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Original Article

Dodder (*Cuscuta campestris* Yunck.) in Sugar Beet Fields of Iran: Distribution, Impact, and Integrated Management Strategies

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Abstract

Sugar beet (*Beta vulgaris* L.) is one of the foundation of Iran's agriculture and food security, supplying a substantial proportion of the country's sugar demand. The obligate stem holoparasite field dodder (*Cuscuta campestris* Yunck.) is a serious parasitic weed of sugar beet and has become a major constraint to sugar beet production in key regions including West Azerbaijan, Khuzestan, Khorasan Razavi, and Kermanshah. Dodder infestation has significant economic impacts because it reduces both yield and quality. Losses of root yields of up to 15-50% and absolute losses of 1.06-1.8 percentage points of sucrose content have been reported in Iranian studies and have affected processing efficiency. The parasite physiologically reduces the host's metabolic resources, leading to severe reductions in chlorophyll content (up to 38%) and total biomass. This review presents the current status of dodder management in Iran, including cultural, chemical, and biological control measures. Basic non-chemical methods include using certified dodder-free seed, planting non-host crops such as summer cereals, and cleaning farm equipment. Chemical control is also essential, and studies have found propyzamide (500 g L^{-1} Emulsifiable Concentrate (EC) at 2.5 kg a.i. ha^{-1}) to be the most effective pre-attachment herbicide reported to achieve control rates of up to 100% under specific experimental conditions. However, excessive dependence on chemical herbicides cannot be sustained. Host plant resistance represents a promising long term management strategy. Studies have identified commercial cultivars such as Flores with greater resistance to dodder infestation, which may serve as valuable genetic resources for national breeding programs. Future sustainability seems to require an Integrated Weed Management (IWM) approach that combines multiple complementary control tactics. In addition, further research is needed to evaluate emerging options, such as silicon-based soil amendments for enhanced plant protection and the identification and development of native biological control agents. Given the rapid spread potential and persistent seed bank of *C. campestris*, conventional economic thresholds are of limited practical value for this parasite. Unlike most annual weeds, even low dodder infestation levels can escalate rapidly; therefore, early detection and immediate intervention at the first signs of infestation are generally recommended rather than threshold-based decision-making.

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سس زراعی (*Cuscuta campestris* Yunck.) در مزارع چغندرقند ایران: پراکنش، خسارت، و راهکارهای مدیریت تلفیقی

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چکیده

چغندرقند (*Beta vulgaris* L.) یکی از پایه‌های کشاورزی و امنیت غذایی ایران است و حدود ۹۰ درصد شکر مورد نیاز کشور را تأمین می‌کند. انگل کامل ساقه، سس زراعی (*Cuscuta campestris* Yunck)، یک آفت جدی برای این محصول اساسی است و به یکی از عوامل محدودکننده کلیدی در اکثر مناطق کشت اصلی مانند آذربایجان غربی، خوزستان، خراسان رضوی و کرمانشاه تبدیل شده است. آلودگی به سس به‌علت کاهش قابل توجه عملکرد و کیفیت محصول، آثار مخرب زیادی بر اقتصاد مبتنی بر کشاورزی می‌گذارد. در مطالعات پژوهشگران ایرانی، کاهش عملکرد ریشه تا ۱۵درصد و تا ۵۰ درصد و کاهش مطلق۱/۰۶ تا ۱/۸ درصدی محتوای ساکارزی گزارش شده است، که بر بازدهی فرآوری نیز تأثیر گذاشته است. این علف‌هرز انگلی از نظر فیزیولوژیکی منابع متابولیک میزبان را کاهش می‌دهد و منجر به کاهش گسترده محتوای کلروفیل (تا ۳۸ درصد) و زیست‌توده کل می‌شود. این مقاله مروری، ترکیبی از وضعیت فعلی مدیریت سس در ایران است که اقدامات کنترل زراعی، شیمیایی و بیولوژیکی را پوشش می‌دهد. روش‌های پایه غیرشیمیایی شامل استفاده از بذر گواهی‌شده عاری از سس، کاشت گیاهان غیرمیزبان مانند گندم و ذرت، و نگهداری (سرویس) تجهیزات کشاورزی است. کنترل شیمیایی نیز ضروری است و مطالعات نشان داده‌اند که پروپیزامید (propyzamide) مؤثرترین علف‌کش پیش از اتصال با حداکثر کنترل ۱۰۰ درصد است. بااین‌حال، اتکای بیش از حد به راه‌حل‌های شیمیایی پایدار نیست. مطالعات مقاومت گیاه میزبان راه‌حل‌های بلندمدتی ارائه می‌دهند و وجود ارقام تجاری مانند فلورس (Flores) را تأیید کرده‌اند که مقاومت بسیار بیشتری در برابر انگل‌شدن توسط سس دارند و می‌توانند به‌عنوان یک منبع ژنتیکی حیاتی برای برنامه‌های ملی اصلاح نباتات مورد استفاده قرار گیرند. پایداری آینده به اتخاذ یک رویکرد مدیریت یکپارچه علف‌های هرز (IWM) که این استراتژی‌ها را ترکیب می‌کند، بستگی دارد. این استراتژی باید با مطالعات اضافی در مورد راهکارهای جدید، از جمله افزودن سیلیسیم به خاک برای بهبود حفاظت از گیاه و توسعه عوامل کنترل بیولوژیکی بومی، تکمیل شود. شکاف موجود در دانش در مورد آستانه‌های اقتصادی و تأثیر تغییرات آب و هوایی بر تعاملات میزبان و انگل، برای پایداری بلندمدت صنعت چغندرقند ایران حیاتی است.

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Introduction

Global Importance of Sugar Beet as a Primary Sugar Source

Sugar beet (Beta vulgaris L.) is one of the pillars of the sugar industry worldwide, ranking second after sugarcane (Saccharum officinarum L.) in production volume. It supplies the world with approximately 30-40% of total sugar, making it an essential commodity in the global food system (Subrahmanyeswari and Gantait, 2022; Sun et al., 2024). The main cultivation regions are temperate climates, where Europe is estimated to produce 67% of global production (Kun et al., 2022). Its agronomic characteristics, especially the shorter growing period of five to six months and much lower water requirements compared to the 12-14 month cycle of sugarcane, make it a more strategic crop in arid and semi-arid regions facing the impact of water scarcity and climate change (Żarski et al., 2020). The sugar beet industry has a significant economic impact on the global market, estimated to be tens of billions of dollars (Industrial Beet Sugar Market Size, Share | Industry Report, 2023). In addition to sucrose production, it is identified as a multifaceted value-chain product in terms of its vital by-products, such as molasses used in industrial fermentation, pulp for animal feed, and biomass used in bioethanol production, among others (Lima & Beacorn, 2022; Ptak et al., 2021).

Sugar Beet Production in Iran Production Statistics (2020-2025)

Iran holds an important position in sugar production, ranked 12th globally in sugar production and 11th in the sugar beet industry in 2023 (Tridge, 2025). The crop forms approximately 60% of the country's domestic sugar supply. Recent years have seen significant and planned growth in cultivation, especially of fall-sown crops. Iran reported a record sugar beet harvest in the 2023-2024 crop year, with an estimated 8.57 million metric tons produced on approximately 137,962 hectares (Isna, 2024). This represented almost a 50% increase in cultivated area compared to the previous year, indicating rapid and successful implementation of national agricultural policies (Table 1).

Table 1. National sugar beet production overview (2021/2022 - 2023/2024)

Crop Year	Total Production (Metric tons)	Area Harvested (Hectares)	Average Yield (kg/Hectare)
2021/2022	7,466,913	132,185	56,488
2022/2023	6,670,042	116,501	57,253
2023/2024	8,574,975	137,962	58,530

Source: Adapted from Isna (2024) and Tridge (2025)

This growth trend is projected to continue. The 2024-2025 season of contractual cultivation reached an all-time high of 138,000 hectares, with 106,000 hectares of conventional spring crops and 32,000 hectares of growing fall crops. The overall output is predicted to exceed 8.5 million metric tons, of which over 6.5 million metric tons will be produced during the spring harvest and over 2 million metric tons during the fall harvest. Sugar beet production is concentrated in a few major provinces. West Azerbaijan is the largest producer in terms of production volume and cultivated area, with a share of more than 23.9% of total national production. Khorasan Razavi (15.2%), Khuzestan (15.4%), Kermanshah, and Fars are other regions that produce the spring crop in large quantities. Strategic development of fall cultivation targets provinces with warmer winters, and Khuzestan (16.2%) has allocated approximately 20,000 hectares to autumn crops in 2023-2024, along with Fars, Kermanshah, and Golestan.

Cuscuta campestris: Biology and Ecology

Parasitic weeds present a unique and serious challenge among biotic constraints that threaten world agriculture. A highly harmful example from the family Convolvulaceae is *Cuscuta campestris* Yunck., commonly known as field dodder (Hartenstein et al., 2023). It is an obligate stem holoparasite, meaning it can only survive by entirely depending on a host plant (Kaiser et al., 2015). *Cuscuta campestris* exemplifies an organism that has become evolutionarily specialized for parasitic life. It lacks a typical root system, does not have fully developed leaves, and possesses insignificant amounts of chlorophyll, rendering it unable to sustain autotrophic nutrition (Bernal-Galeano et al., 2022). Its thin, thread-like seedling, upon germination, must locate and attach to a suitable host within a few days or it will perish. The parasite develops an intimate relationship by creating specialized invasive organs known as haustoria, which penetrate the host's tissues and establish direct connections to its vascular system—both xylem and phloem. Through this connection, dodder extracts water, carbohydrates, minerals, and other vital solutes, essentially appropriating the metabolic resources of the host for its own growth and reproduction (Jhu & Sinha, 2022; Shimizu & Aoki, 2019).

Seed germination of *C. campestris* is highly temperature-dependent, with optimal germination occurring between 25-33°C and maximum germination rates observed at 30-33°C (Hutchinson & Ashton, 1980). Seeds can germinate across a broad temperature range of 10-30°C but fail to germinate below 10°C or above 39°C. This temperature requirement is critical for timing management practices, as germination typically occurs during late spring through summer when soil temperatures exceed the base temperature threshold of approximately 10°C. Understanding these thermal requirements enables farmers to optimize planting dates for sugar beet, ensuring the crop establishes a competitive advantage before dodder emergence (Goldwasser et al., 2016).

Cuscuta campestris achieves efficient reproduction mainly by producing large numbers of seeds. A single plant may produce tens of thousands of seeds, with some estimates exceeding 100,000 (Sarić-Krsmanović et al., 2022). These seeds are characterized by a hard, impermeable seed coat that confers long-term dormancy lasting more than ten years in soil. This creates a persistent seed bank, making management more difficult and ensuring the parasite's presence in infested fields for several years (Sarić-Krsmanović et al., 2022). *Cuscuta campestris* is native to North America but has spread nearly worldwide through contaminated crop seeds in international trade. Its broad host range of hundreds of dicotyledonous species and ability to propagate from stem fragments further enhance its invasive capacity, enabling it to colonize diverse agricultural and natural ecosystems globally (Parker, 2008).

Global Impact of C. campestris on Sugar Beet Production

The interaction between sugar beet cultivation and *C. campestris* infestation represents a significant agronomic and economic challenge internationally. Dodder parasitism causes serious damage to sugar beet, a highly vulnerable host, through various mechanisms (Zagorchev et al., 2025). The primary effect is direct and substantial yield loss. Dodder acts as a strong metabolic sink, depleting essential resources, inhibiting growth, causing underdeveloped roots, and reducing biomass (Figure 1). Sugar beet root yield losses of 15-50% in infested fields have been consistently documented in scientific literature from various countries (Aliverdi and Mansouri, 2025a).

Figure 1. *Cuscuta campestris* on sugar beet (Urmia, West Azerbaijan, Iran, 2024)

In addition to quantitative yield losses, dodder infestation severely impacts harvested crop quality. The parasite imposes significant costs on the host's photosynthesis, reportedly reducing absolute sugar concentration by 1.0-2.6 units in beet roots (Aliverdi and Mansouri, 2025a). This directly affects the crop's economic value and sugar extraction process efficiency. Moreover, dodder affects its host beyond parasitic feeding. The haustorial connections provide systemic links between plants, making dodder an effective vector for plant pathogens (Aliverdi and Mansouri, 2025a). It has been demonstrated to transfer several viruses and other disease-causing agents between hosts, consequently causing secondary crop damage and enhancing overall agricultural losses (Zagorchev et al., 2025).

Distribution and Impact of *Cuscuta campestris* in Iranian Sugar Beet Production

Geographic Distribution

Cuscuta campestris has established itself as a pervasive and economically damaging weed in key sugar beet production areas of Iran (Figure 2).

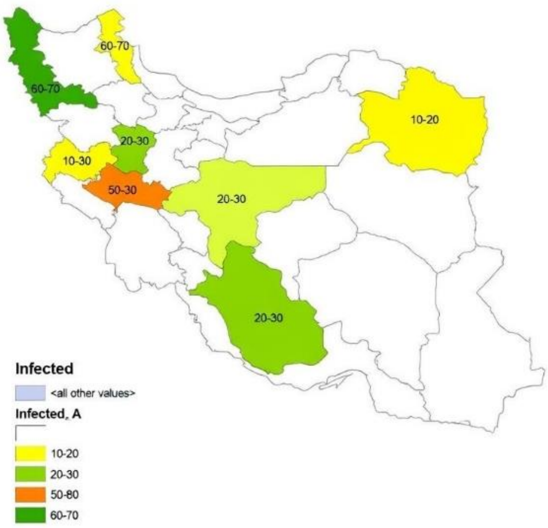

Figure 2. Geographic distribution of *C. campestris* in Iranian sugar beet production provinces. Shading intensity indicates infestation severity (Green = severe, Orange = moderate, yellow = localized). Data sources: Field survey by Jafarzadeh (2015); Meighani et al. (2017); Najafi (2024b).

Infestation is particularly acute in provinces forming the center of the country's sugar beet industry. West Azerbaijan, the most productive province, has struggled with severe dodder cases since at least 2005, with the parasite directly threatening crop yield and factory sustainability (Jafarzadeh, 2015). Khorasan Razavi province also experiences high and destructive infestation levels, making dodder a major issue for farmers in this large agricultural center (Fallahpour et al., 2013). The problem extends to other significant cultivation areas. According to reports from the Iranian Plant Protection Research Institute, Kermanshah, Hamedan, and Fars are among provinces where dodder has covered wide areas of sugar beet fields, qualifying as a significant production-limiting factor (Najafi, 2024b). This widespread threat has been officially recognized and has led to research efforts to monitor its spread. Although Geographic Information Systems (GIS) use for mapping weed distribution, including dodder, has not been extensively developed, Iranian researchers have already attempted to map dodder distribution using GIS, representing a strategic step toward more data-driven approaches to monitoring and managing this invasive parasite (Mainbashi Moeini et al., 2012).

Table 2. Summary of Iranian research on dodder in Sugar beet

Study	Location	Focus	Key Findings
Jafarzadeh (2015)	West Azerbaijan	Germination, phenology, physiological impact	Up to 38% chlorophyll reduction, 18% foliage dry weight decrease, 25% root yield loss, 1.8 units sugar content reduction
Fallahpour et al. (2013)	Khorasan Razavi	Cultivar resistance screening	Flores most resistant, Castel most susceptible
Amir et al. (2011)	Khorasan Razavi (Chenaran)	Economic impact	15% root yield loss, 1.06 units sugar reduction, 32% sodium increase, 20.75% processed sugar decrease
Meighani et al. (2017)	Isfahan	Biology and management handbook	35-50% yield reduction in West Azerbaijan
Jafarzadeh & Najafi (2020)	West Azerbaijan (Miandoab)	Integrated management	Early planting + propyzamide highly effective
Hoseyni et al. (2018)	Various	Herbicide efficacy	Propyzamide 99.6-100% control at 2.5 L ha^{-1}
Sharifi Ziveh et al. (2016)	Various	Chemical control	Propyzamide recommended at 2500 g ha^{-1}
Sohrabi et al. (2001)	Various	Chemical control, phytotoxicity	Propyzamide effective, wheat rotation evaluated
Aliverdi & Mansouri (2025a,b)	Laboratory	Silicon amendments	44.9% shoot and 57.5% root biomass reduction from dodder; silicon improves resistance
Zamanipour et al. (2025)	Laboratory	Nanoparticle control	Silver nanoparticles show dodder suppression potential

Physiological and Biochemical Impacts

External symptoms of dodder infestation, including retarded growth and yellowing, are manifestations of underlying physiological imbalances in the sugar beet host. Systematic depletion of the host's metabolic resources is the primary mechanism by which the parasite undermines fundamental biological processes (Qin et al., 2019).

Iranian studies have revealed that dodder parasitism seriously affects sugar beet's photosynthetic capacity. Infested plants lose substantial photosynthetic pigments, with chlorophyll a levels decreasing by up to 30%, chlorophyll b by up to 18%, and total chlorophyll by up to 38% (Jafarzadeh et al., 2015). This direct attack on the plant's energy production capacity is a main reason for the 18% reduction in foliage dry weight (Jafarzadeh et al., 2015).

Beyond resource depletion, dodder infestation causes severe physiological stress in the host plant (Duan et al., 2022). These stress responses have been elucidated by recent Iranian studies examining mitigation measures. Research at Bu-Ali Sina University showed that dodder parasitism resulted in 44.9% reduction in shoot biomass and 57.5% reduction in root biomass compared to weed-free controls.

Economic Damage: Yield Loss and Quality Degradation

Iranian research confirms the immense damage potential documented globally. Dodder epidemics have reduced sugar beet growth and yield by 35-50% in West Azerbaijan (Meighani et al., 2017). These effects were further quantified by field studies in Urmia region of the same province, which reported 25% reduction in total root yield, 1.8 units reduction in sugar content (an absolute reduction equivalent to a relative quality reduction of more than 10% of the baseline value of 16-17%), and 18.5% reduction in impure sugar (Jafarzadeh et al., 2015). Similar findings have been reported elsewhere. In Chenaran, Khorasan Razavi province, dodder parasitism resulted in average root yield loss of 15% and sugar content reduction of 1.06 percentage points. Notably, effects on processing quality were also highlighted, with a 32% increase in sodium concentration (a harmful impurity complicating sugar extraction) and 20.75% decrease in processed sugar yield (Amir et al., 2011). In key impacted provinces, agronomists agree that damage from dodder affects approximately 40% of infested fields, making it one of the major economic threats to the industry (Najafi, 2024a).

Simultaneous reduction in yield and quality creates compounded economic loss extending throughout the value chain. Farmers are typically paid based on beet raw weight and sucrose concentration (AgMRC, 2022). Dodder infestation negatively impacts both parameters, resulting in lower volumes of sellable material and reduced price per ton. For sugar factories, consequences are equally critical. Processing beets with reduced sugar content and high impurity concentrations like sodium is inherently less efficient (Üstüner, 2018). This requires greater energy inputs to extract marketable white sugar and results in larger proportions of low-value by-products such as molasses (Amir et al., 2011). Therefore, dodder's harmful effects are not limited to farms but extend to causing significant inefficiencies in industrial processing, damaging the profitability of the national sugar industry and undermining economic foundations of national self-sufficiency goals.

Management of Dodder in Sugar Beet Fields

Prevention Strategies

Prevention is universally accepted as the most effective and cost-efficient long-term method for combating dodder infestation. Field observations in several Iranian provinces indicate that use of fresh animal manure, livestock grazing, and contamination of field margins are the primary pathways of dodder introduction into sugar beet production areas (authors' unpublished observations; Najafi, 2024b).

Farm-Level Sanitation: This is the foundation of dodder prevention and involves several absolutely essential practices. In Iranian sugar beet production, where certified seed is provided without weed seed contamination and no farm-saved seed is used, particular focus should be on field sanitation and border control. Key sanitation practices include: thorough cleaning of farm equipment, especially harvesters, when moving between infested and uninfested fields; elimination of dodder from field margins; maintenance of clean irrigation systems; use of composted animal manure to eliminate possible dodder seeds; limitation of animal grazing in infested areas; and elimination of host weeds supporting dodder growth (Najafi, 2024b).

Non-Chemical Management Methods

Crop Rotation: This is a powerful agronomic approach to dodder management working through multiple mechanisms. Since *C. campestris* cannot parasitize monocotyledonous species, strategic crop rotation with cereals can effectively deplete the dodder seed bank. However, timing and selection of rotation crops is critical. *Cuscuta campestris* is a summer annual weed germinating when soil temperatures exceed 10-15°C, typically from late spring through summer. Therefore, fall-planted cereals such as wheat and barley do not stimulate dodder germination due to low temperatures during their growth period, resulting in minimal seed bank depletion. In contrast, summer cereals such as maize, millet, and sorghum are more effective for dodder management as they are planted during the dodder germination window. These warm-season crops stimulate dodder seed germination but prevent the parasite from completing its life cycle, thereby actively depleting the soil seed bank (Sarić-Krsmanović & Vrbničanin, 2015). For optimal seed bank reduction, infested fields should be rotated with summer cereals for 4-5 consecutive years. Rotation interferes with the parasite's life cycle, hindering reproduction and seed production. When dodder seedlings germinate in a cereal system, they cannot find suitable hosts and die within days, slowly depleting the soil seed bank. Heavily infested sites are often recommended to be rotated for at least four to five years without susceptible crops. Figure 3 shows a schematic illustration of an educationally beneficial rotation cycle (Sarić-Krsmanović et al., 2022).

***Mechanical and Physical Methods*:**

Mechanical methods are most effective where infestations are small-scale and identified early. Such tactics have been proven effective by empirical evidence in Iran and other countries. Isolated dodder patches are removed or hoed manually, preventing seed production and further propagation (Mishra, 2009). Mechanical eradication at early stages has been effective in controlling small-scale infestations in Kermanshah and Khuzestan province fields. If dodder is eliminated after flowering, plant biomass should be cut and destroyed (e.g., through burning) to prevent mature seed dispersal. Mechanical control programs have been found successful in Californian sugar beet operations and European production systems (Mishra, 2009). Tillage can also be used strategically; shallow cultivation can uproot and destroy nascent dodder seedlings before host attachment. However, deep plowing may bury fresh seeds below germination depth but also bring older, dormant seeds from deeper layers to the surface (Mishra, 2009).

***Planting Date and Crop Density*:** Changes to agronomic practices can create more unfavorable environments for dodder colonization. Delayed sugar beet planting enables an early flush of dodder germination followed by seedling death in absence of suitable hosts (Mishra, 2009). Conversely, research in Miandoab, Iran, proved that early planting schedules combined with timely propyzamide application are highly effective integrated methods, as early-planted crops outcompete later-emerging dodder (Jafarzadeh & Najafi, 2020). Increasing crop density by reducing row spacing also inhibits dodder growth by promoting rapid canopy cover that shades the soil surface, inhibiting germination and growth of the parasite's light-dependent physiology. Combined control programs integrating cultural and chemical methods have shown promising results in Iranian field trials (authors' unpublished data).

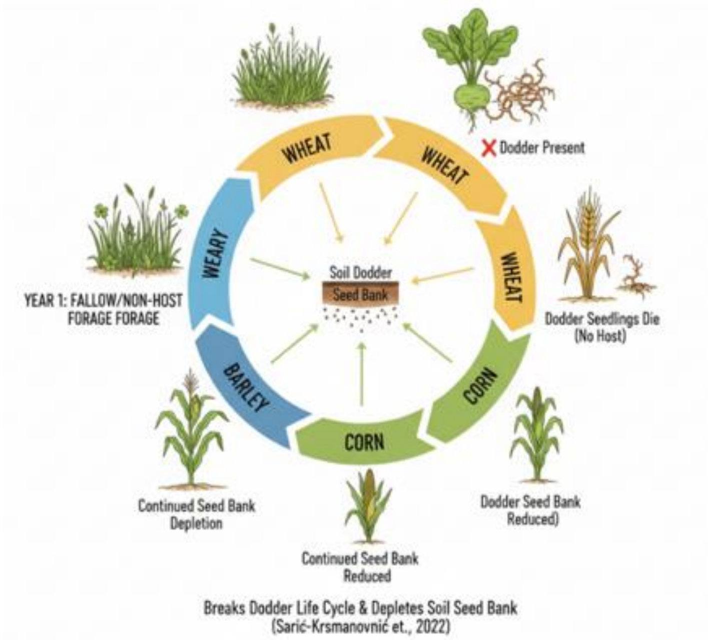

Figure 3. Dodder management: 5-year crop rotation cycle (Sarić-Krsmanović et al., 2022).

Chemical Control

Active Ingredients: Efficacy and Application

Extensive herbicide evaluation in Iran has consistently identified propyzamide as the most effective active ingredient for specific control of *C. campestris*.

***Propyzamide*:** In several studies, propyzamide (in 50% Suspension Concentrate (SC) and 50% Wettable Powder (WP) formulations) has proven most effective. At 2.5 L ha^{-1}, it achieved 99.6-100% control of dodder biomass, effectively eradicating the parasite in treated plots (Hoseyni et al., 2018). Propyzamide was also highly effective at lower application rates of 1.925 L ha^{-1} with 87-99% control (Hoseyni et al., 2018; Sohrabi et al., 2001). Propyzamide is officially registered with a recommended dosage of 2500 g a.i./ha and must be applied before dodder attachment to sugar beet (Sharifi Ziveh et al., 2016). Successive germination flushes of dodder seeds at different times due to seed dormancy necessitate repeated spraying every 20 days for late-germinating seeds. Degree-day accumulation can also be used to determine optimal herbicide application timing (authors' unpublished data).

***Ethofumesate*:** Ethofumesate, developed as a 200 g/L spray concentrate, has shown moderate to good efficacy on dodder. At the legally registered rate of 2000 g a.i./ha, it provides good control in Iranian sugar beet agro-systems. Its effect on parasite biomass is usually less than propyzamide (Sohrabi et al., 2001) but plays an important role in combined weed control. Field experiments established that tank mixtures of ethofumesate (2 L ha^{-1}) with haloxyfop-R methyl ester (a graminicide for grassy weeds) showed the highest overall yield increment, reaching 86.5% improvement compared to controls (Hoseyni et al., 2018). This finding highlights farmers' need to control entire weed communities rather than focusing on single problematic species. Given propyzamide's and ethofumesate's low efficacy on broadleaf weeds, combining with broadleaf herbicides like Betanal Progress OF (a formulation of desmedipham, phenmedipham, and ethofumesate) is suggested to ensure complete weed suppression (Chitband et al., 2014).

***Trifluralin*:** Proper timing and application methods are required for trifluralin (48% Emulsifiable Concentrate (EC) formulation). Trifluralin can control germinating dodder seeds when properly incorporated into soil after sugar beet thinning at the 4-6 leaf stage, at recommended dosages without causing crop phytotoxicity (authors' unpublished data; Sohrabi et al., 2001). However, inappropriate timing can cause severe crop injury. Strategic trifluralin use typically involves initial propyzamide application followed by timely trifluralin application to inhibit later dodder germination waves and other weed species. This sequential approach eliminates the need for further herbicide applications while providing comprehensive weed management (authors' unpublished data).

Glyphosate**:** Glyphosate is a non-selective systemic herbicide effective for dodder control, available in various formulations. However, it must be used cautiously in conventional sugar beet fields due to potential crop damage. Low-rate experiments with applications of 100-350 m L ha^{-1} have been investigated in Iran, effectively inhibiting the parasite with reduced phytotoxicity risk. Recent field tests indicate applications up to 350 mL ha^{-1} do not cause serious crop damage (authors' unpublished data). Therefore, glyphosate should be used as spot treatment for isolated infestation foci or, more strategically, with glyphosate-resistant sugar beet cultivars, enabling safe, broad-spectrum post-emergence applications (Zagorchev et al., 2025).

Other Herbicides**:** A 2024-2025 case study by Najafi and Hatami in Miandoab and Karaj (West Azerbaijan and Alborz provinces, Iran) showed several treatments provided 100% dodder control, reducing overall density and dry weight by 100%, comparable to hand-weeding in weed-free control plots. Highly effective treatments included split application of Prowl (pendimethalin 45.5% Capsule Suspension (CS)) at the 8-leaf stage at 1 L ha^{-1} and single application at the 6-8 leaf stage at 2 L ha^{-1}. It is important to note this herbicide is not registered for sugar beet in Iran and requires approval procedures. Similarly, Sesout (propyzamide 50% SC) at 1.25 L ha^{-1} applied after germination but before attachment, with split application repeated 21 days later, resulted in 100% control. Additionally, treatment with Kalmis (propyzamide 50% WP) at 3500 g/ha following dodder germination, combined with tank mix of Treflan (trifluralin 48% EC) at 2 L ha^{-1} and Prowl at 1 L ha^{-1} at the 8-leaf stage, also led to complete parasite eradication (Najafi and Hatami, 2024, unpublished data).

Results from these local studies reveal important practical considerations for integrated weed management. Although propyzamide was superior for dodder destruction, ethofumesate-based mixtures provided best crop outcomes through better overall weed control. This indicates that dodder, despite being very destructive, is often found within larger communities of competing weeds. Successful chemical programs should address this entire weed assemblage. The best strategy is not always the single best anti-dodder herbicide but a combined approach, likely including well-chosen tank mixes such as propyzamide with graminicides, as proposed by one study (Hoseyni et al., 2018), to provide comprehensive effects and highest farmer profitability.

Sugar Beet Cultivar Resistance

Screening Commercial Cultivars in Iran

Use of resistant host-plant cultivars is a critical and sustainable long-term approach to controlling *C. campestris*. Iranian scientists have initiated screening programs of commercially available sugar beet cultivars to determine their dodder susceptibility, with promising results. One important study in highly infested Khorasan Razavi province measured the reaction of five commercial sugar beet varieties to parasitism: Castel, Paulina, Brigitta, Flores, and Laetitia (Fallahpour et al., 2013). The analysis found significant genetic variation in host response (Table 3).

Table 3. Comparative resistance of commercial sugar beet cultivars to *C. campestris* in Iran

Cultivar	Resistance Classification	Key Performance Indicators
Flores	Resistant	Lowest reduction in root and shoot dry weight under dodder infestation; supported lowest dodder biomass with fewest haustoria connections
Castel	Susceptible	Supported highest dodder biomass and number of haustoria
Paulina	Susceptible	Showed greatest percentage reduction in root and shoot dry weight when parasitized
Brigitta	Intermediate	Performance fell between resistant and susceptible extremes
Laetitia	Intermediate	Performance fell between resistant and susceptible extremes

Data from Fallahpour et al. (2013)

Flores was the most resistant cultivar. In infested plants, root and shoot dry weight reductions were least compared to uninfected controls, implying greater tolerance to the parasite's presence. Additionally, dodder biomass was lowest on Flores with the fewest haustoria found on its stems, indicating true resistance or host unsuitability. Conversely, Castel was most vulnerable, supporting maximum dodder biomass accumulation and haustorial connections. Paulina was also very sensitive, recording the highest percentage biomass loss when parasitized (Fallahpour et al., 2013).

This study provides clear evidence that genetic resistance to dodder exists in commercial sugar beet germplasm available in Iran. This is supported by the country's active breeding and evaluation programs testing different cultivars, including Ardabili, Aras, and Persia, against other important pests, indicating strong infrastructure for crop improvement (Fathi and Abedi, 2014).

Mechanisms explaining resistance in cultivars like Flores appear related to inherent incompatibility preventing effective parasite establishment and host exploitation. Flores' resistance suggests it may possess physical or biochemical characteristics, such as thicker epidermis and cuticle or synthesis of antimicrobial compounds, that prevent or delay haustorial penetration and growth after attachment (Fallahpour et al., 2013).

Discovery of this resistant germplasm has strategic value of indescribable importance for national sugar beet breeding programs in Iran. It provides accessible genetic material that can be integrated into high-quality breeding lines. This possibility represents a paradigm shift from strictly reactive, chemically dependent management systems to proactive, genetically determined, and ultimately more sustainable approaches. Nevertheless, for this strategy's success and wide farmer adoption, dodder resistance cannot be sought as a single characteristic. In addition to dodder resistance, farmers need cultivars with high yield potential, high sugar content, and resistance to other significant diseases including Rhizomania and cyst nematodes, which are important in Iran (IPPN, 2022; Soltani Idliki et al., 2016). Consequently, breeders must stack these characteristics.

The future of sustainable sugar beet production in Iran depends on breeding programs' capability to incorporate dodder resistance screening in current pipelines, producing new cultivars with multiple layers of genetic protection against the entire range of biotic challenges. This strategic shift from short-term chemical remedies to long-term genetic solutions is essential for the industry's long-term sustainability and profitability.

Challenges and Solutions

Key Challenges

Managing *C. campestris* infestations in Iranian sugar beet fields is complex, hindered by multiple biological, economic, and logistical barriers. The biggest biological barrier is the persistent seed bank of this parasitic weed; surviving more than ten years in soil, management requires long-term approaches to reduce infestation pressure. Chemical control methods are also restricted and time-sensitive; beneficial herbicides such as propyzamide can only be applied before dodder attachment, giving farmers very limited timeframes for effective control. Additionally, economic and logistical pressures from crop processing problems may reduce farmers' motivation to invest in costly preventive control measures. Finally, knowledge gaps remain important barriers, highlighting the need to improve extension services and farmer education to facilitate Integrated Weed Management (IWM) principles implementation.

Integrated Weed Management Framework

Relying on one control method will fail against a noxious pest like dodder. A complex IWM framework is the only way to achieve sustainable long-term control. This is not a single prescription but a multi-tactic approach using preventive, cultural, mechanical, and chemical methods in coherent, logical sequences (Sarić-Krsmanović and Vrbničanin, 2015). A successful IWM plan for dodder management in Iranian sugar beet fields is organized as follows:

Prevention (Foundation): This is the first and most important protection level, based on high farm hygiene standards requiring use of certified, dodder-free seed, cleaning all farm machinery before field entry, and careful attention to field boundaries and irrigation channels to eliminate external infestation sources. Other preventive strategies include cleaning field margins, removing small dodder patches to prevent seed bank reinforcement, eliminating uncomposted organic fertilizers and manures potentially containing dodder seeds, and limiting livestock grazing in infested areas to prevent seed dispersal through animal movement (Najafi, 2024b).

Cultural Control (Proactive Management): This relates to agronomic activities reducing agroecosystem attractiveness for dodder. Key elements include properly designed crop rotation with non-host cereal crops such as maize or sorghum to break the parasite's life cycle. Sugar beet can also gain competitive advantages by optimizing planting dates and using increased crop densities to achieve rapid canopy cover (Najafi, 2024b).

Mechanical and Physical Control (Early Intervention): This layer addresses infestations as they occur, involving careful scouting and direct destruction of small, isolated dodder patches by hand-pulling or hoeing before seed production. Where infestation is more widespread, focused burning has been effective (Mishra, 2009).

Chemical Control (Judicious and Targeted Use): Herbicides should not be initial defense mechanisms but rather strategic tools employed when other mechanisms are insufficient. This requires using the best selective herbicide (propyzamide) at the right time before plant attachment. Propyzamide is best applied in broader programs potentially including tank-mixing with other herbicides such as graminicides depending on particular field weed pressure. Additionally, trifluralin use after sugar beet thinning is useful in preventing subsequent dodder germination, providing long-term control (Hoseyni et al., 2018).

Genetic Control (Long-Term Solution): The final and most sustainable level is widespread use of genetically resistant sugar beet cultivars. This enables farmers to have inherent protection against dodder throughout the season. As breeders succeed in transferring resistance from cultivars such as Flores into new high-yielding varieties, this will largely eliminate needs for chemical and mechanical pest elimination methods (Fallahpour et al., 2013).

Biological Control (Alternative Method): Biological control is a potential direction for long-term, environmentally friendly dodder management, although practical implementation in Iran remains mainly in research and development phases. Iranian scientists have identified native natural enemies for *C. campestris*. These initiatives have discovered potential biological control agents including various insects and fungal pathogens. Potential biological control agents identified in Iran include various insect species, though most studies have focused on *C. monogyna* rather than *C. campestris*. Larvae of the moth Porphyrinia polygramma, which feed on dodder reproductive structures, show promise for *C. campestris* management (Norouzi, 2020).

However, developing these native organisms into stable, commercially viable biocontrol agents is complicated, requiring extensive research in mass production, formulation, and field efficacy; thus, they are not yet available for large-scale use. Iranian studies have also recently addressed new biotechnological approaches. Innovative research was conducted on phyto-synthesis of silver nanoparticles with Rhazya stricta plant extract. These nanoparticles were effective herbicides in laboratory tests, suppressing dodder seed germination and seedling growth (Zamanipour et al., 2025).

Conclusions and Future Research Needs

Concluding Remarks

Control of *C. campestris* in sugar beet fields in Iran represents a complex agronomic problem at the interface of national food security policy, industrial infrastructure, and on-farm practice. The country's strategic, successful shift toward water-saving fall production has increased the necessity to safeguard this precious crop against yield-reducing threats. Although effective chemical tools (primarily propyzamide) are available, reliance on one mode of action is neither economically nor ecologically viable long-term. A progressive practical path requires strong movement toward robust, multi-tactic Integrated Weed Management (IWM) frameworks. Prevention and sanitation must form such frameworks' foundation, supported by preventive cultural measures such as crop rotation and supplemented by reasonable chemical use. Finally, the most sustainable and resilient solution can be found in national breeding programs creating and introducing high-yielding sugar beet breeds with high genetic resistance to dodder and other important pathogens.

Knowledge Gaps for Future Research

Although much progress has been made, several knowledge gaps remain, justifying specific future studies. Research potential of new controls such as silicon amendments and bio-herbicides needs confirmation with large-scale, multi-location field trials to determine real-world effectiveness, cost-effectiveness, and practical applicability for producers. Furthermore, creating economic thresholds for *C. campestris* infestation of Iranian sugar beet fields, given potential yield increases, would provide farmers with scientifically-based guidance on when chemical control is necessary. The effect of changing climatic patterns on host-parasite interactions, especially dodder phenology, geographical distribution, and virulence with respect to growing fall-sown sugar beet crops, also needs elucidation. Finally, while potential native biological control agents have been identified, thorough research is needed to determine their efficacy, safety, and host specificity before release.

Emerging Research and Novel Approaches

Simultaneously with optimizing current IWM policies, Iranian studies are actively investigating new solutions potentially providing new dodder management tools. Silicon (Si) soil amendment use is one promising area. Recent research has shown that potassium silicate soil application improves sugar beet's natural defenses, enhancing cell wall lignification (increasing physical resistance to haustorial penetration) and increasing antioxidant defenses, allowing plants to better withstand physiological stress from parasitism. This method represents a new way of increasing crop resilience rather than attacking the weed.

Another active research frontier is biocontrol agent development. Research on silver nanoparticles produced using plant extracts and compost extracts has demonstrated potential for selective dodder control in laboratory environments (Zamanipour et al., 2025). Although not yet commercialized, these investigations are leading toward a future where dodder management could be based on environmentally friendly, biologically based compounds.

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