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REVIEW

Overview of Techniques for Sustainable Sugar Beet Production

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Abstract
European sugar production is influenced by the demand for alternative sweeteners, new technologies, and Common Agricultural Policy. Sugar beet is a biological resource with high carbon accumulation; chemically and energy-intensive crop with high rate of assimilation and carbon-dependent microbiome. The structure of associated greenhouse gas emissions is well known. In this review, currently available tools able to reduce environmental burden and the risk of resistance are summarized from the viewpoint of sustainability. In the field of herbicide protection, strip tillage combined with early-sown, fast-growing and freezing out intercrops is discussed, combined with tolerance to acetolactate synthase enzyme inhibitors, herbicide point application techniques, and autonomous inter-row weeding systems. Modern methods of insecticidal protection are based on cultivation of companion crops with camouflage or repellent effects, biological traps used by organic sugar beet growers and plant protection products based on essential oils. Current state of European insecticide scene calls for the utmost need for the integration of signaling methods and techniques of chemical and physical fixation of conventional plant protection products not burdened by resistance. Protection against pathogens is discussed according to the activity of the associated microflora, subsequently categorized into four lines of defense. Biofungicides are widely available, but for now, too technology-demanding and costly. The implementation of new fungicidal biotechnologies based on breeding associated with microbiome is very close, but – for now – still missing proper impulse for their introduction into practice, caused by a fundamental legislative restriction or economic pressure.

Keywords Sugar beet · Plant protection · Weed · Pest · Pathogen · Sustainability

Introduction

Sugar production is slightly declining in the European Union (Kolář, 2021; Pole, 2022). Due to current trends in human nutrition, sugar intake is being reduced (WHO, 2023) and replaced by sweet-taste alternatives (Arshad et al., 2022). At the same time, with no exemptions granted for the use of neonicotinoid stains (Judgement of the Court, 2023), sugar beet areas are destabilized. The declining trend in sugar beet area since the end of the EU sugar quota system, the EU beet area has decreased by 200,000 ha or 12% since 2017 (Pole, 2022). Increasing pressure for protection against soil erosion (Panagos et al., 2020, 2021) and higher influence of the benefits of carbon agriculture (Radley et al., 2022; COWI 2020) could further stimulate the decline of cultivation areas. Sugar beet acreage in the EU is expected to be falling further by 5–8% in the upcoming 2025/26 season according to Tereos (Angel, 2025). On the other hand, European economy and the trend towards reducing fossil fuels provide space for biological resources with high carbon accumulation (Panella, 2010; Ptak et al., 2022). Market price of sugar beet increased significantly due to common agricultural policy (Eurostat, 2023a, b). The price of sugar increased from 2020 to 2023 by up to 60%, followed by sharp decline of prices in recent years. Sugar prices in EU dropped to 541 EUR per metric ton, down by 35%, during

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the last year due to export from Ukraine, high output and falling consumption, which are factors that could destabilize back to higher prices in near future (Angel, 2025). Current growers' effort is making sugar beet cultivation more sustainable; the trend is to increase interest in biofertilization and stimulation, breed tolerant varieties, and apply biological protection (Wolfgang et al., 2023). Following overview discusses strategies for sustainable sugar beet cultivation in the EU zone with an emphasis on the use of biological plant protection methods.

Protection Against Weeds

Sugar beet is characterized by a high level of chemical intensity (European Environment Agency, 2023). Herbicides represent the most expensive element of chemical protection (Nichterlein et al., 2013), also contributing the most to pesticide carbon footprint (Cech et al., 2022). The results from experimental plots from Poland and Germany showed high efficiency of growing glyphosate-resistant sugar beet (4–18% higher yield of sugar), the amount of active substances was significantly reduced compared to conventional herbicide programs (Nichterlein et al., 2013) and the use of glyphosate was approved on November 28th 2023 until 2033 (EC, 2023a). However, cultivation of glyphosate-resistant beet is not allowed in the EU. The paradox of high degree herbicide load is the allelopathic effects of sugar beet, described for both mono- and dicotyledonous weeds (Dadkhah, 2013; El-Wakeel et al., 2019).

Very few regional projects in Europe study the potential of biological protection of crops against weeds. Only one research program for the biological control of fern (*Pteridium aquilinum*) in the UK is now in advanced phase (EC, 2023b). Experiments with herbicidal microorganisms, e.g. with some species of the phytopathogenic genus *Colletotrichum*, selective for sugar beet, on the other hand, showed some effect only for a limited number of weed species (Harding & Raizada, 2015).

The basic prerequisites to reduce the rate of weeding have been the principles of crop rotation. For sugar beet, the most suitable crop to limit weed occurrence is black medick (*Medicago lupulina* L.), whose allelopathic properties can be used in the cultivation of organic sugar beet (Götze et al., 2017; Ghimire et al., 2019). While the effects of direct seeding on cultivation efficiency are not fully explored yet, a cultivation system combining intercropping with strip tillage can reduce weeds (Afshar et al., 2019; Kunz et al., 2017;) and leads to higher sugar beet production efficiency (Tarkalson & King, 2017; Kunz et al., 2016) with increased carbon sequestration (Overstreet, 2009). Strip-till technology can be combined with a herbicide program when growing varieties equipped with specific tolerance to ALS (acetolactate synthase enzyme) inhibitors. Despite obvious risks (Wenninger Löbmann et al., 2019), this technology represents a rational choice thanks to intensive financial and energy savings, as well as further reduction of carbon footprint (Fishkis et al., 2024). Selection of suitable agrotechnology is often based on other factors, for example demands for optimal yield of the following crop. The method of soil management, technology used to deal with post-harvest residues, as well as the seeding density and usage of nitrogen fertilizers can have a statistically significant effect on the production parameters of spring barley, of which sugar beet is a frequent forecrop (Cerkal et al., 2001).

Currently, time-modulated pulse (PMW) technology is routinely used to increase the accuracy of plant protection product applications; the field sprayer has electrovalves for individual nozzles that can be selectively turned on/off and the herbicide is only applied locally according to the prescription map. However, the requirements for taking photographs from unmanned drone and subsequent automated process of weed identification for the creation of application map are often too high for growers, or financially demanding. Real-time weed identification is a different approach. Standardized data communication protocols between the sensor, control unit and sprayer are already available, but the identification algorithms for a wide spectrum of weeds did not show sufficient reliability necessary to expand targeted applications into the cultivation practice (Butts et al., 2019; Rejeb et al., 2022; Allmendinger et al., 2022; Sabanci & Aydin, 2017). In the context of sustainability, systems of automated/autonomous inter-row seeding are the only one widely accepted and dynamically developing low-energy technology, which can also be used in organic farming conditions (Shang et al., 2023). Conventional mechanical methods, although not presenting toxicological risks and negative effects on soil biota, soil erosion and sugar yield, according to field trials, lead to 100–150% greenhouse gas emissions increase compared to conventional herbicide application (Fishkis et al., 2024).

Protection Against Pests

The volume of pesticides traded in the Czech Republic decrease by 36% from 2011 to 2021 (Eurostat, 2023c), reflecting continuous decline of active substances application. Neonicotinoid seed dressing, which provides effective protection against predatory pests and virus vectors, was declared risky for non-target organisms, primarily bees, despite the fact that production sugar beets does not form flowering stands (Viric Gasparic et al., 2020; Hauer et al., 2017). New strategies are asserted, combining the absence of insecticide treatments with the diversification of agroecosystems (Guinet et al., 2023) in the form of cultivation of camouflage crops, repellent crops or, for example, the use of biological traps, based on the introduction of a mixture of cruciferous plants that capture the perch in beet stands; however, robust data demonstrating the effective use of companion crops in agricultural practice are not available yet (Scagliarini et al., 2023). In addition to resistance-affected pyrethroids, carbamates that fail under high pest pressure, and highly selective diamides, alternative plant protection products, transparently evaluated in terms of effectiveness, durability, applicability, and practicality, can be used to directly protect emerging sugar beet plants. Products based on spinosad and azadirachtin as active substances have been evaluated as effective against a wide range of pests and potentially useful for seed treatment, but not yet registered for sugar beet (Viric Gasparic et al., 2020; Verheggen et al., 2022; Holy & Skuhrovec, 2020; Bažok et al., 2016).

Registered products based on potassium salts of natural fatty acids can be used in agricultural practice; their effectiveness is limited only to sucking pests. Terpenic oils, for example products extracted from citrus peel, cover a wider range of targets. Inhibition of acetylcholinesterase and octopamines in insects, mediated by monoterpenes and sesquiterpenes, is well studied and documented (Viric Gasparic et al., 2020; Villafañe et al., 2011; El-Fakharany et al., 2012; Tripathi et al., 2009). Widely available *Pongamia pinnata* (L.) seed oil shown high level of insecticidal and larvicidal efficiency, but requires higher frequency of applications due to low water solubility, photosensitivity and high volatility, which is reflected in higher costs (Purkait et al., 2021).

Neither the efforts to hasten the authorization of plant protection products based on microorganisms, supported by four Commission (EU) Regulations from 2022 and the resulting change in criteria for approval of active substances in EU countries (EC, 2023c), nor the increasing interest in organic sugar beet cultivation (European Environment Agency, 2023) have contributed yet to the registration of effective bioinsecticides based on polyphagous fungi from *Metarhizium* and *Beauveria* genera (Zottele et al., 2023; Francis et al., 2022), metabolic products of the *Bacillus* genus or parasitic nematode *Heterorhabditis bacteriophora* Poinar, proven to protect against pests during later growth stages of sugar beet (Drmić et al., 2020). Due to the lack of crop protection alternatives, the European Parliament rejected the Commission's proposal to reduce the volume of pesticides by 50% by 2030 (on November 22nd, 2023) (European Parliament, 2023). Although there is no immediate risk of lack as for active insecticide substances, the resistance issues, accelerated by the prohibition of neonicotinoid staining (Viric Gasparic et al., 2021), requires the consolidation of all available IOR procedures, including signaling methods for the detection of pest occurrence (Petrovic-Obradovic et al., 2023; Kocourek et al., 2002; Knodel, 2017; Bittner et al., 2019) and measures to maximize the effectiveness of registered insecticides.

Application of contact insecticides can be difficult to coordinate with simultaneous use of foliar nutrition which can contribute to higher average weight of sugar beet tubers and slightly increase the content of carbohydrate´s precursors (Hřivna & Cerkal, 2009). Buffers (not acids) can be used to stabilize optimal pH of the spray solution, thus preventing hydrolysis and photodegradation of active substances (Liang et al., 2019; Takahashi et al., 1985), protection against *washing away* and photodegradation (Zhu et al., 2018). Organic sugar beet producers can only rely on natural biostimulants based on fermentative hydrolysates, accelerating biomass growth in the initial stages of development (De Pascale et al., 2018) and direct protection of plants against pests during early growth stages (Petrović et al., 2032), based on the application of mineral and natural oils (Villafañe et al., 2011; El-Fakharany et al., 2012; Tripathi et al., 2009; Purkait et al., 2021).

Protection Against Pathogens

Low-energy crop cultivation techniques with minimal impact on the ecosystem represent the future of sustainable agriculture. The protection of sugar beet plants won't be based on new active substances, but on the implementation of techniques of molecular genetics and ecology. Carbon-excess root exudation makes sugar beet a suitable model for holobiont-based plant protection research. The collective genome of plant-associated microbiota far exceeds the host genome in both size and number of functions. Microorganisms contained in seeds provide ideal starter cultures for emerging plants, while soil-derived microorganisms enable adaptation to local conditions.

Model interaction with *Rhizoctonia solani* was used to describe several defense mechanisms of sugar beet according to the activity of the associated microflora, subsequently categorized into "four lines of defense". The first line of defense uses "long-range" antagonists contained in the rhizosphere, e.g. *Streptomyces* spp. And *Paraburkholderia graminis*, that inhibit pathogens via volatile organic compounds. Second line of defense is activated by oxalic and phenylacetic acids produced by the pathogen. The numbers of colonies of *Oxalobacteraceae*, *Burkholderiaceae*, *Sphingobacteriaceae* and *Sphingomonadaceae* family microorganisms increase significantly in the rhizosphere. Alarmons are activated, triggering a cascade of defense mechanisms leading to activation of other rhizobial microorganisms. The third line of defense includes the root endophytes *Pseudomonas*, *Chitinophaga*, and *Flavobacterium*, which can alter their metabolic profiles to produce antibiotics (Wolfgang et al., 2023; Safara et al., 2022; Carrión et al., 2019).

Sea beet, *Beta vulgaris* L. subsp. *maritima*, was commonly used as a source of key characters due to evolutionary closeness of this taxon to cultivated *Beta vulgaris*. Wild populations of *B. vulgaris maritima* grow spontaneously along European coasts and show high plasticity in response to cercospore leaf spot or rhizomania; new biomarkers derived from the sea beet microbiome are investigated (Stevanato et al., 2001). By sequencing the microbiome of extrinsic leaf endophytes, the genera *Methylobacterium* and *Mucilaginibacter* were identified in sensitive plants, showing significantly higher frequency of colonization after the plants were infected by cercospora. On the other hand, the presence of *Sphingomonas* and *Acidovorax* genera was observed exclusively in asymptomatic plants (Broccanello et al., 2022). Bacterial community of sugar beet seeds can be modified relatively easily using the substrate of the mother plant. Although the list of bacterial bio-agens suitable for the protection of sugar beet is wide and readily available and the transplantation of suitable microbiomes to seed represents an important direction of biological protection (Wolfgang et al., 2023; Sacristán-Pérez-Minayo et al., 2020), their contribution to agricultural practice won't be realized without a proper impulse caused by major legislative restriction or economic pressure. Further dramatic increase in fertilizer prices would cause mass introduction of endophyte-based preparations, as was the case of *Gluconacetobacter diazotrophicus* introduction (Ceballos-Aguirre et al., 2023; Tufail et al., 2021). The fourth line includes defense mechanisms and physiological traits specific to the plant host (Wolfgang et al., 2023).

Pythium oligandrum Drechs. attracted considerable attention thanks to mycoparasitism and antibiosis abilities, catalytic enzyme production, and nutrient competition. The cell walls of *P. oligandrum* produce two structural types of proteins. Their elicitation capacity was proved by laboratory exposure of the rhizosphere of sugar beet plants to *R. solani* isolate. Attack symptoms inhibition was accompanied by increased activity of phenylalanine ammonium lyase and chitinase along with increased concentration of cell wall-bound antioxidants (Takenaka et al., 2003). Currently, *P. oligandrium* is the only biofungicide registered for sugar beet treatment.

Methods of direct protection against foliar diseases usable in organic farming are widely available today. Biofungicides based on microorganisms can be used, namely *Bacillus pumilus* QST 2808 against beet powdery mildew (Anastassiadou et al., 2020) and *Bacillus subtilis* strain QST 713 against cercosporium leaf spot (Anastassiadou et al., 2021). Preparations combining terpene oil with copper compounds or with elemental sulfur are also available, with an emphasis on particle size reduction and high wettability.

The maximum effect can be achieved by integrating direct protection methods with predictive modeling of disease occurrence, which has already been automated and is widely distributed among the growers. The most commonly predicted disease is cercospore leaf spot; its occurrence is indicated by a sequence of continuous rain (four hours) preceding the onset of the infectious event, followed by a four-hour period at a relative humidity $\geq$90% and a nine-hour period at a relative humidity $\geq$60%, during which the daytime temperature is $\geq$16 °C and night temperature $\geq$10 °C (Wolf & Verreet, 2002; El Jarroudi et al., 2021).

Pesticides are carbon intensive, expensive, carry the risk of resistance and are threatened by restrictions. Differences in greenhouse gas emissions vary significantly among the growers. In the area of plant protection products and fertilizers, variability can reach up to 40%. Thus, the opportunity to reduce environmental load is apparent here (Żyłowski & Jerzy, 2020; Garcia Gonzalez & Björnsson, 2022).

Conclusion

Sugar beet has high yield of assimilation; it is able to sequester significant portion of carbon from the ecosystem. According to carbon footprint studies and data on greenhouse gas emissions, implementation of modern cultivation technologies could further reduce energy, economic and environmental burden. The use of sustainable plant protection tools is still limited. An overview of legislative-approved and quality-unthreatening plant protection procedures is given in this review. Sugar beet can be grown – using currently available tools – in an organic farming regime, under reduced energy input or using a combination of both technologies. Plant residues, root exudation and associated microbiome represent promising areas of future research to increase social and ecological status of the crop.

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Declarations

Conflict of Interest The authors received no funding support and declare no conflict of interest.

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