. 2016).

Table 3 Recommended doses of herbicides for the control of resistant *S. halepense* populations

Herbicide(s)-resistant population	Herbicide	Dose (kg a.i. ha ⁻¹)	References
Propaquizafop, quizalofop, and haloxyfop	S-metolachlor	0.96	Scarabel et al. (2014)
Nicosulfuron, Foramsulfuron, Iodosulfuron	S-metolachlor	1.44	Ortiz et al. (2014)
-do-	Pendimethalin	1.92	Ortiz et al. (2014)
-do-	Isoxaflutole	0.052	Ortiz et al. (2014)
-do-	Profoxydim	0.16	Ortiz et al. (2014)
-do-	Glyphosate	2.04	Ortiz et al. (2014)
-do-	Bispyribac-sodium	0.04	Ortiz et al. (2014)
Glyphosate	Glufosinate	0.59	Johnson et al. (2014b)
Glyphosate	Glufosinate <i>fb</i> Glufosinate	0.7 <i>fb</i> 0.5	Landry et al. (2016)

Failures in weed control are usually associated with a mismatch between the weed population, herbicide application time, and herbicide sub-doses (Uremis et al. 2009). Although effective control of a heavy infestation of *S. halepense* requires several herbicide applications with proper timing, the efficacy increases as the timing of application approaches the minimum rhizome biomass period (Baghestani et al. 2007; Uremis et al. 2009). In addition to this, management of herbicide-resistant weeds requires a complete understanding of the resistance mechanisms involved. Unfortunately, resistance management strategies for *S. halepense* are limited to stale seedbed preparation, nonselective pre-sowing herbicides, crop rotation and POST applied sulfonylurea. In order to minimize the risk of herbicide resistance, timely monitoring is prerequisite to avoid further spread into non-infested areas, and for limiting the movement of resistant seeds. Mixtures, and rotations of different herbicides with a discrete mode of action, could prove significant in minimizing the herbicide resistance risks in *S. halepense*. However, the integration of agronomic practices with chemical options offers the most scope for designing long-term strategies to restrict the spread of herbicide resistant *S. halepense* populations. Furthermore, there is a need to study more populations to determine specific mutations; therefore, future research should be designed to investigate the role of mutation in the development of resistance in *S. halepense* to various herbicide modes of action.

Biological approaches

Increasing concern over herbicide resistance has forced farmers to adopt alternative options for the

chemical control of *S. halepense* (Norris et al. 2002). Control through biological agents provides another option to reduce the risk of herbicide resistance development in weeds like *S. halepense*. Various scientists who have evaluated different biological agents have highlighted their potential for the control of this weed species (Chandramohan and Charudattan 2001; Tilley and Walker 2002). Previously, fungal pathogens *Exserohilum turcicum*, *Colletotrichum graminicola*, and *Gloeocercospora sorghi* were used as potential myco-herbicides for the control of *S. halepense* in dicotyledonous crops (Chiang et al. 1989). However, while these pathogens did not cause significant damage to monocot crops such as wheat, oat, and barley, they were found to be too virulent in closely-related crops, such as maize and sorghum. Inoculation of *S. halepense* with *Curvularia intermedia* Boedijn caused flecking or necrotic lesions, resulting in significantly reduced dry weight and up to 86% weed mortality (Tilley and Walker 2002). Similarly, a mixture of three fungal pathogens, *D. gigantean*, *E. longirostratum*, and *E. rostratum* at 2×10^5 , caused severe disease symptoms in four-week-old *S. halepense* seedlings, resulting in 83–100% weed control two weeks after treatment (Chandramohan and Charudattan 2001). Inoculation of *S. halepense* at the seedling stage with teliospores of *Sporisorium cruentum* (1×10^6) in a water-surfactant suspension at 935 L ha⁻¹ caused infection in 98% plants of *S. halepense* and found non-competitive to sugarcane crop when compared with non-infected plants (Millhollon 2000). Additionally, various insects and nematodes were reported to be associated with the aerial portion and root systems of this weed species (Vega et al. 1995). Unfortunately, no studies have

been conducted to confirm the biological potential of these agents for controlling *S. halepense* populations in different ecosystems. Previous studies have shown that fungal pathogens have potential as a biocontrol agent against *S. halepense* (Millhollon 2000; Chandramohan and Charudattan 2001). However, more research is needed for the development of bioherbicides from such biocontrol agents. Use of one or more pathogens, in combination with different modes of action or sites of action, will aid in achieving broad spectrum weed control, providing assurance against any possible failure and eliminating the risk of resistance development.

Allelopathic approaches

Several studies have investigated the allelopathic potential of different plants and crop species for the control of *S. halepense* under different cropping systems (Uremis et al. 2009; Butnariu 2012). Incorporation of crop cultivars with strong allelopathic potential has been reported to show maximum suppression of *S. halepense*, for example, black radish (*Raphanus sativus* var. *niger*) and rapeseed (*Brassica napus* L.) suppressed this weed by up to 90% (Uremis et al. 2009). Seed germination, root and shoot length, and biomass of *S. halepense* were negatively influenced by the allelopathic extracts of crop and weed species, when applied at a high concentration (Mahmoodzadeh and Mahmoodzadeh 2014; Afridi et al. 2014; Farhoudi et al. 2015). Similarly, increased concentrations of the alcoholic extract and tropane alkaloid of *Hypericum perforatum* L. and *Datura stramonium* L., respectively, also reduced the seed germination and severely affected the seedling growth of *S. halepense* (Butnariu 2012; Alipour et al. 2013). The presence of allelochemicals suppressed *S. halepense* seedling growth through inhibiting photosynthesis and enzyme activity, which significantly decreased the malondialdehyde concentration and photosynthetic rate (Farhoudi et al. 2015). Additionally, increased lipid peroxidation exerted a toxic influence on *S. halepense* cellular structure, physiological mechanisms, and biochemical reactions, resulting in its complete control. In conclusion, allelopathy can play a vital role in the management of *S. halepense*. Further research is needed to explore

the allelopathic potential of different plant species against *S. halepense* under field conditions. Improvement in the allelopathic potential of rice and other crops are possible areas for future research.

Integrated approaches

Efficacy of chemical herbicides could be enhanced through supplementary cultural practices, such as cultivation and narrowing row spacing. For example, nicosulfuron used together with narrow row spacing or tillage can completely suppress *S. halepense* (Nalewaja 1999; Rosales-Robels et al. 1999; Nosratti et al. 2007). Optimal application of herbicides at reduced doses, together with cultivation or altered crop management practices, can significantly improve herbicide efficiency for controlling the aboveground and rhizome biomass of *S. halepense* (Nosratti et al. 2007). For example, deep plowing followed by a single glyphosate application (0.98 kg a.i. ha⁻¹) is an option for controlling *S. halepense* in rainfed areas (Zahoor et al. 2015). Recent research has also demonstrated that herbicide efficacy against this weed can be significantly improved through the addition of surfactants and adjuvants. For example, POST applied haloxyfop-p-methyl (0.304 kg a.i. ha⁻¹), combined with an adjuvant Adigor® (0.5%), provided 95% control of *S. halepense* in soybean (Parsa et al. 2013). These integrated approaches can reduce herbicide requirements, and hence decrease herbicide costs and inputs by 27 and 64%, respectively, without affecting crop yield (Nosratti et al. 2007). In addition to improved environmental safety, no-till systems resulted in reduced fuel and labor costs, as well as low depreciation and maintenance of machinery. However, differences between *S. halepense* populations could limit the design and implementation of integrated weed management strategies in different crop production systems (Acciaresi and Chidichimo 2005). Attempts to reduce the dependence on herbicides for environmental and economic reasons have promoted the development of several integrated weed management strategies. Limited work has been done on the integrated management of *S. halepense* across the world. Manipulation of agronomic practices, such as competitive cultivars, narrow row spacing, altered row orientation, and high planting density, integrated

with other chemical and non-chemical options, need to be researched.

Conclusions and future directions

Seed dormancy, prolific seed production, ability to germinate over a wide temperature range, strong allelopathic potential, and herbicide resistance favor its successful invasion of *Sorghum halepense*. No doubt, plentiful efforts has been taken and are being designed to control the agricultural, environmental, and economic impact of this invasive weed. Unfortunately, limited information is available on the invasive mechanism and interference on ecosystem stability. Effective management strategies are of no use without understanding the invasive mechanism of *S. halepense*. Therefore, future studies needs to be designed on the morphological attributes, reproductive biology, competitive abilities, and escape for natural enemies, photosynthesis pathways involved in *S. halepense* invasiveness. In addition, researchers should exposure the role of genetic diversities among the different populations and biotypes on climatic, edaphic and ecological bases in its invasion. As far as the control of this species is concerned, management of resistant biotypes of *S. halepense* is possible using herbicides with different modes of action. Biological and allelopathic approaches also have potential for the effective control of *S. halepense* in a range of agroecosystems. Additionally, manipulation of agronomic techniques could be an effective means of control for this weed species. A combination of these effective techniques should be employed in developing an effective strategy, in order to slow or reverse the invasion of *S. halepense*. Long-term management strategies will need to focus on integrating chemical and non-chemical approaches in a sustainable manner. Integrated use of different approaches, such as soil-applied and post-emergent herbicides, crop rotations, and deep tillage practices, could be helpful in destroying both the plants and the underground rhizome network of *S. halepense*, which will ultimately prevent its widespread invasion.

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