Journal of Agriculture and Food Research 24 (2025) 102343



Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research



The case of sugar beet in Europe: a review of the challenges for a traditional food crop on the verge of climate change and circular agriculture

Jan-Peter Nap [a], Frank J. de Ruijter [b], Daan S. van Es [c], Ingrid M. van der Meer [a,*]

[a] Wageningen Plant Research, Bioscience, Wageningen University & Research, P.O. Box 16, 6700AA, Wageningen, the Netherlands
[b] Wageningen Plant Research, Agrosystems Research, Wageningen University & Research, P.O. Box 16, 6700AA, Wageningen, the Netherlands
[c] Wageningen Food & Biobased Research, Biobased Products, Sustainable Chemistry & Technology, Wageningen University & Research, P.O. Box 17, 6700AA, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Biorefinery
Circular agriculture
Climate impact
Crop yield
Plant breeding
Sugar feedstock
Resilience

ABSTRACT

Sugar beet (*Beta vulgaris* L.) accounts for about 20% of the world's sugar production, half of which (17 million metric tonnes) is produced in the European Union, whose temperate climate suits the crop's cultivation requirements. Besides the traditional food component sucrose, added value comes from the byproducts of sugar extraction (pulp, molasse, carbonation lime) and possibly the crop's aboveground parts. Sucrose as a biobased industrial feedstock may help replace fossil carbon for non-food applications. To promote such use, yields should go up. Sugar beet yield has increased over time despite the presence of many pests/pathogens during growth and harvest. Careful crop rotation is vital for high land-use efficiency. Climate change will present a mix of potentially positive (*e.g.,* extended growing season) and negative (*e.g.,* new pests) effects. The latter are likely to outweigh the former. Changing weather conditions may affect yield, and extreme environmental conditions, such as flooding or drought, can threaten the yield and attractiveness of European sugar beet cultivation. New farming practices (precision agriculture) and improved plant materials are key. Sugar beet has attractive wild germplasm and is amenable to genetic and genome engineering, assuming timely and appropriate regulations and market acceptance. Biotech breeding may speed up the necessary trait modifications. Higher yields may depend on the sink-source relationships in sugar beet. We present strategies and possibilities in the context of the challenges of sugar beet management and breeding for resilience, provided the concept of resilience is well operationalized regarding variable environments, field testing, and future cultivar registration.

1. Introduction

Europe is currently the world's leading sugar beet (*Beta vulgaris* subspecies *vulgaris* variety *altissima* Döll) sugar-producing area, with the EU-27 supplying about half of the world's beet sugar (17 million metric tonnes (Mmt) [1]. Total world sugar production was about 177 Mmt in 2023/2024 [2], the bulk (80%) of which comes from sugarcane (*Saccharum officinarum* L. and hybrids) growing in tropical and subtropical regions (Fig. 1). Global sugar demand is expected to increase, driven by both rising consumption resulting from population growth and higher incomes, as well as growing sugar use in biobased industrial applications in the transition from a fossil resources-based economy to a circular and renewable resource system [3,4].

Europe has the temperate climate that suits sugar beet cultivation (Fig. 1). However, sugar beet farming and sugar yield in Europe are likely vulnerable to climate changes that will result in the permanent change of the environment and weather patterns that will become more variable, extreme, and less predictable [5]. The issue addressed in this comprehensive review is the future of sugar beet in Europe. Given the anticipated effects of climate change and potential increase in sugar demands, the challenges in sugar beet breeding, cultivation, and processing are reviewed to determine how these challenges can be addressed through advanced breeding, precision agriculture, and more diversified use of plant material.

2. Value from sugar beet

2.1. Sucrose

2.1.1. Production and yield

Sucrose is the primary value driver of sugar beet, so sugar yield is of

* Corresponding author.
E-mail address: ingrid.vandermeer@wur.nl (I.M. van der Meer).

https://doi.org/10.1016/j.jafr.2025.102343
Received 7 August 2024; Received in revised form 7 August 2025; Accepted 8 September 2025
Available online 9 September 2025
2666-1543/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

List of abbreviations

ABA	Abscisic Acid
AI	Artificial Intelligence
BNYVV	Beet Necrotic Yellow Vein Virus
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CEFS	Comité Européen des Fabricants de Sucre (European Association of Sugar Manufacturers)
CLS	Cercospora Leaf Spot
COVID	Coronavirus Disease
EC	European Commission
EEA	European Environment Agency
EP	European Parliament
EPPO	European and Mediterranean Plant Protection Organization
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GM	Genetically Modified
GPS	Global Positioning System
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
IRS	Instituut voor Rationele Suikerproductie (Institute for Rational Sugar Production)
ISAAA	International Service for the Acquisition of Agri-biotech Applications
ISO	International Sugar Organization
IT	Information Technology
Mmt	million metric tonnes
mt	metric tonnes
OECD	Organization for Economic Co-operation and Development
PE	polyethylene
PLA	polylactic acid
SBR	Syndrome des Basses Richesses
SOM	Soil Organic Matter
ssp	subspecies
TSE	Thunder Said Energy
UNEP	United Nations Environment Program
USA	United States of America
VRT	Variable Rate Technology
WHO	World Health Organization
WMO	World Meteorological Organization
VY	Virus Yellows

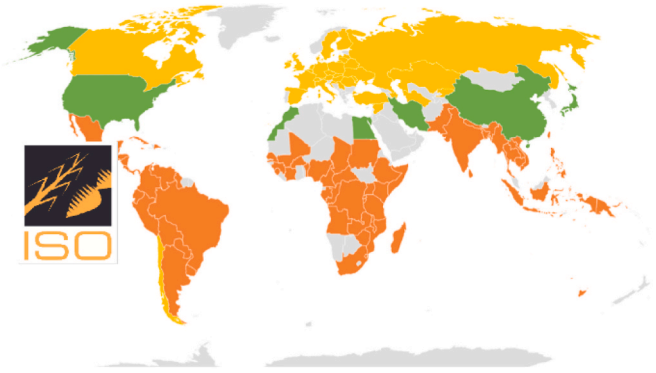

Fig. 1. The area of cultivation of sugar beet (yellow), sugarcane (orange), or both (green) in 2024. This picture is obtained from and reprinted with the kind permission of the International Sugar Organization (ISO; www.isosugar.org). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

utmost importance. Sugar beet gives, on average, in the EU-27, a yield of up to about 12 metric tons (mt) of sugar per hectare (Fig. 2A) from about 80 mt of roots. This yield is estimated to be about half the theoretical maximum [6]. The total production of roots is presented in Fig. 2B. There is a notable variation in root yield between different locations, from 30 to 90 mt/ha [7], and up to 10% variation around the multi-year average [8], primarily due to variations in weather conditions and cultivation practices [9,10].

European legislation has impacted the European sugar industry considerably. After the EU sugar market reform in 2006 [11] and the end of the quota system in 2017 [12], the volatility of sugar prices increased [13]. The number of sugar beet factories in the EU declined from 189 (in 2006) to 107 (in 2018) and 88 in 2023 [14,15]. The area used for sugar beet cultivation in Europe decreased to approximately 1.5 million hectares (Fig. 2C). In 2017, the first year without quota, the EU was a net exporter of sugar, but since then, the EU has imported more sugar than it exports [1,16]. Relative to its agricultural area, the Netherlands has the largest sugar beet cultivation area in the EU: sugar beets are grown on nearly 5 percent of the Dutch agricultural acreage [17]. Therefore, the relative importance of sugar beet for agriculture is higher for the Netherlands than for other EU countries.

The (expensive) transport of relatively high volumes of beet material makes sugar production a primarily regional system. Beet factories must be less than 100 km from the harvest field [8,18]. Sugar yields have steadily increased (Fig. 2A). Harvest is highly mechanized, storage conditions are well-established, and processing sugar beets into the final product(s) is a mature technology [19].

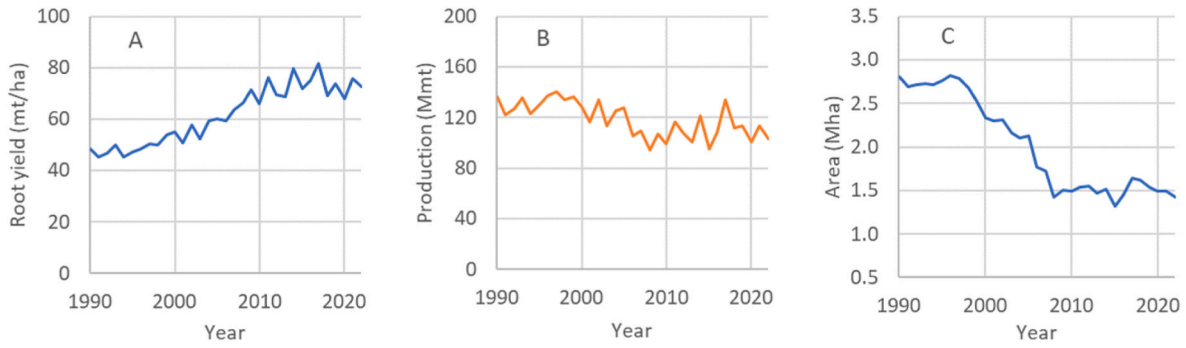

Fig. 2. Key statistics of sugar beet cultivation in the EU-27 over time. (A) root yield (in mt/ha); (B) total beet production (in Mmt); (C) the total area of sugar beet cultivation (in Mha) [7].

The harvested beet may contain up to 20% sucrose, 75% water, and 5% pulp. Therefore, a beet sugar factory must process five to seven metric tons of beets (assuming a content of 15–20% sucrose) for a yield of 1 metric ton of sucrose. The variation in sugar content is considerable (12–20%), and the lower the sugar content, the more beet processing is required to achieve the desired yield.

2.1.2. Application and demand

Sucrose has many uses. It is a commodity that is easily stored, traded, and applied. It is predominantly used as a caloric sweetener in food [20]. For health reasons, governments and the food industry are discussing reducing the sugar content of processed foods, such as sugar-sweetened beverages [21,22]. Sucrose also finds its applications in the pharmaceutical, cosmetic, and chemical industries. It is readily fermentable and can be converted to versatile feedstocks for the chemical industry [23,24], as well as to energy, such as (bio)ethanol or methane for transportation or heat.

Europe is currently considering more self-sufficiency regarding materials, fueled by the vulnerability of supply chains as demonstrated by the COVID-19 pandemic [25,26]. Dependencies on resource origin or climate impact are undesired [27], also in light of ongoing geopolitical developments [28]. Such developments are also implied in the European Green Deal, which helps shape the transition from fossil-based systems toward systems based on renewable, biobased resources [29].

Biobased feedstock is essential for (part of) the carbon-based non-food demands in a future circular economy [30], in addition to more emphasis on recycling [31] and the direct use of carbon dioxide [32,33]. Demands are expected to increase, driven by the need for fossil fuel alternatives. Sugar and sucrose-based feedstock as biobased materials are part of such considerations. Industrial use of sugar would contribute to the transition to renewable biobased resource systems [3–5,22].

The European sugar consumption (as food) is about 15.4 Mmt/year [34], and sugar for biobased use (industrial fermentation including bioethanol and biochemicals) now comprises about 1.4 Mmt (calculated as the total minus food and retail) [35], so the total use is about 16.8 Mmt/year. Europe produced about 15.6 Mmt beet sugar (in 2023/2024) on an estimated area of 1.5 Mha [1,36], so only a moderate -and feasible-area increase would suffice to meet current demand.

However, this estimate does not include the potential sugar demand for the chemical industry. The example elaborated here is the bioplastics demand of the EU in 2050. Estimates of future plastics demand (worldwide) vary enormously, depending on plastic type, production efficiency, and recycling rates [31,37,38]. Plastics production is projected to be about 1231 Mmt in 2060 [39], so about 1000 Mmt in 2050. Assuming the EU will continue to consume about 15% of that amount, it needs 150 Mmt of plastic. The amount of sugar required for the production of bioplastics can be estimated by comparing two extremes. The production of one mt of (bio)polylactic acid (bioPLA) requires about 1.4 mt of glucose, whereas one mt of (bio)polyethylene (bioPE) requires about 3.2 mt of glucose [24,40]. The production of 150 Mmt of bioplastics, assuming 80% recycling [31], would require between 42 (for bioPE) and 96 Mmt (for bioPLA) of glucose. The European production of 16.8 Mmt beet sugar (sucrose), assuming direct use in fermentation, is well below the amount needed for such bioplastics production. Therefore, sugar import remains necessary, or bioplastic production should be outsourced, besides using other feedstock sources, such as starch, or (renewable) carbon dioxide [31]. Likely, the chemical industry can make use of less pure sugar than fully refined, food-grade sucrose; it would lower the (processing) costs.

The obvious alternative source of sugar is sugarcane. Importing sugarcane sugar from South America, India, and others (Fig. 1) may be the easiest solution to meet Europe's increasing sugar demand in the short to medium term. However, such imports do not contribute to Europe's desired self-sufficiency, and geopolitical developments may impact sugarcane sugar imports as well. Comparative studies indicate that for Europe, sugar from locally grown sugar beet has a lower environmental impact than the import of sugar from sugarcane [41–43]. Expanding the sugar cane growing area may result in undesired deforestation, loss of biodiversity and habitat destruction, deteriorating soil quality (erosion, degradation, nutrient depletion), pollution of freshwater ecosystems, or depletion of local freshwater resources, in addition to discussions and concerns about appropriate land-use and local working conditions. Climate change may also affect future sugarcane yields: a worrisome global yield reduction of almost 60% by 2080 has been predicted for sugarcane [44]. Sugarcane's complex genetics [45,46] will make tailoring the crop to suit Europe's future climate conditions and sugar demands unlikely, despite the promises of genome editing in sugar cane [47].

While the import of sugar may be necessary to meet European sugar demand, focusing on enhancing Europe's self-sufficiency for sugar through improved sugar beet production is warranted as a key strategy for the future. Europe may have to consider reorganizing its internal sugar markets accordingly.

2.2. Added value besides sucrose

In addition to sucrose, value from sugar beet is or can be derived from the byproducts of processing (pulp, molasse, carbonation lime) and the aboveground parts [19].

(a) **Pulp.** The pulp remains after raw juice extraction. It consists mainly of plant cell wall material. The sugar beet's plant cell wall is atypical as it contains almost no lignin and high levels of pectin [48]. The pulp is used as animal feed [49,50] or fermented to bioenergy [51] and other biobased products [52]. In the past, the 'energy beet' concept received much attention [48]. High energy prices and the call for 'green' energy may revive such use of pulp. Particular monosaccharides derived from the pulp may be marketed separately [53]. Other applications include making particle board [54], paper coating [55], and as an addition to paper [56,57], such as in the 'Bright Beet Book' [58].

(b) **Molasse.** Molasse is the thick, syrupy byproduct of sugar production that still contains about 50% sugar (sucrose and invert sugar) but is unsuited for human consumption without additional processing. The molasse is marketed independently. Its primary use is livestock feed [59]. When used as an additive, it improves silage quality, and when blended with pulp, it makes an enhanced feed product [49,50]. Other applications are as a fermentation substrate [60], as a relatively low-cost feedstock for the enzymatic production of inulin-type fructo-oligosaccharides [61], or as feedstock for sustainable chemical production chains.

(c) **Carbonation lime.** The standard purification process of the sugar juice involves a so-called double carbonation process, which is treatment with 'milk of lime' (calcium hydroxide; $Ca(OH)_2$) in combination with carbon dioxide [19]. It results in precipitated calcium carbonate ($CaCO_3$), a product that is chemically similar to natural limestone. It is used to increase the pH of acid soils and could be used to reduce carbon emissions in cement production [62].

(d) **Aboveground parts.** The aboveground part of the harvestable sugar beet, about 29 Mt/ha, is about one-third of the wet weight of the mature crop [63]. Leaves generally stay behind on the field as green manure.

In the context of the desired circular agriculture and biobased economy, sugar beet factories may shape the concept of the future biorefinery [64]. The additional value drivers need more consideration as they may contribute to or safeguard the future business case of sugar beet cultivation and processing in Europe.

3. Sugar beet: cultivation, breeding, and biotechnology

The sugar yield of sugar beet largely depends on cultivation practices from seed to harvest, good cultivars, and local variations in weather conditions [9,10]. The yield potential of sugar beet, *i.e.,* the yield of sugar when grown in an optimal environment, without any stress (biotic, abiotic) or limitations (nutrients, light, water), is estimated to be about 24 metric tons of sugar per hectare [6]. Only about half of this potential (based on 80 mt root yield per ha; Fig. 2A) is currently achieved in practice (other than in cultivar registration trials) due to losses during cultivation, harvest, and storage. It indicates the promise for improved crop management. Sugar beet needs to be adequately managed to ensure good yields of beets and sucrose [65]. These aspects will contribute to the future of sugar beet in Europe and are detailed below.

3.1. Cultivation practices

3.1.1. Seed production and pelleting

Sugar beet is typically grown from seed. Although the use of transplanted seedlings from controlled environments may have advantages in some places in the world [66,67], it does not seem to warrant the extra investments in Europe (or the USA). Early and consistent field emergence is required for maximum root development and sugar yield [68]. Seed batches should be high quality, characterized by high germination ability, vigor, and purity, which are all key for good plant and field establishment. Sugar beet seed production should be considered a separate sector with crop management strategies (locations, nutrients, crop protection) that differ from the crop management practices in sugar beet cultivation for sugar production. In seed production, the goal is to induce flowering as quickly as possible, whereas in sugar production, flowering should be prevented.

Sugar beet needs low temperatures (vernalization) to induce bolting. Areas suitable for seed production should have sufficient cold in winter (4–10 °C, for about 15–20 weeks) to induce homogeneous bolting without frost damage. Such conditions are found in the Mediterranean area of Europe (South of France, Northern Italy, Turkey) and Oregon in the USA [68]. It takes about a year to produce sugar beet seed, from the choice of material planted in late July to replanting the seedling, known as steckling, *i.e.*, the tiny late-planted seedling that is protected over winter in February, and harvest of the seeds in August/July. Most sugar beets flower during 3–4 weeks, and pollination occurs mainly by wind [68]. Generally, use is made of virgin fields, preferably never used for growing sugar beet or any other Beta species, and free of the main sugar beet pests and diseases (see below), such as rhizomania and nematode infestations.

After seed harvest, cleaning, and quality control, the seed is treated in various ways before packaging and shipping. Treatments can involve (a) excess pericarp removal, as the pericarp contains germination inhibitors, (b) priming (pre-germination) to obtain faster and more homogeneous germination, (c) pelleting (Fig. 3) to generate a regular, standardized round or oval product, and (d) coating with a layer containing plant protection chemicals (Fig. 3). The latter often involves fungicides against black root rot and leaf spot. Standard pellet sizes for European sugar beet are between 3.50 and 4.75 mm [68]. Generally, details of these seed treatment procedures are specific to a particular seed producer and kept confidential as a trade secret. Details may differ between cultivars and the intended growth locations. One kg of pelleted sugar beet seed contains about 100.000 pellets sufficient for about 1 ha at standard sowing distance [70].

3.1.2. Seedling and plant development

To create good conditions for sowing, plant emergence, and root development, soil tillage is carried out before seeding. Traditionally, primary soil tillage is based on ploughing to prevent soil compaction and promote root development. However, there is increased interest in reduced tillage that omits ploughing and saves time and energy. Seedbed preparation is important for a high and homogeneous field emergence. The seedbed should have a firm, moist base covered by a layer of loose soil with sufficient aggregate size to reduce evaporation [66]. After proper seedbed preparation, seed germination and emergence are the subsequent critical phases for the harvestable yield of sugar beet (Fig. 4). These stages are affected most by adverse weather conditions, such as frost or heavy rain [20,71].

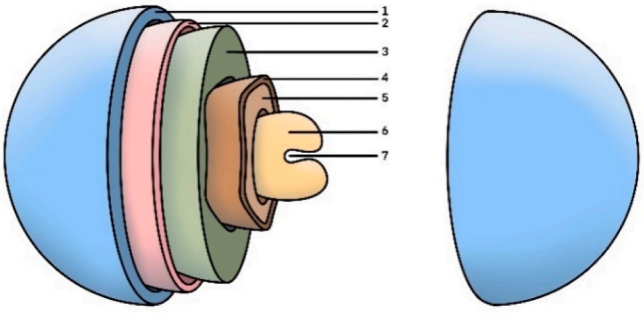

Fig. 3. The typical sugar beet pellet. The pellet's consistent size and round shape improve handling and prevent loss. (1) seed coat. The coating usually carries a colored pigment that assists planting and identifies the vendor or batch; (2) (optional) layer with additional fungicide and insecticide; (3) layer with inert material; (4) layer with fungicide; (5) perisperm; (6) embryo; (7) pericarp; (5+6+7) seed, irregularly shaped and sized. Modified after [68,69].

Precision seeding machines sow seeds at a depth of 2–4 cm in rows 45 or 50 cm apart. In-row spacing depends on the desired plant density and expected seedling establishment rate. Optimal plant densities for maximum economic return are achieved with 70,000 to 90,000 plants per hectare. About 87,500 to 112,500 seeds per hectare at an in-row spacing of 23 to 18 cm result in an average plant establishment of about 80% [70,72]. In the temperate regions (Northern and Central Europe), seeds are sown in spring (summer beets); in warmer regions (South of France, Spain), sugar beet is planted in autumn (winter beets).

The successive stages of sugar beet development, the main sensitivities in cultivation, and the risks of crop damage are outlined in Fig. 4. Seedling emergence depends on the priming of the seeds, sowing depth, as well as the texture, water content, and temperature of the soil [75,76]. Under optimal conditions, emergence is a function of the cumulative amount of heat (thermal time; Fig. 4). Sugar beet has a relatively long growing period of 140–200 days (Fig. 4). The optimum temperature for growth is about 18°C [73]. In its first year, the crop grows leaves and develops the large, napiform, fleshy taproot that accumulates the desired sucrose. This taproot grows to about 0.6–1.4 kg at harvest and contains 12–20% sucrose by fresh weight. A good sugar yield is obtained with a mild climate throughout the growing period, well-distributed precipitation (or irrigation to compensate for a lack of water), and sufficient sunlight before harvest. Extreme weather conditions negatively affect sugar yield [73]. With suitable conditions, the sugar beet plant will produce leaves sufficiently rapidly after emergence (Fig. 4) and have a leaf canopy (rosette) with extensive field coverage, allowing the crop to intercept as much solar radiation as possible. This canopy promotes the taproot's development as the system's carbon sink [6,65].

3.1.3. Pests and diseases

Unfortunately, the sugar beet crop is susceptible to numerous pests and diseases at all stages of growth and during storage after harvest. Many of these can cause severe yield reduction if not adequately managed: pests and diseases may explain about 50% of yield differences between different growers [10]. Table 1 summarizes the principal pests and diseases of sugar beet in Europe. The Supplementary Table S1 presents an extensive overview of all current sugar beet pests and pathogens. These pests and diseases have resulted in elaborate

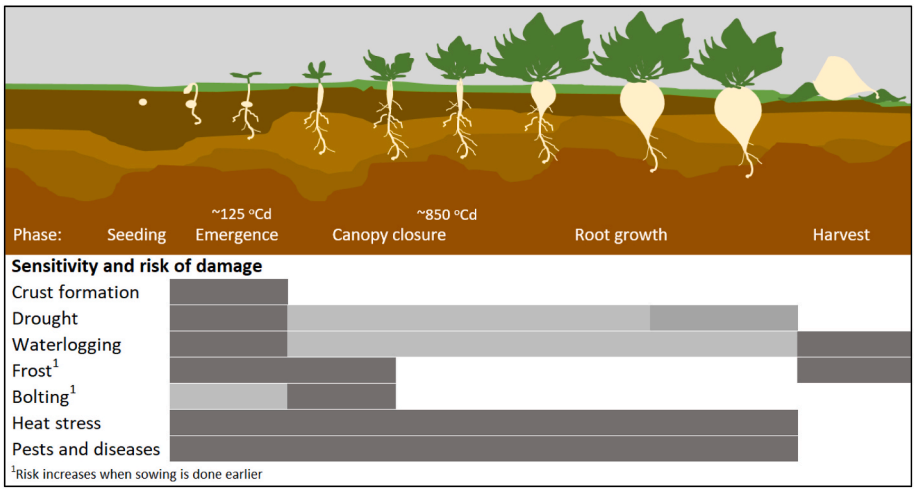

Fig. 4. Outline indicating (a) the key stages of sugar beet growth (cartoon, top) and (b) assessment of the sensitivity of the sugar beet plant to damage in different conditions (indicated on the left) during its growing period (horizontal bars, bottom). The darker the bar, the more sensitive sugar beet is to damage and yield loss. The rate of development in the first half of the season is mainly driven by temperature (above 3°C). The approximate duration is given in thermal time (°Cd; degree days), calculated from the sum of daily temperatures (as the mean of the maximum and minimum daily temperature) above the threshold value of 3C. The figure was modified after several literature sources [20,70,73,74].

recommendations for sanitary precautions and protective measures in sugar beet cultivation, harvest, and storage [70,77]. Integrated Pest Management (IPM) strategies have, therefore, become an integral part of sugar beet cultivation and management [78,79].

Rhizomania (root madness or the crazy root disease) is a root disease caused by beet necrotic yellow vein virus (BNYVV; *Benyvirus necrobetae*). The virus is transmitted by the soil-borne, fungal-like obligate parasite *Polymyxa betae*. This organism is widespread but relatively harmless without the virus. BNYVV is a multipartite positive-stranded RNA virus with four to five RNA particles [80,81]. Resistance against BNYVV has been accomplished in sugar beet cultivars, and, therefore, rhizomania is currently under control [82]. However, the resistance is challenged [81,83], which may cause future problems.

As long as rhizomania is under control, Cercospora leaf spot (CLS), caused by the fungus *Cercospora beticola* Sacc., is likely Europe's most damaging sugar beet disease. Infection can cause yield losses of up to ~40% of recoverable sugar and up to 100% without fungicide treatment [84,85]. The fungus overwinters on infected plant residues (not necessarily sugar beet) in or on the soil and is spread in spring through wind and insects [86]. It may occur in the seed coat and start CLS upon sowing [87].

Various virus strains cause Virus Yellows (VY), resulting in highly variable sugar yields and losses up to 47%, depending on inoculation density and time of infection [88]. All these viral strains are monopartite, positive-stranded RNA viruses transmitted by aphids. *Myzus persicae*, the green peach aphid, is the primary vector for transmission in sugar beet. In Europe, the abundant VY strains are beet yellows virus, beet mild yellowing virus, and beet chlorosis virus. Other strains predominate in the USA and Asia [89].

Crop rotation is essential to counteract the occurrence and impact of notably soil-borne pests and diseases. It also helps to maintain or increase soil fertility and structure [90]. The frequency of sugar beet cultivation depends on local conditions. In the Netherlands, a sugar beet cropping interval (i.e., the number of years in between sugar beet cultivations [90]) of at least three years (once in four years), but preferably five years (once in six years) is recommended [70]. This period reduces soil-borne pests and diseases, especially beet cyst nematodes and rhizoctonia. The choice of crops rotated with sugar beet is critical. These should not be hosts of diseases or pests. In the case of the beet cyst nematode, no spinach or rape should be selected. In the case of rhizoctonia, no carrot or maize [70].

Insects may become more problematic in sugar beet with specific preceding crops. For example, thrips are problematic the year after flax or pea cultivation, while leatherjackets and wireworms may be problematic the year after grass cultivation. Carryover of diseases (*e.g.*, Cercospora, beet weevil) should be avoided by not growing sugar beet adjacent to a beet plot from the previous year [70].

European policies determine considerably what a European farmer can do to manage sugar beet pests and diseases. The EU aims to reduce the use and risk of plant protection chemicals in agriculture by replacing harmful pesticides with less damaging alternatives and prioritizing non-chemical plant protection methods, focusing on the development of advanced Integrated Pest Management (IPM) strategies [91]. In the past years, several agrochemicals used in sugar beet cultivation have been banned, presenting challenges for the sector [92]: sugar beet farmers indicate difficulties with the reduced availability of protection agents [93]. For example, the ban on neonicotinoid insecticides due to their harmful effects on pollinators such as bees has deprived sugar beet growers of an effective tool for managing insect pests, such as aphids and others [94,95]. Likewise, herbicides may be banned. Without suitable herbicides, future weed control may become challenging, especially for emerging sugar beet seedlings. Farms with a high proportion of sugar beet in their crop rotation show a high correlation between chemical inputs, production, and profitability [96].

3.1.4. Weeds

Besides yield reductions caused by pests and diseases, weeds compete with beets for resources, reducing beet and sugar yields. Moreover, weeds may attract, carry, transmit, or propagate pests and diseases. Therefore, proper weed control is another element of successful sugar beet cultivation.

Especially in the early stages of germination and emergence, weeds compete with the emerging sugar beet crop and can cause crop failure [97]. Therefore, herbicides and mechanical weeding are used. In the USA and Canada, most (>95%) of the current cultivars are glyphosate-tolerant Roundup-Ready sugar beet [98]. See the information in Supplementary Table 2. The unprecedented adoption of these genetically modified (GM) sugar beets in the USA implies that the GM trait helped solve a serious problem cost-effectively [98]. In European sugar beet cultivation, glyphosate is occasionally used before seedbed preparation. Generally, a soil herbicide is applied at or shortly after sowing to reduce the number of weeds after the emergence of the beets

Table 1
Principal pests and diseases of sugar beet in Europe.

Disease	Symptoms	Causative agent	Current cure
Rhizomania (root madness)	Pale green, narrow/wilting leaves, root hair bearding, taproot narrowing, very low sugar content	Beet necrotic yellow vein virus (BNYVV) vector: *Polymyxa betae*	No chemical control, resistant varieties, crop hygiene
Virus yellows (VY)	Rapid yellowing and thickening of leaves	A range of virus vectors: aphids	Foliar insecticides, weed control, resistant varieties (in development)
Leaf diseases	Leaf spots, low sugar contents	Various fungi, some bacteria	Phytosanitation, crop rotation, fungicides
Leaf-feeding damage	Foliar damage, reduced leaf integrity and surface, reduced photosynthesis	Various insect species (also other host plants)	Crop rotation, phytosanitation, biological control (predatory insects), insecticides (seed pelleting, foliar sprays)
Rhizoctonia	Chlorosis, death of leaves, severe root rot, disappearing root	*Rhizoctonia solani* (many host plants)	No chemical control (in USA: fungicide), resistant varieties; crop rotation
Beet cyst nematode	Stunted, wilting leaves, small taproot, root hairs with cysts	*Heterodera schachtii*	Weed control, crop rotation; non-fumigant nematicides (in USA, broader options), tolerant varieties
Aphanomyces root rot	Seedling damping off, chlorosis	*Aphanomyces cochloides* (oomycete)	Crop rotation, seed treatment
Root-knot nematode	Galls on taproot and lateral roots	Various *Meloidogyne* species	Weed control; crop rotation; controlled flooding; non-fumigant nematicides (in USA, more broad options); tolerant varieties
Syndrome des basses richesses (SBR)	Chlorosis, asymmetric new leaves, very low sugar content	Bacteria & phytoplasma, vector: *Pentastiridius leporinus*	Crop rotation, vector control (incl. reservoir host (weed) control); tolerant varieties (in development)
Rubbery taproot disease (RTD)	Leaf wilting, affected tap roots, hampered processing, storability	Stolbur phytoplasma vector: *Pentastiridius leporinus* and others	Crop rotation, vector control (incl. reservoir host (weed) control), tolerant varieties (in development)

Data assembled from literature and multiple online sources, such as www.irs.nl/en, www.int-koop.de/schaeden, www.cabidigitallibrary.org, www.sesvanderhave.com/uk, https://pnwhandbooks.org/insect/agronomic/sugar-beet , and more.

and simplify post-emergence control [70].

An innovative approach to advanced weed control in sugar beet has been the introduction of herbicide-tolerant sugar beet varieties. The CONVISO® SMART varieties are selected for their tolerance for the acetolactate (ALS)-inhibiting herbicide Conviso One® [99], allowing effective weed management in sugar beet. It may contribute to the efficiency and sustainability of sugar beet cultivation, although it may not contribute to the EU roadmap to prioritizing non-chemical plant protection [91]. Unfortunately, ALS resistance of weeds is already becoming a concern [100].

3.1.5. Nutrients

Management of nutrients also requires attention, notably in the period of vigorous leaf growth. Fertilizer nitrogen (N) is applied around sowing based on recommendations considering soil mineral N and mineralization [20,70]. Especially for N fertilization, there is a delicate balance between increasing root yield (weight), sugar content, and sugar recovery. Too much nitrogen reduces the sugar content in the beet and hinders sugar recovery in processing [101]. Optimal sugar yield is achieved with substantially lower amounts of nitrogen than maximum root yield [102]. Over time, the nitrogen input has decreased considerably, suggesting an increased efficiency of nitrogen use [78,103].

A primary EU target is to reduce nutrient losses by at least 50% while ensuring no reduction of soil fertility, which is expected to result in a fertilizer application reduction of 20% in 2030 [91]. Reducing nitrogen use is possible for sugar beet growers who still apply more N than the optimum for sugar yield [78]. Further reduction of fertilizer use is feasible when a slight decrease in sugar yield is accepted. About 95% of the attainable sugar yield was achieved with a nitrogen dose about a quarter lower than now recommended for the maximum sugar yield [104]. The optimum depends on local parameters (climate, soil, management) [105].

Phosphorus (P) and potassium (K) are applied based on soil analysis. Magnesium (Mg) and micronutrients, especially boron (B) and manganese (Mn), can be applied to the leaves. Applying sodium (Na) may increase sugar content [70].

3.1.6. Harvest

Summer beets should be harvested before the first frost [20,74]. Winter beets are harvested in spring to avoid the heat in summer. Therefore, in terms of production, sugar beet can be considered an annual crop. Harvesting of beets generally starts when the processing factory is ready. For summer beets, that is nowadays often early September, and it lasts until about the beginning of February. In some areas, the period of harvesting and processing beets is known as 'the beet campaign' or 'the sugar campaign.' Beets should be processed relatively quickly after harvest because sugar content may decline rapidly upon storage due to rot and respiration [106,107]. Respiration due to wound repair, sprouting, fungal or bacterial rot, and accumulation of invert sugar (*i.e.*, the mixture of glucose and fructose upon sucrose degradation) affect subsequent processing and yield [106]. Optimizing the conditions for longer-term storage and avoiding sugar losses are areas of active research [106] that also involve breeding and selection of improved plant material [108].

3.1.7. Processing

The processing consists of slicing the beet, extracting the raw juice, purifying, evaporating, and then crystallizing the sucrose [19]. Earlier, the plant's crown was removed as it was supposed to contain substances that would interfere with extraction and purification [109]. Nowadays, due to its higher quality, the crown is taken along as much as possible, and only the leaves are cut away [70,110]. The storability of sugar beet may be taken along as breeding target to reduce storage losses and improve yield upon processing [111]. Sugar-extracting factories operate non-stop for 90–150 days a year to process all beets [112]. Many continue to process the byproducts (pulp, molasse) in summer [19], before proceeding to cleaning and maintenance as preparation for the next campaign. Extended use of the production capacity of the factory reduces the fixed costs and favors the business case [8].

3.1.8. Sustainability

Current sugar beet cultivation is assessed as adequately sustainable based on generic sustainability criteria such as input use, greenhouse gas emission, and carbon footprint, with possibilities for further improvements [77]. The impacts of sugar beet are limited to relatively small areas because of its high land-use efficiency: no other crop or biomass can produce more sugar per hectare [23]. Harvesting all sugar beet

biomass as proposed above for a favorable business case reduces organic matter input to the soil, which may impact soil quality in the long run [113]. Within an arable crop rotation, crops such as winter wheat increase soil organic carbon more than sugar beet [114]. It will be necessary to assess how much sugar beet residue is required to maintain good soil quality. The amount of soil organic matter (SOM) results from the supply and degradation of organic matter and depends on local conditions.

3.2. Sugar beet breeding and biotechnology

Together with an improved agronomic management, the increase in sugar beet yield (Fig. 2A) has been based on the breeding of new cultivars [6]. Sugar beet breeding primarily aims to increase the yield of white sugar per hectare [18]. The rich history of sugar beet breeding is well documented, and we refer to these reviews for details [18,20,66].

3.2.1. Genetics and breeding

Sugar beet is a herbaceous dicotyledon member of the *Amaranthaceae* (formerly *Chenopodiaceae)* family (order *Caryophyllales*, subfamily *Betoideae*). It is a relatively recently domesticated diploid ($2n = 18$) species with a haploid genome of nine chromosomes and an estimated haploid genome size of about 714–758 Mb [115], but different ploidy levels exist [116,117]. All cultivated sugar beets are biennial, unlike several crossable wild relatives. As a biennial crop, a sugar beet plant will bolt, flower, and set seed in its second year. This way, the sugar beet's entire two-year life cycle is essential for propagation and breeding. However, it is possible to have a biennial sugar beet generate seed in about a year when a cold period is included for vernalization [68]. This approach accelerates sugar beet breeding but may promote early bolting phenotypes. The latter compromises yield, so effective control of bolting remains important. Genetic maps [118,119] with a variety of (molecular) markers [120–122] steer breeding [123–125]. Marker technologies to follow introduced genetic material over generations are generally proprietary within the commercial sugar beet breeding sector [126].

Sugar beet is generally strongly self-incompatible [18], with the occasional pseudo-self-fertility helpful for and used in breeding [127]. Monogerm (*i.e.,* one embryo per seed; the wild beet is multigerm) breeding lines with almost obligate self-fertility are now used to develop inbred lines. In the earlier days of sugar beet breeding (~1930), autotetraploid (with $4 \times 9 = 36$ chromosomes; formally $2n = 4x = 36$) sugar beets were generated, expecting higher yields than from equivalent diploids. This expectation did not come true. Triploid hybrids, the material of choice for a long time, have also disappeared because triploid hybrid breeding and seed production were too costly and complex [128]. Most current commercial cultivars are monogerm diploid hybrids developed and maintained with the help of mitochondrial genome-based cytoplasmic male sterility (CMS) systems. Monogerm seeds and CMS systems speed up sugar beet breeding and increase yields [18].

Sugar beet has ample wild germplasm available for breeding [129], despite the challenges posed by the Nagoya protocol [130]. For example, the close relative sea beet (*Beta vulgaris* subsp. *maritima*) has genetic diversity available [131], and also fodder beet is a valuable source of genes [132,133]. The wild germplasm is well documented: there is a separate *Beta* working group in the European Cooperative Program for Plant Genetic Resources (ECPGR; https://www.ecpgr.cgiar.org/working-groups/beta), with attention to the conservation of beet genetic resources, both *in situ* and *ex situ* [134] as well as digital. The International Database for Beet (IDBB; http://idbb.julius-kuehn.de/idbb/) is currently hosted by the Julius Kühn Institute, headquartered in Quedlinburg, Germany. The Agricultural Research Service of the US Department of Agriculture (ARS-USDA; https://www.ars.usda.gov) maintains the USA National Germplasm System as part of its Germplasm Resource Information Network projects (GRIN; https://www.grin-global.org; [135]). The future of these US resources is, unfortunately, unclear.

Stress and disease resistance. Over 80% of the published sugar beet breeding literature concerns stress and disease tolerance [18], showing the prime importance of (a)biotic stress tolerance for sugar yield. Sea beet contains various genes for biotic stress tolerance [136], of which so far only a few have been used in practice. It is the source of many rhizomania resistance genes, two of which (Rz1 and Rz2) are now used in commercial material. These two belong to the well-known class of plant R genes characterized by nucleotide-binding leucine-rich-repeat (NB-LRR) motifs and various others. Many such motifs occur near Rz1 and Rz2 [137] and may function as a pool of new resistance genes [138]. Other, potentially different, resistance genes are characterized and evaluated [139]. Sugar beet varieties that have a dual tolerance to both rhizomania and rhizoctonia are commercially available [140].

The genetics of CLS resistance or tolerance is complex [141,142], but CLS-tolerant genotypes exist [143]. These are currently not sufficient to manage CLS completely, and so additional phytosanitary measures remain necessary [144,145]. BvCR4, also an NB-LRR R gene, shows a high CLS resistance and high yield but may also face the possible rapid development of new virulent strains [146].

The HS1pro-1 gene from another related species (now classified as Patellifolia procumbens) that confers (partial) resistance against the beet cyst nematode is also an R gene [147]. Not-easily crossable wild relatives, such as members of species in Patellifolia, also harbour traits of interest, but introgression is problematic because of a severe lack of recombination [18,20].

In addition, 'mature plant resistance', based on the observation that the tolerance for some pests and diseases increases with plant age, may contribute to plant protection in sugar beet [148].

Drought tolerance. Breeding for drought tolerance in crops is considered a cost-effective and sustainable strategy for increased productivity and yield [149]. However, it is a complex phenotype to improve. Drought tolerance involves numerous genes, and there is much crosstalk between pathways. For sugar beet, drought tolerance is closely associated with sugar yield potential, heat stress, salt stress, and water use. For details, we refer to a comprehensive overview of the complexity of drought tolerance in sugar beet [133]. The long list of potential targets for tolerance suggests much remains to be discovered and tested. A trial with six hybrid genotypes showed no special adaptation to drought stress conditions. [150], suggesting limited influence of drought on yield. However, the analysis of more extreme environments and genotypes is warranted. Other studies indicate differences in drought tolerance in different genotypes or germplasms that may be of use in breeding [151–153]. Germplasm resources with drought tolerance, such as fodder beet, are identified and evaluated [132,133,150].

The challenging complexity is demonstrated by the multiple actions of the plant hormone abscisic acid (ABA). In sugar beet, ABA was also identified as an indicator of drought stress, and foliar application may alleviate drought stress [154], at least temporarily. In several crops, however, not (yet?) including sugar beet, transgenic ABA modification contributes to drought tolerance. However, the hormone negatively affects overall plant growth and development, hampering agronomic application.

Despite the extensive resources available, sugar beet breeding is slow. It takes about ten to fifteen years to develop a new variety, apart from the additional (usually also lengthy) time required for registration and permission to market [136,155]. Keeping up with legal decisions on, for example, the withdrawal of the market admission of crop protection agents is challenging. New resistance and genes are necessary for developing new varieties sufficiently in time to cope with the declining number of registered crop protection agents [156] and the impacts of climate change [27], as discussed below.

3.2.2. Molecular breeding and biotechnology

Molecular genetics. Sugar beet is amenable to the complete toolbox

of modern (molecular) plant breeding and biotechnology that can speed up breeding. *In vitro*-based mass regeneration and clonal propagation are in development for application on a commercial scale [157] to expedite propagation of suitable material. Three sugar beet reference genomes are available [115,158] McGrath, 2023 #544], as well as the genomes of crossable wild relatives [159], numerous (>600) individual lines [160], and pan-genome approaches [161]. In addition, omics data support gene identification and use [162,163]. Data on RNA (transcriptomics [164]), protein (proteomics [165]), metabolites (metabolomics [166]), and phenotypes (phenomics [167]), in combination with advanced tools for integrated analysis and visualization [168], are in place. Genetic transformation technologies are available [169,170], including chloroplast transformation [171], allowing genetic engineering and genome editing.

Genetic engineering. Genetic engineering of sugar beet documented in the literature is summarized in Supplementary Table S2. Our overview focuses on rooted transformants and does not include callus or hairy root clones (obtained by *Agrobacterium rhizogenes* transformation), in contrast to earlier surveys [169,170]. It explains the absence of entries for GM nematode resistance in Supplementary Table S2. Although a protocol to obtain rooted plantlets from sugar beet hairy roots exists [172], the resulting hairy root phenotype may interfere with taproot development and sugar accumulation, making it a strategy attractive for gene function analyses but likely less suitable for actual sugar beet improvement.

Most examples of documented sugar beet genetic engineering have been confined to the laboratory, and many involve technology development using reporter or marker genes. Other GM sugar beets target the various threats to sugar beet growth and yield, or attempt to speed up breeding. Despite a few reports of field trials (see Supplementary Table S2), some in the context of biosafety research [173,174] or field demonstration of rhizomania resistance [175], no events other than herbicide tolerance have reached the state of commercialization, likely due to worldwide regulatory issues. The regulation of transgenesis as 'genetic modification' implemented in many parts of the world is accompanied by additional lengthy and costly safety assessments, strict labeling requirements that generate world trade issues, and an inherent uncertainty about the industrial and public (consumer) acceptance of such material. So far, three transgenic sugar beet lines have been commercialized, all three herbicide-tolerant [176], and all three in the USA. Of these, the glyphosate-tolerant (Roundup-ready) sugar beet has seen an adoption rate unprecedented for any other GM crop [98], despite ongoing discussions and legal battles over the health aspects of glyphosate [177–179].

Genome editing. No examples of successful nuclear genome editing of sugar beet are yet (August 2025) documented in the PGED (plantcrispr.org; [180]) and EUSAGE databases (www.eu-sage.eu; [181]), or the scientific literature. The many ideas for practical applications of gene editing cover many breeding targets [182,183]. Whereas genome editing is likely to be regulated as conventional breeding in many countries [184], with New Zealand and South Africa as notable exceptions, the EU awaits the decision on whether or not to consider this technology as an example of genetic modification. The EC proposed new regulations in July 2023. These were supported by a (modest) majority of the EP in February 2024 [185]. In China and Russia, the decision is also due. Resistance to BCTIV (the Beet Curly Top Iran Virus) was accomplished by targeting viral gene expression via agroinfiltration using Cas9 constructs of the CRISPR-Cas system [186]. Related strategies of environmental RNA interference may be equally attractive [187]. Although such approaches need demonstration of the proof-of-concept in the field and await regulatory approval, the future will likely see more examples and applications.

4. Impact of climate change on sugar beet cultivation and yield

Europe is currently the world's fastest-warming continent; the higher temperatures are accompanied by changing precipitation patterns and the increased likelihood of weather extremes [27,188]. Different regions of Europe have different projections: in the sugar beet-growing area of northern Europe, summers get drier and winters get wetter. For the North Sea region, an increase in extreme windstorms is suggested, depending on the choice of model and climate scenario [189,190]. Such climate and weather changes will affect growing conditions and pest pressures, potentially altering the area suitable for growing sugar beets, and impact the economic viability of beet cultivation and sugar processing. Concerns are that Europe's policies and actions are too slow and incremental to keep pace with the reality of climate risks [27]. The aspects of climate change considered for sugar beet cultivation and yield are higher temperatures and more extreme environmental conditions. In all cases, the effects of and possible measures against climate change should be considered in terms of cost-benefit relationships and return on investments.

4.1. Higher temperatures

Temperature increases due to climate change may allow earlier sowing of sugar beet in Europe's northern and continental parts, as long as the soil is dry enough for seedbed preparation and allows sowing without soil compaction [10]. The higher temperature could result in faster plant establishment in spring, a longer growing season, and ultimately higher sugar yields. The higher temperatures are associated with higher carbon dioxide (CO_2) concentrations in the atmosphere, which can affect photosynthesis and water-use efficiency [191]. Free-air CO_2 enrichment studies suggested an average yield increase of C_3 crops, the photosynthesis type of sugar beet [192], of about 18% at about 200 ppm increase of CO_2, depending on nitrogen and water conditions [193]. Also, the higher temperatures may promote increased use of winter beets. Earlier sowing in autumn may become feasible, aimed at faster canopy closure in spring to increase light interception and yield. It requires non-bolting and frost-resistant cultivars [194], and the increased growth in spring should not be counter-balanced by increased drought stress later in the growing season [194,195]. A shift from summer to winter beet cultivation, or year-round sugar beet cultivation, may contribute to land-use efficiency. A meta-analysis assessing data from 41 studies on the impact of climate change in Europe suggested an average yield increase of about 15% for sugar beet by the 2050s [196].

However, the adverse effects of a higher temperature are likely to outweigh the potentially positive effects [197]. With earlier sowing in spring, there is a higher risk of a cold period at the beginning of growth (Fig. 4, bar labeled frost) that increases the likelihood of premature bolting (vernalization) [198]. Higher temperatures in autumn are likely to increase respiration, negatively impacting sugar accumulation in beets. In autumn, the highest sugar production is achieved during sunny daytime weather and cold, clear nights. In relatively warm weather, depending on the amount of nitrogen available, beets may resume growth at the expense of sugar yield [70]. Higher temperatures, especially in combination with more intense temperature fluctuations, moisture stress, and damage during harvest [6], will increase post-harvest storage losses due to mold and rots [106].

The potentially positive effects of higher CO_2 concentrations are unclear: no evident change in photosynthetic metabolism was observed in sugar beet over a century, despite considerable increases in CO_2 concentrations. It indicates a relative insensitivity of sugar beet to acclimate to higher CO_2 levels [199]. Dedicated sugar beet trials showed a modest 7–12% increase in biomass in response to higher CO_2 levels and a 12–13% increase in sugar yield [200,201], but no increase in the shoot-to-root ratio [202].

Higher temperatures are expected to impact the distribution and impact of sugar beet pests and diseases. These could move to higher latitudes and increase the spread of current pests and diseases, introduce pests or diseases currently unknown in a given area, or give rise to entirely new pests and diseases (*e.g.*, due to host expansion). In addition

to the effects on disease spread, milder winters may allow higher survival rates and increase the pressure of pests and diseases [198].

For example, the sugar beet disease known as 'Syndrome des Basses Richesses' (SBR) is caused by bacteria and transmitted by an insect. A planthopper (*Pentastiridius leporinus*) is the primary vector of the (proteo)bacterium '*Candidatus Arsenophonus phytopathogenicus*' [203] that causes SBR. SBR occurred in France about 20 years ago and is now gaining importance in sugar beet growing areas, supposedly due to climate change, possibly related to the broader distribution of the transmitting plant hopper [155,204]. Similar concerns apply to rubbery tap root disease (RTD), which has a comparable biology [205]. Likewise, curly top is a sugar beet viral disease spread by beet leaf hoppers (*Circulifer tenellus* and others). It is USA-based, but the presence of curly top virus is documented in Italy [206], and the leafhoppers may expand their territory with a changing climate. This way, curly top may become a future issue for sugar beet in Europe [207].

Similar considerations apply to the occurrence and persistence of competing weeds [208]. Higher temperatures may decrease the competitiveness of crops against weeds, as the weed population is likely to have higher adaptability than crops [209]. New weeds could spread because of the temperature changes and pose new problems. For example, in the USA, the tumbleweed Kochia (*Bassia scoparia*, also known as *Kochia scoparia*) can cause over 90% yield loss in sugar beet, with an average yield loss of almost 50% [210]. The effect is partly due to its ability to accumulate different types of herbicide resistance, leaving an increasingly limited range of herbicides available to manage invasive Kochia populations. Notably, glyphosate-resistant kochia has become problematic [211]. Kochia is native to Middle and Central Europe but is not considered invasive or weedy. It is grown as an ornamental in some parts of Europe [206]. Due to temperature changes, especially in combination with herbicide applications, it may become invasive and problematic in future European sugar beet cultivation and yield.

A sugar beet variety known as 'tropical (sugar) beet' was first introduced in India [212] to allow sugar beet cultivation in a tropical climate [213]. Because it requires less water and has a shorter growth period than sugarcane, it may help expand the area of sugar beet cultivation to the subtropics [214]. It resulted from the continued selection of hybrids that withstood heat and tropical diseases. Farmer adoption, and sugar yields are competitive [213,215,216]. The experiences with such a crop regarding breeding and cultivation in the tropics may yield valuable insights for future strategies for sugar beet in a warmer Europe.

4.2. Extreme environments

More extreme weather is associated with climate change. However, predicting and managing such extreme events is challenging. First, the event will likely be local, affecting a possibly small area (very) hard, but bypassing a similar area nearby. Second, the event can come in many forms and shapes, each requiring different coping methods. The main parameters of weather are temperature, water, and wind. Temperatures can come as extreme heat or cold, prolonged or short, at an undesired time in the growing season. Water conditions can range from extreme drought to flooding, either long-term or short-term (flash flooding), at an unfit time in the season. When water comes as hail, plant damage and defoliation may cause considerable yield reduction [217]. Also, the quality of the fresh water matters: contaminants such as salt may interfere with sugar beet growth. Wind can come as severe as devastating storms in a Europe that is not accustomed to or prepared for such winds.

4.2.1. Water

Sugar beet needs about 200 L of water to produce 1 kg of dry matter [20] and belongs to the crop category with the lowest water footprint [218]. Scarcity of water is generally due to a lack of precipitation, often accompanied by low soil moisture levels. Due to complex sink-source relationships between leaf and taproot, the primary cause for yield reduction in sugar beet upon drought stress may be reduced sugar accumulation in leaves rather than reduced photosynthesis [20].

Sugar beet is vulnerable to drought during sowing and crop emergence (Fig. 4). With drought after sowing, seed imbibition is impaired, reducing or preventing germination [71]. At later stages of growth, moderate drought does not impair sucrose accumulation: sugar beet is relatively tolerant to drought stress due to its deep rooting [20]. However, drought reduces the value of the sugar beet due to reduced sugar accumulation and reduced quality by accumulating compounds that affect processing in the factory, such as free amino acids, K, Na, and betaine [20]. Prolonged or persistent water scarcity will result in the yellowing and wilting of leaves, interfering with the production of sugars and ultimately leading to the death of the plant. With the increased likelihood of water shortage and drought in the growing season, irrigation may become necessary to safeguard yield. Irrigation can increase sugar beet yield by up to 30%, depending on local conditions [219], but requires sufficient freshwater availability.

Water logging is equally problematic throughout the season. Heavy rain during germination may disturb soil aggregates, resulting in soil crusting that prevents the sugar beet seedling from penetrating the soil and reduces emergence [220]. High-intensity rainfall that causes ponding water can significantly damage the developing sugar beet crop. Larger plants tolerate water-saturated soils better, but this environment can result in damage such as stunting, nutrient deficiency, root diseases, and root rot. Inundation for only 1–3 days may corrupt 80–100% of the sugar beet yield [221].

Too wet conditions make harvesting more challenging. When it is (too) wet, harvesters do much damage to both the taproots and the soil. Sugar beet harvesters are heavy, and undesired soil compaction during beet harvest is a concern [222]. Also, more soil will stick to the beet upon harvesting. The sugar beet harvester will then use a higher cleaning intensity, leading to more root tip breakage and surface damage to the beet [6]. Damaged sugar beets have a lower storability due to pathogen infestation and an increased respiration rate for wound healing [223,224]. The wet soil and its constituents in the storage heap lead to obstruction of the venting of the sugar beets and, therefore, higher storage losses [70].

4.2.2. Salinity

Most coastal regions in Europe already see the effects of the global warming-related increase in sea level relative to land: the supply of freshwater from mountain-fed rivers no longer counteracts the entry of seawater [225]. Seawater intrusion salinizes agricultural land. Seawater salts, primarily sodium chloride (NaCl), affect wetlands and pollute aquifers, harming their flora and fauna. Salt limits the availability and use of farmland, the amount of water that can be extracted safely without increasing seawater intrusion, and the availability of ground and surface water suitable for irrigation [226].

The cultivated sugar beet is relatively tolerant to saline soil [227,228] due to the salt tolerance of the sea beet, the wild ancestor of the current cultivated sugar beet. The molecular mechanisms involved are well documented, and sugar beet is considered to be a model system for studying salt tolerance of crops [229]. However, germination of sugar beet seed and the growth of the sugar beet seedling are more vulnerable to saline conditions than the maturing crop, so the cultivation of sugar beet on saline land may promote the future use of transplanting seedlings [67].

Although sugar beet yields best on non-saline soil, it can be grown on moderately saline-affected land that is or has become underutilized otherwise [228]. Such cultivation of sugar beet could offer a viable option for additional land use, provided that the spread of (new?) halophytic weeds can be controlled satisfactorily [230]. Salinity field experiments are required to assess the optimal management strategies for sugar yield and soil quality [225].

4.2.3. Temperature

Sugar beet is relatively sensitive to extreme temperatures. Low soil temperatures reduce the rate of seedling emergence [231]. Frost, particularly in late spring during the early vegetative stages, can kill young seedlings. If mild temperatures and extended periods of sunlight follow the cold period, premature bolting is promoted. Early bolting diverts metabolic energy from sugar production, resulting in yield loss. It can generate fibrous and fangy roots that are difficult to harvest and of too low quality to warrant processing [77]. Bolting resistance is an important aim in sugar beet breeding [18].

Too much heat during the vegetative stage can result in a decline in canopy development and a deterioration of leaves. Extreme heat causes more water evaporation and is closely related to water deficit. Losing leaves adversely affects sucrose accumulation [8]. Too high temperatures at the final stages of growth, particularly at night, prolong root growth at the expense of sugar storage in the taproot, hence the yield [232]. Temperature is also relevant during beet storage, as the respiration rate of sugar beets is higher at higher temperatures, implying post-harvest sugar losses [66].

4.2.4. Wind

Wind erosion can damage the seedlings of the sugar beet [233]. It may require resowing, which shortens the sugar beet's growing period and lowers sugar yields. Wind erosion may result in soil degradation and is a particular problem on light and sandy soils. Wind will cause less damage at the later stages of growth when the sugar beet plants are well established. Wind and wind-induced canopy movement may interfere with photosynthesis and yield [234]. Protective measures are adding mulch [233], orienting the row relative to the primary wind direction [235], and others [70,236]. These may not be sufficient against extreme wind speeds.

5. Sugar beet towards 2025

The wishes and demands for sugar beet in 2050 and beyond do not necessarily conflict with the current wishes and desires. However, strategies in breeding, farming, processing, and marketing will need more integration and innovation to adapt to the challenges of climate change. In addition to sugar yield, better use of all materials the crop has to offer will contribute to a viable and attractive business case of sugar beet cultivation.

5.1. Cultivation

Advanced farming practices and IPM will be essential to maintain or increase the yield levels of sugar beet in the future. The developments can be categorized under the umbrella term of 'precision agriculture,' the advanced management strategy that involves the use of information technology (IT) and artificial intelligence (AI) technologies for global positioning systems (GPS), sensors, drones, robotics, and data-driven approaches [237–239].

Precision agriculture develops and uses decision support systems to guide decisions on irrigation, (local) nutrient supply, local pest, disease, or stress pressure, and their control, while reducing manual labor costs. Approaches may result in detailed prescription maps that can guide appropriate machinery for variable rate technology (VRT) to apply inputs at precise locations and rates. GPS-based planting systems ensure more accurate seed placement and spacing of sugar beet to promote more uniform crop growth [240]. New approaches such as strip cropping or intercropping should be evaluated [241,242].

VRT-enabled tractors and drones will further optimize fertilizer use [243]. Cercospora leaf spot disease severity can be predicted using drone images [244]. Likewise, site-specific application of herbicides may save considerable amounts of the required herbicide [245]. Automated weed detection [246] will encourage the use of robotics for sensor-guided mechanical and chemical weed removal [245,247]. Despite the issue of freshwater availability [248], the development of advanced irrigation technologies like drip irrigation will combat drought stress or salinity [249] and can contribute to nutrient use efficiency (fertigation) [250]. Integrative agroecological strategies should be able to bridge the yield gap between current and precision farming practices. Such strategies result in higher yield, environmental sustainability, and overall climate resilience at a reduced cost, assuming appropriate technical expertise is available and the benefits warrant the investments [238]. A future farming practice that deserves research attention for sugar beet is the application of biocontrols, the use of beneficial microorganisms that contribute to plant growth and health. Sugar beet's pre- and postharvest microbiome may have positive effects, such as promoting plant growth and protection, assuming the beneficial organisms can be separated from the harmful organisms in a controlled and reproducible way [111,251]. Future analyses should indicate which diseases can be biocontrolled acceptably.

Similarly, the application of biostimulants should be considered. A plant biostimulant is any substance or organism applied to plants to enhance (a)biotic stress tolerance, growth, yield, or quality, regardless of its nutrient content [252,253]. These include extracts from algae or seaweed [254], protein lysates [255], or root- and rhizosphere-colonizing non-pathogenic microorganisms [256]. Notably, mycorrhizal fungi and rhizobacteria are considered. Most biostimulants are organic. For example, adding keratin-rich material to soil may suppress Rhizoctonia in sugar beet seedlings [257]. Also, minerals may have positive effects, *e.g.,* foliar application of silicon, mainly as silicon dioxide, is reported to have a biostimulatory effect on sugar beet [258].

Rhizosphere dynamics and the interactions with soil health are gaining widespread recognition for improved plant performance [259], including sugar beet [251]. Strategies targeting the sugar beet leaf microbiome are equally promising [260]. Insight into the different sugar beet microbiomes will likely yield new avenues and strategies for improving sugar beet cultivation and yield.

5.2. Crop improvement

Facing the challenges outlined above, breeding should focus on the combination of different resistances against the main pests (Table 1), and new threats that may be exacerbated by changing weather and climate patterns. New genes are needed continuously, and new, notably faster, breeding approaches are welcome. Analogous to 'precision agriculture,' sugar breeding will continue developing into 'precision breeding.' [261]. In Europe, this development will be without the use of genome editing technology, for the time being. Omics technologies (from DNA to phenotype) integrated with germplasms, genetics, and agronomy will elucidate gene and pathway function in complex functional networks to allow better and faster gene variant identification and promote selection in the field. The advent of artificial intelligence (AI) will result in integrated data analyses and predictive simulation models of sugar beet growth and yield under different climate scenarios to steer informed breeding decisions [262,263]. It will contribute to establishing sugar beets better adapted to a changing climate.

Breeding based on selection and use of the available natural variation in the sugar beet gene pool will have to intensify, but may lack the pace required. To obtain the desired and necessary pace currently lacking in Europe [27], these may involve the use of (extensive) gene editing or gene transfer [183]. ABA-related approaches are considered attractive for sugar beet genome editing towards abiotic (drought) stress tolerance [183,264]. In addition to CRISPR-based genome editing, recombination and various other approaches may become suitable for genome engineering of sugar beet [265]. Such strategies assume that in the not-too-distant future, all regulatory, legal, and acceptance issues of these approaches will have been satisfactorily addressed for all stakeholders in the sugar beet value chain in Europe.

New sugar beet varieties have been announced for VY tolerance, combining precision gene editing and gene silencing [266]. If successful

and approved for broad market access, more applications of such technology are likely.

5.2.1. Improving sink strength

The sink strength of the taproot of sugar beet is considered the prime limiting factor for sugar accumulation and yield [6]. In a pot experiment in controlled conditions, it was demonstrated that a single sugar beet plant could accumulate (in over 850 days, well over four times the normal growing period) the amount of sugar that would be equivalent to a yield of 50 t per hectare (with 100.000 plants per hectare) [6,267], which is about twice the yield now considered the theoretical maximum. The sugar beet tap root will continue to grow if vernalization is inhibited [267]. Therefore, research into the precise molecular and cellular mechanisms of vernalization may help outline strategies to let the tap root grow.

It might be feasible to adjust the photosynthetic efficiency and sink-source traffic so that the light is used more efficiently and a similar high yield is obtained in a much shorter period. Strategies for higher photosynthetic efficiency exist [268]. The taproot can become (considerably) bigger. The cell walls should become stronger or the number of cells should increase [6], despite the complexity of plant organ size [269]. If the sink limitation can be overcome, polyploidization could be reconsidered to obtain larger plants and higher yields, despite previous disappointments with polyploidization [116]. Other strategies to increase sink strength may include overexpression of particular transcription factors that regulate the expression of genes related to both cell wall and sucrose metabolism [270].

5.2.2. Biological nitrogen fixation

The introduction of biological (or symbiotic) nitrogen fixation in sugar beet may help further reduce nitrogen fertilizer use and make sugar beet less dependent on or even self-fertilizing for nitrogen. Legumes, such as peas or lentils, can enter a beneficial symbiotic relationship with microorganisms that result in nitrogen fixation. Engineering should be feasible [271,272] given the data that the lack of biological nitrogen fixation is due to the loss of a relatively small number of genes [273]. However, the transfer of biological nitrogen fixation to non-host plants remains elusive. A possible new approach is to help the nitrogen-fixing microorganisms enter the new host [274]. For sugar beet, it will be interesting to evaluate how a strategy of root-based biological nitrogen fixation relates to canopy and taproot development.

5.2.3. Breeding for resilience

The generic term for a crop to cope with highly variable, continuously changing, and unpredictable conditions is 'resilience.' [275]. Resistance or tolerance to biotic and abiotic stresses is often seen as (part of) breeding for resilience and will result in better performance and yield. However, the above approaches may underestimate the true challenge of breeding for resilience: coping with highly variable, continuously changing, and unpredictable conditions. The issues that may be underestimated here are variation and combination. For example, resistance to abiotic stresses may have conflicting demands: increased drought stress will not help against waterlogging. Improving one aspect may affect another, and the combined demands may be contradictory. Besides, environmental conditions are expected to become more extreme more rapidly. Therefore, new approaches and outlooks are required.

The new sugar beet may necessitate currently unthinkable decisions and strategies. Current breeding strategies focus on yield in different (adverse) conditions that tend to be highly controlled [275] but not yet on conditions that may differ dramatically during a growing season. For example, in the absence of diseases, current sugar beet varieties perform well in different drought environments [150]. However, such results may not reproduce in the case of drought followed by heat stress or waterlogging in the same growing season, possibly combined with different disease pressures. The need for resilience may challenge the breeding strategy to develop cultivars for a given environment with well-defined growing conditions. Yield predictability and stability in a variable environment over the years may become more important than yield predictability and stability for a defined environment: a resilient cultivar should perform well in a multitude of highly variable growing conditions and seasons, possibly (likely?) at the expense of maximum yield in optimal conditions.

Lower yields should become acceptable against the insurance of the lesser likelihood of a complete yield loss. How such a phenotype should be generated and tested is a future challenge. It may well be that average yield will become a more critical parameter for future improvement than the current focus on optimal or maximal yield in given conditions. It will require new crop improvement, management strategies, and economic setups other than contracts based on the amounts of sugar produced. More flexibility in contracts is warranted. It likely also needs adjustments to the logic and philosophy of the cultivar registration procedures. It is currently unclear how such trials should consider environmental resilience. The current variety trials may consider testing for future biotic stresses (or asking for such analyses from the submitting entities) and including more (abiotic) environmental variability to assess the multi-year and multi-environment sugar yield or yield potential.

5.3. Processing and byproduct use

Processing sugar beets into the final product(s) is a mature technology [19]. Future improvements focus on resource efficiency (energy, water), reducing (fossil) energy consumption and carbon emissions (decarbonization), in addition to the electrification of individual process steps, such as transport, evaporation, and crystallization [276]. Whereas the current sugar factories require up to 1200 kWh per ton of sugar (excluding pulp drying), the aim for the future is to halve that energy demand [277]. Many of these developments are still in the research and development phase. The considerable implementation costs may hamper their adoption. The EU agricultural framework should help stimulate such adoption, assuming that the policies of less resource dependency and increased self-sufficiency take shape and will safeguard the economic viability of the European sugar sector.

The use and marketing of the byproducts of processing may contribute to the future business case of sugar beet cultivation and processing. It may be attractive to generate more value from the above-ground material (leaves) despite its low dry matter content (<15%; [278]). Sugar beet leaves are a potential source of cattle feed, energy [63] or plant protein [279,280], notably rubisco [281], and possibly other components for the chemical industry, such as phenolics and carbohydrates [282,283]. The leaf pulp remaining after the processing of leaves could be used as soil fertilizer [284] or warrants investigations into other uses [285]. Many of these developments are also still in the research and development phase.

6. Concluding remarks

The future of sugar beet in Europe toward 2050 will depend on sugar market developments, (local) climate conditions, improved farming and processing practices, industrial use of side streams, breeding successes, policy measures, and political and social support for any of these developments.

Local growth and processing of sugar beet align well with the EU policies of reducing dependence and promoting sustainability, provided sufficient support for precision agriculture, resilience breeding, and processing capacity. Additional use of byproducts will be necessary as a contribution to the business case of sugar beet valorisation.

Integration with the incentives of a broader bioeconomy would justify such support. Sugar is likely to see increased use as a renewable carbon source in industrial applications in a world that is parting from oil and other fossil resources. Life cycle assessments of chemical

production processes indicate that beet sugar can be an economically feasible and environmentally sustainable resource for Europe [23]. The use of sugar beyond food would seem both attractive and inevitable, and should surpass the food-versus-fuel debate in the context of renewable carbon [23,286]. However, sugar beet is not likely to meet future (EU) sugar demands when it is also used as a biobased feedstock for bioplastics. Alternative streams should accompany sugar beet sugar.

Options to tailor sugar beet into a resilient crop that can face the challenges of yield in a much more variable and often adverse environment are in place for both farming practices and future crop breeding. Their added value will depend on performance, adoption, regulation, and acceptance. The road to a predictable and feasible yield may start with accepting that less can be more.

CRediT authorship contribution statement

Jan-Peter Nap: Writing – review & editing, Writing – original draft, Software, Resources, Conceptualization. **Frank J. de Ruijter:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Daan S. van Es:** Writing – review & editing, Project administration, Funding acquisition. **Ingrid M. van der Meer:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Visualization.

Declaration of financial support

This research is part of the projects' Biobased materials and chemicals for relieving and replacing the fossil feedstock system' (project number KB-34-010-001) and 'Exploring options for using CO_2 as a building block for materials and fuels' (project number KB-34-003-011), internally funded by the Wageningen Research (WR) Knowledge Base program KB34' Circular and climate neutral society' financed by the Dutch Ministry of Agriculture, Nature, and Food Quality.

Declaration of generative AI and AI-assisted technologies in writing

In preparing this work, the authors have used Grammarly to correct possible grammatical or spelling errors, conform to scientific English, and improve the readability of the text. The authors have used Perplexity to help locate (grey) literature. The authors have carefully reviewed and edited the text as needed and take full responsibility for its contents.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Wageningen Research for funding and ISO (the International Sugar Organization) for permission to use Fig. 1. They thank Mr. Morris J. Mes, MSc, for preparing Fig. 2 and are indebted to Dr. Sinead O'Keeffe (Wageningen University & Research) for sharing information, discussions, and help in preparing Fig. 3. The authors also thank an anonymous reviewer for helpful suggestions and corrections.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.102343.

Data availability

No data was used for the research described in the article.

References

[1] EC, Agriculture and rural development - sugar market observatory. https://agriculture.ec.europa.eu/data-and-analysis/markets/overviews/market-observatories/sugar_en, 2025. (Accessed 10 April 2025).
[2] Statista, Sugar industry - statistics and facts: total sugar production worldwide. https://www.statista.com, 2025. (Accessed 5 August 2025). https://www.statista.com/statistics/249679/total-production-of-sugar-worldwide/. https://www.statista.com/topics/1224/sugar/.
[3] L. Delannoy, P.Y. Longaretti, D.J. Murphy, E. Prados, Peak oil and the low-carbon energy transition: a net-energy perspective, Appl. Energy 304 (2021) 117843, https://doi.org/10.1016/j.apenergy.2021.117843.
[4] UNEP, (United Nations Environment Programme) The Closing Window, Climate crisis calls for rapid transformation of societies, Emissions GAP Report (2022) 132 pp. Nairobi, Kenya, https://www.unep.org/resources/emissions-gap-report-2022.
[5] IPCC, Global warming of 1.5°C : IPCC special report on impacts of global warming of 1.5°C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty, Cambridge University Press, Cambridge, 2022, https://doi.org/10.1017/9781009157940.
[6] C.M. Hoffmann, C. Kenter, Yield potential of sugar beet – have we hit the ceiling? Front. Plant Sci. 9 (2018) 289, https://doi.org/10.3389/fpls.2018.00289.
[7] FAO, (Food and Agriculture Organization of the United Nations). FAOSTAT - Food and Agriculture data, 2025. https://www.fao.org/faostat. Accessed 5 August 2025.
[8] E. Gentile, A. Loi, M. Gentile, M. Bruni, S. Berisio, F. Roda, G. Piccoli, D. Bradley, M. Christodoulou, E. Oliver, C. Berg, S. Uhlenbrock, J. Bracken, T. Scott. Study on the Adaptation Strategies of the Sugar Supply Chain after the End of the Sugar Quotas, Final Report, Publications Office of the European Union, Brussels, Belgium, 2022, p. 267. https://data.europa.eu/doi/10.2762/44128.
[9] C.M. Hoffmann, T. Huijbregts, N. van Swaaij, R. Jansen, Impact of different environments in Europe on yield and quality of sugar beet genotypes, Eur. J. Agron. 30 (2009) 17–26, https://doi.org/10.1016/j.eja.2008.06.004.
[10] B. Hanse, F.G.J. Tijink, J. Maassen, N. van Swaaij, Closing the yield gap of sugar beet in the Netherlands - a joint effort, Front. Plant Sci. 9 (2018) 184, https://doi.org/10.3389/fpls.2018.00184.
[11] M. Aragrande, M. Bruni, A. Loi, R. Esposti, The effect of EU 2006 sugar regime reform on vertical price transmission, Agric. Food Econ. 5 (2017) 18, https://doi.org/10.1186/s40100-017-0087-8.
[12] EC, EU sugar quota system comes to an end (press release), https://ec.europa.eu/commission/presscorner/detail/en/IP_17_3487, 2017. (Accessed 5 August 2025).
[13] M. Maitah, L. Smutka, The development of world sugar prices, Sugar Tech 21 (2019) 1–8, https://doi.org/10.1007/s12355-018-0618-y.
[14] HLG (High-Level Group on Sugar), Report of the High-Level Group on Sugar, Brussels, Belgium, 2019, p. 44. https://agriculture.ec.europa.eu/system/files/2019-07/final-report-high-level-group-meeting-sugar_0.pdf.
[15] CEFS, (European Association of Sugar Manufacturers), CEFS statistics 2023/2024, 16 pp, https://cefs.org/wp-content/uploads/2025/03/250328_CEFS_Statistics_23_24.pdf, 2025. Brussels, Belgium.
[16] J. Berger, B. Brümmer, D.-D. Fiankor, T. Kopp. Sugar Market Policies in the EU and International Sugar Trade 61, Universität Göttingen, 2021. https://www.uni-goettingen.de/de/document/download/77e0723f60776f33c2ed56cfce01439b.pdf/Berger,_Br%C3%BCmmer,_Fiankor,_Kopp_-_2021_-_Sugar_Market_Policies_in_the_EU_and_International_Sugar_Trade.pdf. Göttingen, Germany.
[17] CBS_StatLine, Agriculture; crops, livestock and land use by general farm type, region (update 28 March 2025). https://opendata.cbs.nl/#/CBS/en/dataset/80783eng/table?ts=1742549597309, 2025. (Accessed 5 August 2025).
[18] J.M. McGrath, L. Panella, Sugar beet breeding, Plant Breed. Rev. 42 (2019) 167–218, https://doi.org/10.1002/9781119521358.ch5.
[19] B.M. Muir, Sugar beet processing to sugar, in: V. Misra, S. Srivastava, A.K. Mall (Eds.), Sugar Beet Cultivation, Management and Processing, Ch. 42, Springer, Singapore, 2022, pp. 837–862, https://doi.org/10.1007/978-981-19-2730-0_42.
[20] C.M. Hoffmann, H.J. Koch, B. Märländer, Sugar beet, in: V.O. Sadras, D. F. Calderini (Eds.), Crop Physiology: Case Histories for Major Crops, Ch. 2, Academic Press, Amsterdam, 2021, pp. 634–672, doi.org/610.1016/B1978-1010-1012-819194-819191.800020-819197.
[21] B.M. Popkin, S. Barquera, C. Corvalan, K.J. Hofman, C. Monteiro, S.W. Ng, E. C. Swart, L.S. Taillie, Towards unified and impactful policies to reduce ultra-processed food consumption and promote healthier eating, Lancet Diabetes Endocrinol. 9 (2021) 462–470, https://doi.org/10.1016/S2213-8587(21)00078-4.
[22] WHO, (World Health Organization), Sugar-sweetened beverage taxes in the WHO European Region: success through lessons learned and challenges faced, WHO Europe, Copenhagen, Denmark, 2022, p. 16. https://www.who.int/europe/publications/i/item/WHO-EURO-2022-4781-44544-63081.
[23] L. Dammer, M. Carus, S. Piotrowski. Report nova-Institut 23, 2019. https://assets.website-files.com/6144857e3aac5ad07ebf212f/6163ee75fb4bc963c4530eef_201

9_Nova%20Institute_Sugar%20as%20feedstock%20for%20the%20chemical%20industry.pdf.
[24] T.A. Ewing, N. Nouse, M. van Lint, J. van Haveren, J. Hugenholtz, D.S. van Es, Fermentation for the production of biobased chemicals in a circular economy: a perspective for the period 2022-2050, Green Chem. 24 (2022) 6373–6405, https://doi.org/10.1039/d1gc04758b.
[25] R. van Hoek, Research opportunities for a more resilient post-COVID-19 supply chain – closing the gap between research findings and industry practice, Int. J. Oper. Prod. Manag. 40 (2020) 341–355, https://doi.org/10.1108/IJOPM-03-2020-0165.
[26] M.G. Rivera-Ferre, F. López-i-Gelats, F. Ravera, E. Oteros-Rozas, M. di Masso, R. Binimelis, H. El Bilali, The two-way relationship between food systems and the COVID19 pandemic: causes and consequences, Agric. Syst. 191 (2021) 103134, https://doi.org/10.1016/j.agsy.2021.103134.
[27] EEA, (European Environment Agency), European climate risk assessment, report 01/04 488 pp 2024 https://www.eea.europa.eu/en/analysis/publications/european-climate-risk-assessment Copenhagen, Denmark.
[28] IEA, (International Energy Agency), A 10-point Plan to Reduce the European Union's Reliance on Russian Natural Gas, 2022, p. 12 pp. Paris, France, https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas.
[29] S. Wolf, J. Teitge, J. Mielke, F. Schütze, C. Jaeger, The European Green Deal — more than climate neutrality, Intereconomics 56 (2021) 99–107, https://doi.org/10.1007/s10272-021-0963-z.
[30] H.L. Bos, J. Broeze, Circular bio-based production systems in the context of current biomass and fossil demand, Biofuel Bioprod. Biorefining 14 (2020) 187–197, https://doi.org/10.1002/bbb.2080.
[31] H. Bos, D. van Es, P. Harmsen, The renewable future of materials: how to produce our everyday products once we phased out fossil oil and gas, Wageningen Food & Biobased Research, Wageningen, The Netherlands (2023).
[32] IEA, (International Energy Agency) Putting CO2 to use, Creating Value from Emission, 2019, p. 86 pp. Paris, France, https://www.iea.org/reports/putting-co2-to-use.
[33] S.A. Theofanidis, A.N. Antzaras, A.A. Lemonidou, CO_2 as a building block: from capture to utilization, Curr. Opin. Chem. Eng. 39 (2023) 100902, https://doi.org/10.1016/j.coche.2023.100902.
[34] CMB, (Commodity Board Europe) EU sugar market balance: trends and forecast for 2024/25. 2025. https://cmbroker.cloud/public/news/62842. (Accessed 3 April 2025).
[35] EC, Agri-food data portal - sugar use. https://agridata.ec.europa.eu/extensions/DashboardSugar/SugarUse.html, 2025. (Accessed 3 April 2025).
[36] EC, Eurostat - agricultural production - crops - potatoes and sugar beet. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_crops#Potatoes_and_sugar_beet, 2025. (Accessed 5 August 2025).
[37] J. Zheng, S. Suh, Strategies to reduce the global carbon footprint of plastics, Nat. Clim. Change 9 (2019) 374–378, https://doi.org/10.1038/s41558-019-0459-z.
[38] C.G. Schirmeister, R. Mülhaupt, Closing the carbon loop in the circular plastics economy, Macromol. Rapid Commun. 43 (2022) 2200247, https://doi.org/10.1002/marc.202200247.
[39] OECD, Global Plastics Outlook, Policy Scenarios to 2060, 283 pp, https://www.oecd.org/en/publications/global-plastics-outlook_aa1edf33-en.html, 2022, Paris, France.
[40] K. Iffland, J. Sherwood, M. Carus, A. Raschka, T. Farmer, J. Clark, Definition, calculation and comparison of the "Biomass Utilization Efficiency (BUE)" of various bio-based chemicals, polymers and fuels, nova-Paper #8 (2015) 26–pp. https://renewable-carbon.eu/publications/product/nova-paper-8-on-bio-based-economy-definition-calculation-and-comparison-of-the-biomass-utilization-efficiency-bue-of-various-bio-based-chemicals-polymers-and-fuels-—-full-version. Huerth, Germany.
[41] I. Klenk, B. Landquist, O.R. De Imaña, The product carbon footprint of EU beet sugar (part II), Sugar Ind. 137 (2012) 213–221, https://doi.org/10.36961/si12849.
[42] B. de Crom, J. van Diepen, J. Scholten, Excellent environmental performance of beet sugar production in the Netherlands, Zuckerindustrie 145 (2020) 161–165, https://doi.org/10.36961/si24156.
[43] M.N. Garcia Gonzalez, L. Björnsson, Life cycle assessment of the production of beet sugar and its by-products, J. Clean. Prod. 346 (2022) 131211, https://doi.org/10.1016/j.jclepro.2022.131211.
[44] K.M. Adams, M. Benzie, S. Croft, S. Sadowski, Climate change, trade, and global food security: a global assessment of transboundary climate risks in agricultural commodity flows. SEI Report, Stockholm Environment Institute, Stockhom, Sweden, 2021, p. 90. https://doi.org/10.51414/sei2021.009.
[45] M. Dal-Bianco, M.S. Carneiro, C.T. Hotta, R.G. Chapola, H.P. Hoffmann, A.A. F. Garcia, G.M. Souza, Sugarcane improvement: how far can we go? Curr. Opin. Biotechnol. 23 (2012) 265–270, https://doi.org/10.1016/j.copbio.2011.09.002.
[46] K.S. Dinesh Babu, V. Janakiraman, H. Palaniswamy, L. Kasirajan, R. Gomathi, T. R. Ramkumar, A short review on sugarcane: its domestication, molecular manipulations and future perspectives, Genet. Resour. Crop Evol. 69 (2022) 2623–2643, https://doi.org/10.1007/s10722-022-01430-6.
[47] M. Tanveer, Z.U. Abidin, H.F. Najeeb Alawadi, A.N. Shahzad, A. Mahmood, B. A. Khan, S. Qari, H.F. Oraby, Recent advances in genome editing strategies for balancing growth and defence in sugarcane (*Saccharum officinarum*), Funct. Plant Biol. 51 (2024) Fp24036, https://doi.org/10.1071/FP24036.
[48] J.M. McGrath, B.J. Townsend, Sugar beet, energy beet, and industrial beet, in: M. Von Cruz, D.A. Dierig (Eds.), Industrial Crops: Breeding for Bioenergy and Bioproducts, Springer, New York, 2015, pp. 81–99, https://doi.org/10.1007/978-1-4939-1447-0_5. Ch. 5.
[49] P. Kelly, Sugar beet pulp - a review, Anim. Feed Sci. Technol. 8 (1983) 1–18, https://doi.org/10.1016/0377-8401(83)90038-X.
[50] Z. Usmani, M. Sharma, D. Diwan, M. Tripathi, E. Whale, L.N. Jayakody, B. Moreau, V.K. Thakur, M. Tuohy, V.K. Gupta, Valorization of sugar beet pulp to value-added products: a review, Bioresour. Technol. 346 (2022) 126580, https://doi.org/10.1016/j.biortech.2021.126580.
[51] M. Ptak, A. Skowrońska, H. Pińkowska, M. Krzywonos, Sugar beet pulp in the context of developing the concept of circular bioeconomy, Energies 15 (2022) 175, https://doi.org/10.3390/en15010175.
[52] R. Kumar, V.C. Verma, A.K. Mall, A.D. Pathak, Bioethanol production from sugar beet juices and molasses for economic and environmental perspectives, in: V. Misra, S. Srivastava, A.K. Mall (Eds.), Sugar Beet Cultivation, Management and Processing, Ch. 45, Springer, Singapore, 2022, pp. 905–930, https://doi.org/10.1007/978-981-19-2730-0_45.
[53] L.M. Jansen, V.C.A. Hendriks, H. Bentlage, A. Ranoux, H.W.C. Raaijmakers, T. J. Boltje, The industrial application potential of sugar beet pulp derived monosaccharides D-galacturonic acid and L-arabinose, Chembiochem 25 (2024) e202400521, https://doi.org/10.1002/cbic.202400521.
[54] P. Borysiuk, I. Jenczyk-Tolloczko, R. Auriga, M. Kordzikowski, Sugar beet pulp as raw material for particleboard production, Ind. Crops Prod. 141 (2019) 111829, https://doi.org/10.1016/j.indcrop.2019.111829.
[55] S.M. Fadel, W.S. Abou-Elseoud, E.A. Hassan, S. Ibrahim, M.L. Hassan, Use of sugar beet cellulose nanofibers for paper coating, Ind. Crops Prod. 180 (2022) 114787, https://doi.org/10.1016/j.indcrop.2022.114787.
[56] J. Gigac, M. Fišerová, Influence of sugar beet pulp on the wet web strength of paper, Cellul. Chem. Technol. 42 (2008) 421–427.
[57] H. de Jonge, Markt valt voor papier met vezels uit suikerbiet, Nieuwe Oogst. https://www.nieuweoogst.nl/nieuws/2021/05/31/markt-valt-voor-papier-met-vezels-uit-suikerbietenpulp, 2021.
[58] COSUN, Bright beet book. https://www.brightbeetbook.com/, 2021. (Accessed 3 April 2025).
[59] A.R. Adbhai, S. Dewanjee, K.G. Patel, N. Karmakar, Sugar beet molasses production and utilization, in: V. Misra, S. Srivastava, A.K. Mall (Eds.), Sugar Beet Cultivation, Management and Processing, CH. 44, Springer, Singapore, 2022, pp. 885–904, https://doi.org/10.1007/978-981-19-2730-0_44.
[60] F. Küçükaşik, H. Kazak, D. Güney, I. Finore, A. Poli, O. Yenigün, B. Nicolaus, E. T. Öner, Molasses as fermentation substrate for levan production by *Halomonas* sp, Appl. Microbiol. Biotechnol. 89 (2011) 1729–1740, https://doi.org/10.1007/s00253-010-3055-8.
[61] I. Ghazi, L. Fernandez-Arrojo, A. Gomez De Segura, M. Alcalde, F.J. Plou, A. Ballesteros, Beet sugar syrup and molasses as low-cost feedstock for the enzymatic production of fructo-oligosaccharides, J. Agric. Food Chem. 54 (2006) 2964–2968, https://doi.org/10.1021/jf053023b.
[62] K. Phuyal, U. Sharma, J. Mahar, K. Mondal, M. Mashal, A sustainable and environmentally friendly concrete for structural applications, Sustainability 15 (2023) 14694, https://doi.org/10.3390/su152014694.
[63] F.J. de Ruijter, P.W.A.M. Brooijmans, P. Wilting, A.W.M. Huijbregts, J.F.M. Raap, W.J. Corré. Afvoer en vergisting van bietenloof: burostudie naar de effecten op nutriënten, emissies en energie 48, Plant Research International, Wageningen, 2009. Report no. 241.
[64] V.L. Finkenstadt, A review on the complete utilization of the sugarbeet, Sugar Tech 16 (2014) 339–346, https://doi.org/10.1007/s12355-013-0285-y.
[65] M. Asadi. Beet-Sugar Handbook, Wiley Interscience, Wiley & Sons, Inc., New York, USA, 2006, p. 866.
[66] A.P. Draycott. Sugar Beet, Blackwell Publ, Oxford, UK, 2006, p. 474.
[67] M. Khozaei, A.A. Kamgar Haghighi, S. Zand Parsa, A.R. Sepaskhah, F. Razzaghi, V.A. Yousefabadi, Y. Emam, Evaluation of direct seeding and transplanting in sugar beet for water productivity, yield and quality under different irrigation regimes and planting densities, Agric. Water Manag. 238 (2020) 106230, https://doi.org/10.1016/j.agwat.2020.106230.
[68] A. Kockelmann, R. Tilcher, U. Fischer, Seed production and processing, Sugar Tech 12 (2010) 267–275, https://doi.org/10.1007/s12355-010-0039-z.
[69] P. Halmer, S. Groot, Y. Birnbaum, R. Groeneveld, N. Swaay, Commercial organic pelleting and priming treatments for sugar beet seed (poster), in: E. Lammers van Bueren, R. Ranganathan, N. Sorensen (Eds.), Challenges and Opportunities for the Organic Agriculture and the Seed Industry, Proceedings of the First, World Conference on Organic Seed, FAO, Rome, Italy, 2004. https://edepot.wur.nl/31603.
[70] IRS. Teelthandleiding (Cultivation manual sugar beet), 2022. https://www.irs.nl/volledige-teelthandleiding/. Accessed 5 August 2025.
[71] J.R. Lamichhane, J. Constantin, J.N. Aubertot, C. Dürr, Will climate change affect sugar beet establishment of the 21st century? Insights from a simulation study using a crop emergence model, Field Crops Res. 238 (2019) 64–73, https://doi.org/10.1016/j.fcr.2019.04.022.
[72] K.W. Jaggard, A. Qi, G.F.J. Milford, C.J.A. Clark, E.S. Ober, C. Walters, E. Burks, Determining the optimal population density of sugarbeet crops in England, Int. Sugar J. 113 (2011) 114–119.
[73] C. Kenter, C.M. Hoffmann, B. Märländer, Effects of weather variables on sugar beet yield development (*Beta vulgaris* L.), Eur. J. Agron. 24 (2006) 62–69, https://doi.org/10.1016/j.eja.2005.05.001.
[74] FAO, Crop water information - crops - sugar beet. https://www.fao.org/land-water/databases-and-software/crop-information/en/, 2025. (Accessed 5 August 2025).

[75] H.R. Rimaz, S. Zand-Parsa, M. Taghvaei, A.A. Kamgar-Haghighi, Predicting the seedling emergence time of sugar beet (*Beta vulgaris*) using beta models, Physiol. Mol. Biol. Plants 26 (2020) 2329–2338, https://doi.org/10.1007/s12298-020-00884-1.

[76] C. Chomontowski, H. Wzorek, S. Podlaski, Impact of sugar beet seed priming on seed quality and performance under diversified environmental conditions of germination, emergence and growth, J. Plant Growth Regul. 39 (2020) 183–189, https://doi.org/10.1007/s00344-019-09973-2.

[77] P. Stevanato, C. Chiodi, C. Broccanello, G. Concheri, E. Biancardi, O. Pavli, G. Skaracis, Sustainability of the sugar beet crop, Sugar Tech 21 (2019) 703–716, https://doi.org/10.1007/s12355-019-00734-9.

[78] B. Märländer, C. Hoffmann, H.J. Koch, E. Ladewig, M. Niemann, N. Stockfisch, M. Varrelmann, A.K. Mahlein, Sustainable intensification -a quarter century of research towards higher efficiency in sugar beet cultivation, Zuckerindustrie 143 (2018) 200–217, https://doi.org/10.36961/si19362.

[79] S.H. Muhie, Novel approaches and practices to sustainable agriculture, J. Agric. Food Res. 10 (2022) 100446, https://doi.org/10.1016/j.jafr.2022.100446.

[80] R.M. Harveson, Rhizomania of sugar beet (APS Education - plant disease profiles), Plant Health Instruc 21 (2021), https://doi.org/10.1094/PHI-P-2021-1129.

[81] M.M. Müllender, M. Varrelmann, E. Maiss, S. Liebe, Comparative analysis of virus pathogenicity and resistance-breaking between the P- and A-type from the beet necrotic yellow vein virus using infectious cDNA clones, J. Gen. Virol. 103 (2022) 001777, https://doi.org/10.1099/jgv.0.001777.

[82] K. Benjes, M. Varrelmann, S. Liebe, Control of rhizomania in sugar beet - a success story made possible by resistance breeding, Plant Pathol. 73 (2024) 2248–2259, https://doi.org/10.1111/ppa.14007.

[83] O.I. Pavli, P. Stevanato, E. Biancardi, G.N. Skaracis, Achievements and prospects in breeding for rhizomania resistance in sugar beet, Field Crops Res. 122 (2011) 165–172, https://doi.org/10.1016/j.fcr.2011.03.019.

[84] W.W. Shane, P.S. Teng, Impact of cercospora leaf spot on root weight, sugar yield, and purity of *Beta vulgaris*, Plant Dis. 76 (1992) 812–820, https://doi.org/10.1094/pd-76-0812.

[85] IRS, Gewasbeschermingbulletin (Crop protection bulletin), 2025. https://www.irs.nl/interessegebieden/alle-interessegebieden/gewasbeschermingsbulletin/gewasbeschermingsbulletin-2025. Accessed 18 March 2025.

[86] W. Tan, K. Li, D. Liu, W. Xing, Cercospora leaf spot disease of sugar beet, Plant Signal. Behav. 18 (2023) 2214765, https://doi.org/10.1080/15592324.2023.2214765.

[87] R. Spanner, J. Neubauer, T.M. Heick, M.A. Grusak, O. Hamilton, V. Rivera-Varas, R. de Jonge, S. Pethybridge, K.M. Webb, G. Leubner-Metzger, G.A. Secor, M. D. Bolton, Seedborne *Cercospora beticola* can initiate Cercospora leaf spot from sugar beet (*Beta vulgaris*) fruit tissue, Phytopathology 112 (2022) 1016–1028, https://doi.org/10.1094/PHYTO-03-21-0113-R.

[88] S. Borgolte, M. Varrelmann, R. Hossain, Time point of virus yellows infection is crucial for yield losses in sugar beet, and co-infection with beet mosaic virus is negligible under field conditions, Plant Pathol. 73 (2024) 2056–2070, https://doi.org/10.1111/ppa.13954.

[89] R. Hossain, W. Menzel, C. Lachmann, M. Varrelmann, New insights into virus yellows distribution in Europe and effects of beet yellows virus, beet mild yellowing virus, and beet chlorosis virus on sugar beet yield following field inoculation, Plant Pathol. 70 (2021) 584–593, https://doi.org/10.1111/ppa.13306.

[90] H.J. Koch, K. Trimpler, A. Jacobs, N. Stockfisch, Crop rotational effects on yield formation in current sugar beet production – results from a farm survey and field trials, Front. Plant Sci. 9 (2018) 231, https://doi.org/10.3389/fpls.2018.00231.

[91] EC, Farm to Fork strategy - for a fair, healthy and environmentally-friendly food system. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en, 2022. (Accessed 5 August 2025).

[92] A. Buckwell, E. De Wachter, E. Nadeu, A. Williams. Crop Protection, the EU Food System, Where are they going? Appendix: an Examination of the Issues and Evidence around Crop Protection, RISE Foundation, Brussels, Belgium, 2020, p. 72. https://risefoundation.eu/wp-content/uploads/2020/07/2020_RISE_CP_EU_Appendix.pdf.

[93] Copa*cogeca, Another Disappointing Season for Sugar Beet, Agripress Benelux, Antwerpen, Belgium, 2024. http://www.agripressworld.com/start/artikel/618166/en.

[94] F. Verheggen, B. Barrès, R. Bonafos, N. Desneux, A.J. Escobar-Gutiérrez, E. Gachet, J. Laville, M. Siegwart, D. Thiéry, H. Jactel, Producing sugar beets without neonicotinoids: an evaluation of alternatives for the management of viruses-transmitting aphids, Entomol. Gen. 42 (2022) 491–498, https://doi.org/10.1127/entomologia/2022/1511.

[95] I. Jócsák, F. Csima, F. Pál-Fám, K. Somfalvi-Tóth, S. Keszthelyi, Plant protection consequences in Hungary of the withdrawal of systemic active substances from sugar beet seed treatment, Front. Agron. 6 (2024) 1363950, https://doi.org/10.3389/fagro.2024.1363950.

[96] M. Lechenet, F. Dessaint, G. Py, D. Makowski, N. Munier-Jolain, Reducing pesticide use while preserving crop productivity and profitability on arable farms, Nat. Plants 3 (2017) 17008, https://doi.org/10.1038/nplants.2017.8.

[97] F. Cioni, G. Maines, Weed control in sugarbeet, Sugar Tech 12 (2010) 243–255, https://doi.org/10.1007/s12355-010-0036-2.

[98] K. Dillen, M. Demont, P. Tillie, E. Rodriguez Cerezo, Bred for Europe but grown in America: the case of GM sugar beet, New Biotechnol. 30 (2013) 131–135, https://doi.org/10.1016/j.nbt.2012.11.004.

[99] M. Hauer-Jákli, N. Nause, K. Trimpler, N. Stockfisch, B. Märländer, CONVISO® ONE - approach to a system analysis of the herbicide strategy, Zuckerindustrie 142 (2017) 704–712, https://doi.org/10.36961/si19020.

[100] S. Bhattacharya, M.K. Sen, K. Hamouzová, P. Košnarová, J. Soukup, Insights into the ALS inhibitor resistance in Amaranthus retroflexus: a matter of concern for CONVISO® SMART sugar beet cultivation, Weed Res. 65 (2025) e12676, https://doi.org/10.1111/wre.12676.

[101] C.M. Hoffmann, Changes in N composition of sugar beet varieties in response to increasing N supply, J. Agron. Crop Sci. 191 (2005) 138–145, https://doi.org/10.1111/j.1439-037X.2004.00149.x.

[102] L.G. Campbell, Sugar beet quality improvement, J. Crop Prod. 5 (2002) 395–413, https://doi.org/10.1300/J144v05n01_16.

[103] I. Varga, J. Jović, M. Rastija, A. Markulj Kulundžić, V. Zebec, Z. Lončarić, D. Iljkić, M. Antunović, Efficiency and management of nitrogen fertilization in sugar beet as spring crop: a review, Nitrogen 3 (2022) 170–185, https://doi.org/10.3390/nitrogen3020013.

[104] H.J. Koch, D. Laufer, O. Nielsen, P. Wilting, Nitrogen requirement of fodder and sugar beet (*Beta vulgaris* L.) cultivars under high-yielding conditions of northwestern Europe, Arch. Agron Soil Sci. 62 (2016) 1222–1235, https://doi.org/10.1080/03650340.2016.1143929.

[105] Y. Zheng, X. Zhu, W. Peng, Effects of nitrogen fertilizer application on sugar beet yield and sugar content: a meta-analysis, Sugar Tech (2025) 015666, https://doi.org/10.1007/s12355-025-01566-6.

[106] T. Huijbregts, G. Legrand, C. Hoffmann, R. Olsson, Å. Olsson, Long-term storage of sugar beet in North-West Europe, COBRI Report no. 1, COBRI (COordination Beet Research International), Holeby, Denmark (2013). https://www.nordicbeet.nu/wp-content/uploads/2016/04/COBRI-storage-report-2013-final-131004.pdf.

[107] R. Majumdar, S.L. Kandel, C.A. Strausbaugh, A. Singh, S. Pokhrel, M. Bill, Root microbiome and metabolome traits associated with improved post-harvest root storage for sugar beet breeding lines under Southern Idaho conditions, Int. J. Mol. Sci. 25 (2024) 12681, https://doi.org/10.3390/ijms252312681.

[108] G. Kleuker, C.M. Hoffmann, Causes of different tissue strength, changes during storage and effect on the storability of sugar beet genotypes, Postharvest Biol. Technol. 183 (2022) 111744, https://doi.org/10.1016/j.postharvbio.2021.111744.

[109] P.J. Last, A.P. Draycott, R. Hull, Influence of level of topping and other cultural factors on sugar beet yield and quality, Int. Sugar J. 78 (1976) 195–199.

[110] C. Hoffmann, Yield and quality of sugar beet crown as well as leaf yield of different sugar beet varieties and a fodder beet, Zuckerindustrie 136 (2011) 555–564, https://doi.org/10.36961/si11858.

[111] D. Wöber, K. Hansel-Hohl, S. Rohringer, M. Dokal, L. Antonielli, W. Imgenberg, H. Eigner, M. Seiter, E.M. Molin, The role of microbial communities in maintaining post-harvest sugar beet storability, Postharvest Biol. Technol. 222 (2025) 113401, https://doi.org/10.1016/j.postharvbio.2025.113401.

[112] CEFS, European association of sugar manufacturers, issue: agriculture. https://cefs.org/issues/agriculture/, 2025. (Accessed 5 August 2025).

[113] B.T. Christensen, A.E. Johnston, Soil organic matter and soil quality - lessons learned from long-term experiments at Askov and Rothamsted, Dev, Soil Sci. 25 (1997) 399–430, https://doi.org/10.1016/S0166-2481(97)80045-1.

[114] D. Grunwald, P. Götze, H.J. Koch, Soil organic carbon stocks in sugar beet rotations differing in residue management and associated rotational crop species, J. Plant Nutr. Soil Sci. 184 (2021) 556–561, https://doi.org/10.1002/jpln.202100122.

[115] J.C. Dohm, A.E. Minoche, D. Holtgräwe, S. Capella-Gutiérrez, F. Zakrzewski, H. Tafer, O. Rupp, T.R. Sörensen, R. Stracke, R. Reinhardt, A. Goesmann, T. Kraft, B. Schulz, P.F. Stadler, T. Schmidt, T. Gabaldón, H. Lehrach, B. Weisshaar, H. Himmelbauer, The genome of the recently domesticated crop plant sugar beet (*Beta vulgaris*), Nature 505 (2014) 546–549, https://doi.org/10.1038/nature12817.

[116] R. Beyaz, B. Alizadeh, S. Gürel, S. Fatih Özcan, M. Yildiz, Sugar beet (*Beta vulgaris* L.) growth at different ploidy levels, Caryologia 66 (2013) 90–95, https://doi.org/10.1080/00087114.2013.787216.

[117] A. Pazuki, F. Aflaki, S. Gürel, A. Ergül, E. Gürel, Production of doubled haploids in sugar beet (*Beta vulgaris*): an efficient method by a multivariate experiment, Plant Cell Tissue Organ Cult. 132 (2018) 85–97, https://doi.org/10.1007/s11240-017-1313-5.

[118] J.M. McGrath, D. Trebbi, A. Fenwick, L. Panella, B. Schulz, V. Laurent, S. Barnes, S.C. Murray, An open-source first-generation molecular genetic map from a sugarbeet × table beet cross and its extension to physical mapping, Crop Sci. 47 (2007) S27–S44, https://doi.org/10.2135/cropsci2006-05-0339tpg.

[119] M. Wang, Y. Xu, Z. Wu, H. Wang, H. Zhang, High-density genetic map construction in sugar beet (*Beta vulgaris* L.) by high-throughput technology, Sugar Tech 20 (2018) 212–219, https://doi.org/10.1007/s12355-017-0550-6.

[120] M.K. Grimmer, S. Trybush, S. Hanley, S.A. Francis, A. Karp, M.J.C. Asher, An anchored linkage map for sugar beet based on AFLP, SNP and RAPD markers and QTL mapping of a new source of resistance to Beet necrotic yellow vein virus, Theor. Appl. Genet. 114 (2007) 1151–1160, https://doi.org/10.1007/s00122-007-0507-3.

[121] D. Holtgräwe, T.R. Sörensen, P. Viehöver, J. Schneider, B. Schulz, D. Borchardt, T. Kraft, H. Himmelbauer, B. Weisshaar, Reliable *in silico* identification of sequence polymorphisms and their application for extending the genetic map of sugar beet *(Beta vulgaris*), PLoS One 9 (2014) e110113, https://doi.org/10.1371/journal.pone.0110113.

[122] M.A. Iquebal, S. Jaiswal, U.B. Angadi, G. Sablok, V. Arora, S. Kumar, A. Rai, D. Kumar, SBMDb: first whole genome putative microsatellite DNA marker database of sugarbeet for bioenergy and industrial applications, Database 2015 (2015) bav111, https://doi.org/10.1093/database/bav111.

[123] T. Würschum, T. Kraft, Evaluation of multi-locus models for genome-wide association studies: a case study in sugar beet, Heredity 114 (2015) 281–290, https://doi.org/10.1038/hdy.2014.98.
[124] V. Garin, V. Wimmer, D. Borchardt, M. Malosetti, F. van Eeuwijk, The influence of QTL allelic diversity on QTL detection in multi-parent populations: a simulation study in sugar beet, BMC Genom. Data 22 (2021) 4, https://doi.org/10.1186/s12863-021-00960-9.
[125] M. Wang, Y. Xu, W. Wang, Z. Wu, W. Xing, H. Zhang, Quantitative Trait Locus (QTL) mapping of sugar yield-related traits in sugar beet (*Beta vulgaris* L.), Sugar Tech 21 (2019) 135–144, https://doi.org/10.1007/s12355-018-0632-0.
[126] J.M. McGrath, A. Funk, P. Galewski, S. Ou, B. Townsend, K. Davenport, H. Daligault, S. Johnson, J. Lee, A. Hastie, A. Darracq, G. Willems, S. Barnes, I. Liachko, S. Sullivan, S. Koren, A. Phillippy, J. Wang, T. Lu, J. Pulman, K. Childs, A. Yocum, D. Fermin, E. Mutasa-Göttgens, P. Stevanato, K. Taguchi, K. Dorn, A contiguous *de novo* genome assembly of sugar beet EL10 (*Beta vulgaris* L.) DNA, Res 30 (1) (2022), https://doi.org/10.1093/dnares/dsac033.
[127] D.A. Levin, The evolutionary significance of pseudo-self-fertility, Am. Nat. 148 (1996) 321–332, https://doi.org/10.1086/285927.
[128] N.O. Bosemark, Genetics and Breeding, in: A.P. Draycott (Ed.), Sugar Beet, Blackwell Publishing Ltd, Oxford, UK, 2006, pp. 50–88, https://doi.org/10.1002/9780470751114.ch4.
[129] L. Frese, Conservation and access to sugarbeet germplasm, Sugar Tech 12 (2010) 207–219, https://doi.org/10.1007/s12355-010-0054-0.
[130] M. Brink, T. van Hintum, Practical consequences of digital sequence information (DSI) definitions and access and benefit-sharing scenarios from a plant genebank's perspective, Plants People Planet 4 (2022) 23–32, https://doi.org/10.1002/ppp3.10201.
[131] M. Andrello, K. Henry, P. Devaux, B. Desprez, S. Manel, Taxonomic, spatial and adaptive genetic variation of *Beta* section *Beta*, Theor. Appl. Genet. 129 (2016) 257–271, https://doi.org/10.1007/s00122-015-2625-7.
[132] A. Wiśniewska, P. Andryka-Dudek, M. Czerwiński, D. Chołuj, Fodder beet is a reservoir of drought tolerance alleles for sugar beet breeding, Plant Physiol. Biochem. 145 (2019) 120–131, https://doi.org/10.1016/j.plaphy.2019.10.031.
[133] S. Yolcu, H. Alavilli, P. Ganesh, M. Panigrahy, K. Song, Salt and drought stress responses in cultivated beets (*Beta vulgaris* L.) and wild beet (*Beta maritima* L.), Plants 10 (2021) 1843, https://doi.org/10.3390/plants10091843.
[134] H. Nóbrega, G. Freitas, M.A. Zavattieri, C. Ragonezi, L. Frese, M.A.A.P. de Carvalho, Monitoring system and *in situ* conservation of endemic and threatened *Beta patula* Aiton populations in Madeira Region, Genet. Resour. Crop Evol. 68 (2021) 939–956, https://doi.org/10.1007/s10722-020-01035-x.
[135] J. Postman, K. Hummer, P. Bretting, G. Kinard, M. Bohning, G. Emberland, Q. Sinnott, P. Cyr, M. Millard, C. Gardner, B. Weaver, T. Ayala-Silva, T. Franko, M. Mackay, L. Guarino, GRIN-Global: an international project to develop a global plant genebank information management system, Acta Hortic. 859 (2010) 49–56, https://doi.org/10.17660/actahortic.2010.859.4.
[136] L. Panella, R.T. Lewellen, Broadening the genetic base of sugar beet: introgression from wild relatives, Euphytica 154 (2007) 383–400, https://doi.org/10.1007/s10681-006-9209-1.
[137] A. Funk, P. Galewski, J.M. McGrath, Nucleotide-binding resistance gene signatures in sugar beet, insights from a new reference genome, Plant J. 95 (2018) 659–671, https://doi.org/10.1111/tpj.13977.
[138] K.L. Richardson, B. Mackey, B. Hellier, Resistance in *Beta vulgaris* L. subsp. *maritima* (L.) Thell. to the Rz1-breaking strain of rhizomania, Genet. Resour. Crop Evol. 66 (2019) 929–939, https://doi.org/10.1007/s10722-019-00749-x.
[139] V.A. Yousefabadi, P. Mehdikhani, F. Nadali, M. Sharifi, H. Azizi, M. Ahmadi, P. Fasahat, Evaluation of yield and stability of sugar beet (*Beta vulgaris* L.) genotypes using GGE biplot and AMMI analysis, Sci. Rep. 14 (2024) 27384, https://doi.org/10.1038/s41598-024-78659-x.
[140] SesvanderHave, Rhizoctonia, 2025. https://www.sesvanderhave.com/uk/our-research-and-innovations/pests-and-diseases/rhizoctonia. (Accessed 4 August 2025).
[141] A. Setiawan, G. Koch, S.R. Barnes, C. Jung, Mapping quantitative trait loci (QTLs) for resistance to Cercospora leaf spot disease (*Cercospora beticola* Sacc.) in sugar beet (*Beta vulgaris* L.), Theor. Appl. Genet. 100 (2000) 1176–1182, https://doi.org/10.1007/s001220051421.
[142] L. Dixon, I.L. Goldman, Genetic architecture of Cercospora leaf spot response in table beet with implications for other *Beta vulgaris* crop types, Crop Sci. 64 (2024) 3352–3371, https://doi.org/10.1002/csc2.21396.
[143] J. Vogel, C. Kenter, C. Holst, B. Märländer, New generation of resistant sugar beet varieties for advanced integrated management of Cercospora leaf spot in central Europe, Front. Plant Sci. 9 (2018) 222, https://doi.org/10.3389/fpls.2018.00222.
[144] L.I. Rangel, R.E. Spanner, M.K. Ebert, S.J. Pethybridge, E.H. Stukenbrock, R. de Jonge, G.A. Secor, M.D. Bolton, *Cercospora beticola*: the intoxicating lifestyle of the leaf spot pathogen of sugar beet, Mol. Plant Pathol. 21 (2020) 1020–1041, https://doi.org/10.1111/mpp.12962.
[145] Y. Yang, M. Varrelmann, S. Liebe, Effect of sugar beet variety resistance on the disease epidemiology of *Cercospora beticola*, Pest Manag. Sci. 81 (2025) 2970–2980, https://doi.org/10.1002/ps.8666.
[146] C. Chen, H. Keunecke, F. Bemm, G. Gyetvai, E. Neu, F.J. Kopisch-Obuch, B. A. McDonald, J. Stapley, GWAS reveals a rapidly evolving candidate avirulence effector in the Cercospora leaf spot pathogen, Mol. Plant Pathol. 25 (2024) e13407, https://doi.org/10.1111/mpp.13407.
[147] D. Cai, M. Kleine, S. Kifle, H.J. Harloff, N.N. Sandal, K.A. Marcker, R.M. Klein-Lankhorst, E.M.J. Salentijn, W. Lange, W.J. Stiekema, U. Wyss, F.M.W. Grundler, C. Jung, Positional cloning of a gene for nematode resistance in sugar beet, Science 275 (1997) 832–834, https://doi.org/10.1126/science.275.5301.832.
[148] S. Schop, K.J. Kloth, E. Raaijmakers, R.A.A. van der Vlugt, The effect of mature plant resistance in sugar beet (*Beta vulgaris* spp. *vulgaris*) on survival, fecundity and behaviour of green peach aphids (*Myzus persicae*), Bull. Entomol. Res. 112 (2022) 707–714, https://doi.org/10.1017/S0007485322000128.
[149] A. Elakhdar, S. Solanki, T. Kubo, A. Abed, I. Elakhdar, R. Khedr, A. Hamwieh, L.J. A. Capo-chichi, M. Abdelsattar, J.D. Franckowiak, C.O. Qualset, Barley with improved drought tolerance: challenges and perspectives, Environ. Exp. Bot. 201 (2022) 104965, https://doi.org/10.1016/j.envexpbot.2022.104965.
[150] H. Ebmeyer, K. Fiedler-Wiechers, C.M. Hoffmann, Drought tolerance of sugar beet – evaluation of genotypic differences in yield potential and yield stability under varying environmental conditions, Eur. J. Agron. 125 (2021) 126262, https://doi.org/10.1016/j.eja.2021.126262.
[151] W. Tan, W. Li, J. Li, D. Liu, W. Xing, Drought resistance evaluation of sugar beet germplasms by response of phenotypic indicators, Plant Signal. Behav. 18 (2023) 2192570, https://doi.org/10.1080/15592324.2023.2192570.
[152] J.D. Pidgeon, E.S. Ober, A. Qi, C.J.A. Clark, A. Royal, K.W. Jaggard, Using multi-environment sugar beet variety trials to screen for drought tolerance, Field Crops Res. 95 (2006) 268–279, https://doi.org/10.1016/j.fcr.2005.04.010.
[153] E.S. Ober, M.C. Luterbacher, Genotypic variation for drought tolerance in *Beta vulgaris*, Ann. Bot. 89 (2002) 917–924, https://doi.org/10.1093/aob/mcf093.
[154] L. Wittenmayer, G. Schilling, Behaviour of sugar-beet plants (*Beta vulgaris* L. ssp. *vulgaris* var. *altissima* [Doeill]) under conditions of changing water supply: abscisic acid as indicator, J. Agron. Crop Sci. 180 (1998) 65–72, https://doi.org/10.1111/j.1439-037X.1998.tb00372.x.
[155] M. Bruins, Sugar rush: what it takes to develop a new sugar beet variety (SeedWorld- Europe). https://www.seedworld.com/europe/2020/04/16/sugar-rush-what-it-takes-to-develop-a-new-sugar-beet-variety/, 2020. (Accessed 5 August 2025).
[156] R. Nishimoto, Global trends in the crop protection industry, J. Pestic. Sci. 44 (2019) 141–147, https://doi.org/10.1584/jpestics.D19-101.
[157] T. Subrahmanyeswari, S. Gantait, Advancements and prospectives of sugar beet (*Beta vulgaris* L.) biotechnology, Appl. Microbiol. Biotechnol. 106 (2022) 7417–7430, https://doi.org/10.1007/s00253-022-12226-0.
[158] X. Li, W. He, J. Fang, Y. Liang, H. Zhang, D. Chen, X. Wu, Z. Zhang, L. Wang, P. Han, B. Zhang, T. Xue, W. Zheng, J. He, C. Bai, Genomic and transcriptomic-based analysis of agronomic traits in sugar beet (*Beta vulgaris* L.) pure line IMA1, Front. Plant Sci. 13 (2022) 1028885, https://doi.org/10.3389/fpls.2022.1028885.
[159] Á. Rodríguez del Río, A.E. Minoche, N.F. Zwickl, A. Friedrich, S. Liedtke, T. Schmidt, H. Himmelbauer, J.C. Dohm, Genomes of the wild beets *Beta patula* and *Beta vulgaris* ssp. *maritima*, Plant J. 99 (2019) 1242–1253, https://doi.org/10.1111/tpj.14413.
[160] F.L. Sandell, N. Stralis-Pavese, J.M. McGrath, B. Schulz, H. Himmelbauer, J. C. Dohm, Genomic distances reveal relationships of wild and cultivated beets, Nat. Commun. 13 (2022) 2021, https://doi.org/10.1038/s41467-022-29676-9.
[161] P.A. Reeves, C.M. Richards, A pan-genome data structure induced by pooled sequencing facilitates variant mining in heterogeneous germplasm, Mol. Breed. 42 (2022) 36, https://doi.org/10.1007/s11032-022-01308-6.
[162] S. Gutschker, J.M. Corral, A. Schmiedl, F. Ludewig, W. Koch, K. Fiedler-Wiechers, O. Czarnecki, K. Harms, I. Keller, C. Martins Rodrigues, B. Pommerrenig, H. E. Neuhaus, W. Zierer, U. Sonnewald, C. Müdsam, Multi-omics data integration reveals link between epigenetic modifications and gene expression in sugar beet (*Beta vulgaris* subsp. *vulgaris*) in response to cold, BMC Genom. 23 (2022) 144, https://doi.org/10.1186/s12864-022-08312-2.
[163] W. Huang, D. Sun, R. Wang, Y. An, Integration of transcriptomics and metabolomics reveals the responses of sugar beet to continuous cropping obstacle, Front. Plant Sci. 12 (2021) 711333, https://doi.org/10.3389/fpls.2021.711333.
[164] Z. Zhang, L. Wang, W. Chen, Z. Fu, S. Zhao, Y. E, H. Zhang, B. Zhang, M. Sun, P. Han, Y. Chang, K. Tang, Y. Gao, H. Zhang, X. Li, W. Zheng, Integration of mRNA and miRNA analysis reveals the molecular mechanisms of sugar beet (*Beta vulgaris* L.) response to salt stress, Sci. Rep. 13 (2023) e22074, https://doi.org/10.1038/s41598-023-49641-w.
[165] L. Wang, G. Geng, Z. Pi, Y. Xu, Y. Liu, R. Li, M. Wang, G. Wang, P. Stevanato, L. Yu, Y. Wang, Comparative proteomic analysis of two contrasting cultivars reveals the mechanism of sugar beet response to freezing stress, Environ. Exp. Bot. 213 (2023) 105452, https://doi.org/10.1016/j.envexpbot.2023.105452.
[166] A.L. Gippert, S. Madritsch, P. Woryna, S. Otte, M. Mayrhofer, H. Eigner, A. Garibay-Hernández, J.C. D'Auria, E.M. Molin, H.P. Mock, Unraveling metabolic patterns and molecular mechanisms underlying storability in sugar beet, BMC Plant Biol. 22 (2022) 430, https://doi.org/10.1186/s12870-022-03784-6.
[167] E. Marks, M. Sodano, F. Magistri, L. Wiesmann, D. Desai, R. Marcuzzi, J. Behley, C. Stachniss, High precision leaf instance segmentation for phenotyping in point clouds obtained under real field conditions, IEEE Rob. Autom. Lett. 8 (2023) 4791–4798, https://doi.org/10.1109/LRA.2023.3288383.
[168] K. Munk, D. Ilina, L. Ziemba, G. Brader, E.M. Molin, Holomics - a user-friendly R shiny application for multi-omics data integration and analysis, BMC Bioinf. 25 (2024) 93, https://doi.org/10.1186/s12859-024-05719-4.
[169] E. Gurel, S. Gurel, P.G. Lemaux, Biotechnology applications for sugar beet, Crit. Rev. Plant Sci. 27 (2008) 108–140, https://doi.org/10.1080/07352680802202000.
[170] E. Mukherjee, S. Gantait, Genetic transformation in sugar beet (*Beta vulgaris* L.): technologies and applications, Sugar Tech 25 (2023) 269–281, https://doi.org/10.1007/s12355-022-01176-6.
[171] F. De Marchis, M. Bellucci, Plastid transformation in sugar beet: an important industrial crop, in: P. Maliga (Ed.), Chloroplast Biotechnology - Methods in

Molecular Biology - Springer Protocols, Part, vol. III, Humana Press Inc. - Springer Science, New York, USA, 2021, pp. 283–290, https://doi.org/10.1007/978-1-0716-1472-3_16. Ch. 16.
[172] A. Trifonova, A. Atanassov, Genetic transformation of sugar beet by *Agrobacterium rhizogenes*, Biotechnol. Biotechnol. Equip. 9 (1995) 23–26, https://doi.org/10.1080/13102818.1995.10818836.
[173] P. Meier, W. Wackernagel, Monitoring the spread of recombinant DNA from field plots with transgenic sugar beet plants by PCR and natural transformation of *Pseudomonas stutzeri*, Transgenic Res. 12 (2003) 293–304, https://doi.org/10.1023/A:1023317104119.
[174] C. Volkmar, M. Lübke-Al Hussein, D. Jany, I. Hunold, L. Richter, T. Kreuter, T. Wetzel, Ecological studies on epigeous arthropod populations of transgenic sugar beet at Friemar (Thuringia, Germany), Agric. Ecosyst. Environ. 95 (2003) 37–47, https://doi.org/10.1016/S0167-8809(02)00166-4.
[175] S. Safar, M. Bazrafshan, M. Khoshnami, A.A. Behrooz, F. Hedayati, M. Maleki, S. B. Mahmoudi, M.A. Malboobi, Field evaluation for rhizomania resistance of transgenic sugar beet events based on gene silencing, Can. J. Plant Pathol 43 (2021) 179–188, https://doi.org/10.1080/07060661.2020.1783575.
[176] ISAAA, GMAD GM Approval Database (entry sugar beet). https://www.isaaa.org/gmapprovaldatabase/default.asp, 2025. (Accessed 5 August 2025).
[177] C. Martins-Gomes, T.L. Silva, T. Andreani, A.M. Silva, Glyphosate vs. glyphosate-based herbicides exposure: a review on their toxicity, J. Xenobiotics 12 (2022) 21–40, https://doi.org/10.3390/jox12010003.
[178] F. Álvarez, M. Arena, D. Auteri, M. Binaglia, A.F. Castoldi, A. Chiusolo, F. Crivellente, M. Egsmose, G. Fait, F. Ferilli, V. Gouliarmou, L.H. Nogareda, A. Ippolito, F. Istace, S. Jarrah, D. Kardassi, A. Kienzler, A. Lanzoni, R. Lava, A. Linguadoca, C. Lythgo, I. Mangas, L. Padovani, M. Panzarea, J.M. Parra Morte, S. Rizzuto, A. Romac, A. Rortais, R. Serafimova, R. Sharp, C. Szentes, A. Terron, A. Theobald, M. Tiramani, G. Vianello, L. Villamar-Bouza, Peer review of the pesticide risk assessment of the active substance glyphosate, EFSA J. 21 (2023) e08164, https://doi.org/10.2903/j.efsa.2023.8164.
[179] R. Finger, N. Möhring, P. Kudsk, Glyphosate ban will have economic impacts on European agriculture but effects are heterogenous and uncertain, Commun. Earth Environ. 4 (2023) 286, https://doi.org/10.1038/s43247-023-00951-x.
[180] Y. Zheng, N. Zhang, G.B. Martin, Z. Fei, Plant genome editing database (PGED): a call for submission of information about genome-edited plant mutants, Mol. Plant 12 (2019) 127–129, https://doi.org/10.1016/j.molp.2019.01.001.
[181] O. Dima, Y. Heyvaert, D. Inzé, Interactive database of genome editing applications in crops and future policy making in the European Union, Trends Plant Sci. 27 (2022) 746–748, https://doi.org/10.1016/j.tplants.2022.05.002.
[182] O. Eini, M. Varrelmann, Challenges and potential applications of genome editing in sugar beet, Sugar Ind. Int. 147 (2022) 274–283, https://doi.org/10.36961/si28687.
[183] V. Misra, H. Pandey, A.K. Mall, Exploring CRISPR/Cas9 gene editing applications for enhancing disease resistance in sugar beet, ACS Agric. Sci. Technol. 4 (2024) 4–21, https://doi.org/10.1021/acsagscitech.3c00193.
[184] ISAAA, Global regulatory landscape for gene-edited crops. https://www.isaaa.org/resources/infographics/globalstatusgeneeditedcrops/default.asp, 2024. (Accessed 5 August 2025).
[185] EP, (European Parliament) New genomic techniques: MEPs back rules to support green transition of farmers (press release), https://www.europarl.europa.eu/news/en/press-room/20240202IPR17320/new-genomic-techniques-meps-back-rules-to-support-green-transition-of-farmers, 2024. (Accessed 5 August 2025).
[186] K. Yıldırım, M. Kavas, İ.S. Küçük, Z. Seçgin, Ç.G. Saraç, Development of highly efficient resistance to Beet Curly Top Iran virus (*Becurtovirus*) in sugar beet *(B. vulgaris*) via CRISPR/Cas9 System, Int. J. Mol. Sci. 24 (2023) 6515, https://doi.org/10.3390/ijms24076515.
[187] K. Germing, C.A.D. Navarrete, A. Schiermeyer, U. Hommen, L. Zühl, S. Eilebrecht, E. Eilebrecht, Crop protection by RNA interference: a review of recent approaches, current state of developments and use as of 2013, Environ. Sci. Eur. 37 (2025) 15, https://doi.org/10.1186/s12302-025-01052-6.
[188] WMO (World Meteorological Organization), European State of the climate - summary 2024, Copernicus Clim. Change Serv. (C3S) (2025). Geneva, Switserland, https://climate.copernicus.eu/esotc/2024.
[189] M.D.K. Priestley, J.L. Catto, Future changes in the extratropical storm tracks and cyclone intensity, wind speed, and structure, Weather. Clim. Dyn. 3 (2022) 337–360, https://doi.org/10.5194/wcd-3-337-2022.
[190] I. Alifdini, J. Moemken, A.M. Ramos, J.G. Pinto, Future changes of European windstorm losses in EURO-CORDEX simulations, Tellus Ser. A Dyn. Meteorol. Oceanogr. 77 (2025) 20–37, https://doi.org/10.16993/tellusa.4094.
[191] A. Blum, Drought resistance, water-use efficiency, and yield potential - are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56 (2005) 1159–1168, https://doi.org/10.1071/AR05069.
[192] X.G. Zhu, S.P. Long, D.R. Ort, Improving photosynthetic efficiency for greater yield, Annu. Rev. Plant Biol. 61 (2010) 235–261, https://doi.org/10.1146/annurev-arplant-042809-112206.
[193] E.A. Ainsworth, S.P. Long, 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? Glob. Change Biol. 27 (2021) 27–49, https://doi.org/10.1111/gcb.15375.
[194] H. Stephan, U. Böttcher, K. Sieling, H. Kage, Yield potential of non-bolting winter sugar beet in Germany, Eur. J. Agron. 115 (2020) 126035, https://doi.org/10.1016/j.eja.2020.126035.
[195] P.D. Jones, D.H. Lister, K.W. Jaggard, J.D. Pidgeon, Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe, Clim. Change 58 (2003) 93–108, https://doi.org/10.1023/A:1023420102432.
[196] J. Knox, A. Daccache, T. Hess, D. Haro, Meta-analysis of climate impacts and uncertainty on crop yields in Europe, Environ. Res. Lett. 11 (2016), https://doi.org/10.1088/1748-9326/11/11/113004.
[197] X. Yuan, S. Li, J. Chen, H. Yu, T. Yang, C. Wang, S. Huang, H. Chen, X. Ao, Impacts of global climate change on agricultural production: a comprehensive review, Agronomy 14 (2024) 1360, https://doi.org/10.3390/agronomy14071360.
[198] S.A. Francis, Development of sugar beet, in: A.P. Draycott (Ed.), Sugar Beet Ch. 2, Blackwell Publishing Ltd, Oxford, UK, 2006, pp. 9–29, https://doi.org/10.1002/9780470751114.ch2.
[199] I. Ehlers, A. Augusti, T.R. Betson, M.B. Nilsson, J.D. Marshall, J. Schleucher, Detecting long-term metabolic shifts using isotopomers: CO_2-driven suppression of photorespiration in C3 plants over the 20th century, Proc. Natl. Acad. Sci. USA 112 (2015) 15585–15590, https://doi.org/10.1073/pnas.1504493112.
[200] R. Manderscheid, A. Pacholski, H.J. Weigel, Effect of free air carbon dioxide enrichment combined with two nitrogen levels on growth, yield and yield quality of sugar beet: evidence for a sink limitation of beet growth under elevated CO_2, Eur. J. Agron. 32 (2010) 228–239, https://doi.org/10.1016/j.eja.2009.12.002.
[201] H.J. Weigel, R. Manderscheid, Crop growth responses to free air CO_2 enrichment and nitrogen fertilization: rotating barley, ryegrass, sugar beet and wheat, Eur. J. Agron. 43 (2012) 97–107, https://doi.org/10.1016/j.eja.2012.05.011.
[202] A. Pacholski, R. Manderscheid, H.J. Weigel, Effects of free air CO_2 enrichment on root growth of barley, sugar beet and wheat grown in a rotation under different nitrogen supply, Eur. J. Agron. 63 (2015) 36–46, https://doi.org/10.1016/j.eja.2014.10.005.
[203] A. Bressan, F.J.M. Garca, E. Boudon-Padieu, The prevalence of 'Candidatus Arsenophonus phytopathogenicus' infecting the planthopper *Pentastiridius leporinus* (*Hemiptera: cixiidae*) increase nonlinearly with the population abundance in sugar beet fields, Environ. Entomol. 40 (2011) 1345–1352, https://doi.org/10.1603/EN10257.
[204] M. Mahillon, R. Groux, F. Bussereau, J. Brodard, C. Debonneville, S. Demal, I. Kellenberger, M. Peter, T. Steinger, O. Schumpp, Virus yellows and " Syndrome Basses Richesses" in Western Switzerland: a dramatic 2020 season calls for urgent control measures, Pathogens 11 (2022) 885, https://doi.org/10.3390/pathogens11080885.
[205] M. Schumann, O. Czarnecki, H. Keunecke, W. Purahong, K. Krüger, '*Candidatus* Phytoplasma solani' and '*Candidatus* Arsenophonus phytopathogenicus' in sugar beet in Germany and Switzerland, Phytopathogenic Mollicutes 13 (2023) 99–100, https://doi.org/10.5958/2249-4677.2023.00050.6.
[206] EPPO, EPPO global database. https://gd.eppo.int/, 2025. (Accessed 5 August 2025).
[207] M. Jeger, C. Bragard, D. Caffier, K. Dehnen-Schmutz, G. Gilioli, J.C. Gregoire, J. A. Jaques Miret, A. MacLeod, M. Navajas Navarro, B. Niere, S. Parnell, R. Potting, T. Rafoss, V. Rossi, G. Urek, A. van Bruggen, W. van der Werf, J. West, E. Chatzivassiliou, S. Winter, G. Hollo, T. Candresse, Pest categorisation of Beet curly top virus (non-EU isolates), EFSA J. 15 (2017) 4998, https://doi.org/10.2903/j.efsa.2017.4998.
[208] K. Peters, L. Breitsameter, B. Gerowitt, Impact of climate change on weeds in agriculture: a review, Agron. Sustain. Dev. 34 (2014) 707–721, https://doi.org/10.1007/s13593-014-0245-2.
[209] A. Karkanis, G. Ntatsi, A. Alemardan, S. Petropoulos, D. Bilalis, Interference of weeds in vegetable crop cultivation, in the changing climate of Southern Europe with emphasis on drought and elevated temperatures: a review, J. Agric. Sci. 156 (2018) 1175–1185, https://doi.org/10.1017/S0021859619000108.
[210] C.M. Geddes, S.M. Sharpe, Crop yield losses due to kochia (*Bassia scoparia*) interference, Crop Prot. 157 (2022) 105981, https://doi.org/10.1016/j.cropro.2022.105981.
[211] V. Kumar, P. Jha, Influence of glyphosate timing on *Kochia scoparia* demographics in glyphosate-resistant sugar beet, Crop Prot. 76 (2015) 39–45, https://doi.org/10.1016/j.cropro.2015.06.010.
[212] ISAAA, Biotech Updates, Syngenta introduces tropical sugar beet in India. https://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=7732007. (Accessed 5 August 2025).
[213] M. Tayyab, A. Wakeel, M.U. Mubarak, A. Artyszak, S. Ali, E.E. Hakki, K. Mahmood, B. Song, M. Ishfaq, Sugar beet cultivation in the tropics and subtropics: challenges and opportunities, Agronomy 13 (2023) 1213, https://doi.org/10.3390/agronomy13051213.
[214] W. Elbersen, L. Oyen, Tropical sugar beet (*Beta vulgaris* L.) Potential of tropical sugar beet for bio-ethanol production, Report 146/WW/001, 9 pp, FACT Foundation, Wageningen, The Netherlands, 2010, https://www.bioenergyforumfact.org/sites/default/files/2018-06/32._Tropical_Sugar_Beet_(Beta_vulgaris_L.)_potential_for_bio-ethanol_production.pdf.
[215] S. Cosyn, K. Van Der Woude, X. Sauvenier, J.N. Evrard, Sugar beet: a complement to sugar cane for sugar and ethanol production in tropical and subtropical areas, Int. Sugar J. 113 (2011) 120–123.
[216] S.D. Behera, M.K. Arvadia, Productivity and profitability of tropical sugar beet (*Beta vulgaris*) varieties under various land configurations in vertisols, Indian J. Agron. 64 (2019) 283–286, https://doi.org/10.59797/ija.v64i2.5270.
[217] J. Muro, I. Irigoyen, C. Lamsfus, Defoliation timing and severity in sugar beet, Agron. J. 90 (1998) 800–804, https://doi.org/10.2134/agronj1998.00021962009000060014x.
[218] M.M. Mekonnen, A.Y. Hoekstra, The green, blue and grey water footprint of crops and derived crop products, Hydrol. Earth Syst. Sci. 15 (2011) 1577–1600, https://doi.org/10.5194/hess-15-1577-2011.

[219] EEA, (European Environment Agency), Climate change adaptation in the agriculture sector in Europe, EEA Report 4/2019 (2019) 108 pp. Copenhagen, Denmark, https://www.eea.europa.eu/en/analysis/publications/cc-adaptation-agriculture.
[220] A. Gallardo-Carrera, J. Léonard, Y. Duval, C. Dürr, Effects of seedbed structure and water content at sowing on the development of soil surface crusting under rainfall, Soil Tillage Res. 95 (2007) 207–217, https://doi.org/10.1016/j.still.2007.01.001.
[221] S. Klaus, H. Kreibich, B. Merz, B. Kuhlmann, K. Schröter, Large-scale, seasonal flood risk analysis for agricultural crops in Germany, Environ. Earth Sci. 75 (2016) 1289, https://doi.org/10.1007/s12665-016-6096-1.
[222] P. Schjønning, J.J.H. van den Akker, T. Keller, M.H. Greve, M. Lamandé, A. Simojoki, M. Stettler, J. Arvidsson, H. Breuning-Madsen, Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction - a European perspective, Adv. Agron. 133 (2015) 183–237, https://doi.org/10.1016/bs.agron.2015.06.001.
[223] D. Cole, Effect of cultivar and mechanical damage on respiration and storability of sugarbeet roots, J. Am. Soc. Sugar Beet Technol. 19 (1977) 240–245, https://doi.org/10.5274/jsbr.19.3.240.
[224] J.J.J. Wiltshire, A.H. Cobb, Bruising of sugar beet roots and consequential sugar loss: current understanding and research needs, Ann. Appl. Biol. 136 (2000) 159–166, https://doi.org/10.1111/j.1744-7348.2000.tb00021.x.
[225] I. Gould, J. De Waegemaeker, D. Tzemi, I. Wright, S. Pearson, E. Ruto, L. Karrasch, L.S. Christensen, H. Aronsson, S. Eich-Greatorex, G. Bosworth, P. Vellinga, Salinization threats to agriculture across the North Sea region, in: K. Negacz, P. Vellinga, E. Barrett-Lennard, R. Choukr-Allah, T. Elzenga (Eds.), Future of Sustainable Agriculture in Saline Environments Ch 5, CRC Press, Taylor & Francis, Boca Raton, Florida, USA, 2022, pp. 71–92, https://doi.org/10.1201/9781003112327-9781003112325.
[226] E. Custodio, G. Bruggeman. Groundwater Problems in Coastal Areas. A Contribution to the International Hydrological Programme, Unesco, Paris, France, 1987, p. 596 pp.
[227] M. Ashraf, Breeding for salinity tolerance in plants, Crit. Rev. Plant Sci. 13 (1994) 17–42, https://doi.org/10.1080/07352689409701906.
[228] M. Tahjib-Ui-Arif, A.A.M. Sohag, S. Afrin, K.K. Bashar, T. Afrin, A.G.M. Sofi Uddin Mahamud, M.A.S. Polash, M.T. Hossain, M.A.T. Sohel, M. Brestic, Y. Murata, Differential response of sugar beet to long-term mild to severe salinity in a soil–pot culture, Agriculture (Switzerland) 9 (2019) 223, https://doi.org/10.3390/agriculture9100223.
[229] X. Lv, S. Chen, Y. Wang, Advances in understanding the physiological and molecular responses of sugar beet to salt stress, Front. Plant Sci. 10 (2019) 1431, https://doi.org/10.3389/fpls.2019.01431.
[230] V. Casolo, M. Tomasella, V. De Col, E. Braidot, T. Savi, A. Nardini, Water relations of an invasive halophyte (*Spartina patens*): osmoregulation and ionic effects on xylem hydraulics, Funct. Plant Biol. 42 (2015) 264–273, https://doi.org/10.1071/FP14172.
[231] L. Campbell, J. Enz, Temperature effects on sugarbeet seedling emergence, J. Sugar Beet Res. 28 (1991) 129–140.
[232] A. Ulrich, Influence of night temperature and nitrogen nutrition on the growth, sucrose accumulation and leaf minerals of sugar beet plants, Plant Physiol. 30 (1955) 250–257, https://doi.org/10.1104/pp.30.3.250.
[233] M.J.P.M. Riksen, J. De Graaff, On-site and off-site effects of wind erosion on European light soils, Land Degrad. Dev. 12 (2001) 1–11, https://doi.org/10.1002/ldr.423.
[234] A.J. Burgess, R. Retkute, S.P. Preston, O.E. Jensen, M.P. Pound, T.P. Pridmore, E. H. Murchie, The 4-dimensional plant: effects of wind-induced canopy movement on light fluctuations and photosynthesis, Front. Plant Sci. 7 (2016) 1392, https://doi.org/10.3389/fpls.2016.01392.
[235] R. Funk, W. Engel, Investigations with a field wind tunnel to estimate the wind erosion risk of row crops, Soil Tillage Res. 145 (2015) 224–232, https://doi.org/10.1016/j.still.2014.09.005.
[236] R. Keshavarz Afshar, C. Chen, J. Eckhoff, C. Flynn, Impact of a living mulch cover crop on sugarbeet establishment, root yield and sucrose purity, Field Crops Res. 223 (2018) 150–154, https://doi.org/10.1016/j.fcr.2018.04.009.
[237] Y. Qiao, J. Valente, D. Su, Z. Zhang, D. He, Editorial: AI, sensors and robotics in plant phenotyping and precision agriculture, Front. Plant Sci. 13 (2022) 1064219, https://doi.org/10.3389/fpls.2022.1064219.
[238] E.M.B.M. Karunathilake, A.T. Le, S. Heo, Y.S. Chung, S. Mansoor, The path to smart farming: innovations and opportunities in precision agriculture, Agriculture (Switzerland) 13 (2023) 1593, https://doi.org/10.3390/agriculture13081593.
[239] B. Petrović, R. Bumbálek, T. Zoubek, R. Kuneš, L. Smutný, P. Bartoš, Application of precision agriculture technologies in Central Europe-review, J. Agric. Food Res. 15 (2024) 101048, https://doi.org/10.1016/j.jafr.2024.101048.
[240] R. Uehleke, L. von Plettenberg, M. Leyer, S. Hüttel, German sugar beet farmers' intention to use autonomous field robots for seeding and weeding, J. Environ. Manag. 370 (2024) 122472, https://doi.org/10.1016/j.jenvman.2024.122472.
[241] W. Czaban, E. Han, O.S. Lund, M.S. Stokholm, S.M. Jensen, K. Thorup-Kristensen, The enhancing effect of intercropping sugar beet with chicory on the deep root growth and nutrient uptake, Agric. Ecosyst. Environ. 347 (2023) 108360, https://doi.org/10.1016/j.agee.2023.108360.
[242] S.D. Juventia, D.F. van Apeldoorn, H. Faber, W.A.H. Rossing, From sole crops to strip cropping: decision rules of frontrunner farmers in the Netherlands, PLoS One 20 (2025) e0329133, https://doi.org/10.1371/journal.pone.0329133.
[243] D. Lambert, J. Lowenberg-De Boer. Precision Agriculture Profitability Review, Purdue University, West Lafayette, Indiana, USA, 2020, p. 153. https://ag.purdue.edu/ssmc/Frames/newsoilsX.pdf.
[244] M. Günder, F.R. Ispizua Yamati, A. Barreto, A.K. Mahlein, R. Sifa, C. Bauckhage, SugarViT - multi-objective regression of UAV images with vision transformers and deep label distribution learning demonstrated on disease severity prediction in sugar beet, PLoS One 20 (2025) e0318097, https://doi.org/10.1371/journal.pone.0318097.
[245] R. Gerhards, P. Risser, M. Spaeth, M. Saile, G. Peteinatos, A comparison of seven innovative robotic weeding systems and reference herbicide strategies in sugar beet (*Beta vulgaris* subsp. *vulgaris* L.) and rapeseed (*Brassica napus* L.), Weed Res. 64 (2024) 42–53, https://doi.org/10.1111/wre.12603.
[246] F.N. Ortatas, U. Ozkaya, M.E. Sahin, H. Ulutas, Sugar beet farming goes high-tech: a method for automated weed detection using machine learning and deep learning in precision agriculture, Neural Comput. Appl. 36 (2024) 4603–4622, https://doi.org/10.1007/s00521-023-09320-3.
[247] O. Fishkis, J. Weller, J. Lehmhus, F. Pöllinger, J. Strassemeyer, H.J. Koch, Ecological and economic evaluation of conventional and new weed control techniques in row crops, Agric. Ecosyst. Environ. 360 (2024) 108786, https://doi.org/10.1016/j.agee.2023.108786.
[248] L. Rosa, D.D. Chiarelli, M.C. Rulli, J. Dell'Angelo, P. D'Odorico, Global agricultural economic water scarcity, Sci. Adv. 6 (2020) eaaz6031, https://doi.org/10.1126/sciadv.aaz6031.
[249] D.D. Tarkalson, B.A. King, D.L. Bjorneberg, Yield production functions of irrigated sugarbeet in an arid climate, Agric. Water Manag. 200 (2018) 1–9, https://doi.org/10.1016/j.agwat.2018.01.003.
[250] H. Zhou, L. Wang, P. Xu, D. Liu, Y. Hao, K. Wang, H. Fan, Silicon drip fertigation improved sugar beet root and canopy growth and alleviated water deficit stress in arid areas, Eur. J. Agron. 159 (2024) 127236, https://doi.org/10.1016/j.eja.2024.127236.
[251] A. Wolfgang, N. Temme, R. Tilcher, G. Berg, Understanding the sugar beet holobiont for sustainable agriculture, Front. Microbiol. 14 (2023) 1151052, https://doi.org/10.3389/fmicb.2023.1151052.
[252] P. du Jardin, Plant biostimulants: definition, concept, main categories and regulation, Sci. Hortic. 196 (2015) 3–14, https://doi.org/10.1016/j.scienta.2015.09.021.
[253] M.J. van Oosten, O. Pepe, S. De Pascale, S. Silletti, A. Maggio, The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants, Chem. Biol. Technol. Agric. 4 (5) (2017), https://doi.org/10.1186/s40538-017-0089-5.
[254] A.O. Deolu-Ajayi, I.M. van der Meer, A. van der Werf, R. Karlova, The power of seaweeds as plant biostimulants to boost crop production under abiotic stress, Plant Cell Environ. 45 (2022) 2537–2553, https://doi.org/10.1111/pce.14391.
[255] O.L. Jolayemi, A.H. Malik, T. Ekblad, K. Fredlund, M.E. Olsson, E. Johansson, Protein-based biostimulants to enhance plant growth—state-of-the-art and future direction with sugar beet as an example, Agronomy 12 (2022) 3211, https://doi.org/10.3390/agronomy12123211.
[256] S.K. Upadhyay, A.K. Srivastava, V.D. Rajput, P.K. Chauhan, A.A. Bhojiya, D. Jain, G. Chaubey, P. Dwivedi, B. Sharma, T. Minkina, Root exudates: mechanistic insight of plant growth promoting rhizobacteria for sustainable crop production, Front. Microbiol. 13 (2022) 916488, https://doi.org/10.3389/fmicb.2022.916488.
[257] L. Russ, B. Andreo Jimenez, E. Nijhuis, J. Postma, *Rhizoctonia solani* disease suppression: addition of keratin-rich soil amendment leads to functional shifts in soil microbial communities, FEMS Microbiol. Ecol. 100 (2024) fiae024, https://doi.org/10.1093/femsec/fiae024.
[258] A. Artyszak, Effect of silicon fertilization on crop yield quantity and quality—A literature review in Europe, Plants 7 (2018) 54, https://doi.org/10.3390/plants7030054.
[259] O.P. Omotayo, O.O. Babalola, Resident rhizosphere microbiome's ecological dynamics and conservation: towards achieving the envisioned Sustainable Development Goals, a review, Int. Soil Water Conserv. Res. 9 (2021) 127–142, https://doi.org/10.1016/j.iswcr.2020.08.002.
[260] C. Zhan, H. Matsumoto, Y. Liu, M. Wang, Pathways to engineering the phyllosphere microbiome for sustainable crop production, Nat. Food 3 (2022) 997–1004, https://doi.org/10.1038/s43016-022-00636-2.
[261] R.K. Salgotra, C. Neal Stewart, Functional markers for precision plant breeding, Int. J. Mol. Sci. 21 (2020) 1–33, https://doi.org/10.3390/ijms21134792.
[262] M.H.U. Khan, S. Wang, J. Wang, S. Ahmar, S. Saeed, S.U. Khan, X. Xu, H. Chen, J. A. Bhat, X. Feng, Applications of artificial intelligence in climate-resilient smart-crop breeding, Int. J. Mol. Sci. 23 (2022) 11156, https://doi.org/10.3390/ijms231911156.
[263] Y. Xu, X. Zhang, H. Li, H. Zheng, J. Zhang, M.S. Olsen, R.K. Varshney, B. M. Prasanna, Q. Qian, Smart breeding driven by big data, artificial intelligence, and integrated genomic-enviromic prediction, Mol. Plant 15 (2022) 1664–1695, https://doi.org/10.1016/j.molp.2022.09.001.
[264] H. Pandey, V. Misra, A.K. Mall, A. Sharma, V. Edwin Hillary, S.A. Ceasar, Enhancing sugar crop resilience to abiotic stress using CRISPR/Cas tools, Sugar Tech 27 (2025) 985–1002, https://doi.org/10.1007/s12355-025-01561-x.
[265] C. Cautereels, J. Smets, J. De Saeger, L. Cool, Y. Zhu, A. Zimmermann, J. Steensels, A. Gorkovskiy, T.B. Jacobs, K.J. Verstrepen, Orthogonal LoxPsym sites allow multiplexed site-specific recombination in prokaryotic and eukaryotic hosts, Nat. Commun. 15 (2024) 1113, https://doi.org/10.1038/s41467-024-44996-8.
[266] GEIGS, GEiGs - Gene editing induced gene silencing. https://www.geigs.com/, 2025. (Accessed 5 August 2025).
[267] K. Schnepel, C.M. Hoffmann, Effect of extending the growing period on yield formation of sugar beet, J. Agron. Crop Sci. 202 (2016) 530–541, https://doi.org/10.1111/jac.12153.

[268] R. Croce, E. Carmo-Silva, Y.B. Cho, M. Ermakova, J. Harbinson, T. Lawson, A. J. McCormick, K.K. Niyogi, D.R. Ort, D. Patel-Tupper, P. Pesaresi, C. Raines, A.P. M. Weber, X.G. Zhu, Perspectives on improving photosynthesis to increase crop yield, Plant Cell 36 (2024) 3944–3973, https://doi.org/10.1093/plcell/koae132.

[269] A.J. Burgess, C. Masclaux-Daubresse, G. Strittmatter, A.P.M. Weber, S.H. Taylor, J. Harbinson, X. Yin, S. Long, M.J. Paul, P. Westhoff, F. Loreto, A. Ceriotti, V.L. R. Saltenis, M. Pribil, P. Nacry, L.B. Scharff, P.E. Jensen, B. Muller, J.P. Cohan, J. Foulkes, P. Rogowsky, P. Debaeke, C. Meyer, H. Nelissen, D. Inzé, R. Klein Lankhorst, M.A.J. Parry, E.H. Murchie, A. Baekelandt, Improving crop yield potential: underlying biological processes and future prospects, Food Energy Secur. 12 (2023) e435, https://doi.org/10.1002/fes3.435.

[270] N. Li, W. Wang, X. Guo, Y. Sun, G. Li, S. Zhang, BvBZR1 improves parenchyma cell development and sucrose accumulation in sugar beet (*Beta vulgaris* L.) taproot, Front. Plant Sci. 16 (2025) 1495161, https://doi.org/10.3389/fpls.2025.1495161.

[271] R. Huisman, R. Geurts, A roadmap toward engineered nitrogen-fixing nodule symbiosis, Plant Commun 1 (2020) 100019, https://doi.org/10.1016/j.xplc.2019.100019.

[272] M.Y. Jhu, G.E.D. Oldroyd, Dancing to a different tune, can we switch from chemical to biological nitrogen fixation for sustainable food security? PLoS Biol. 21 (2023) e3001982 https://doi.org/10.1371/journal.pbio.3001982.

[273] R. van Velzen, R. Holmer, F. Bu, L. Rutten, A. van Zeijl, W. Liu, L. Santuari, Q. Cao, T. Sharma, D. Shen, Y. Roswanjaya, T.A.K. Wardhani, M.S. Kalhor, J. Jansen, V.D.H. Johan, B. Güngör, M. Hartog, J. Hontelez, J. Verver, W.C. Yang, E. Schijlen, R. Repin, M. Schilthuizen, M.E. Schranz, R. Heidstra, K. Miyata, E. Fedorova, W. Kohlen, T. Bisseling, S. Smit, R. Geurts, Comparative genomics of the nonlegume Parasponia reveals insights into evolution of nitrogen-fixing rhizobium symbioses, Proc. Natl. Acad. Sci. USA 115 (2018) E4700–E4709, https://doi.org/10.1073/pnas.1721395115.

[274] Y. Zhao, L. Gao, Z. Gao, B. Tian, T. Chen, J. Xie, J. Cheng, Y. Fu, Y. Li, S. Xiao, T. Bisseling, D. Jiang, Exploring a rhizobium to fix nitrogen in non-leguminous plants by using a tumor-formation root pathogen, Phytopathol. Res. 4 (2022) 48, https://doi.org/10.1186/s42483-022-00154-w.

[275] R. van Tetering, The quest for resilience – future-proofing sugar beet varieties, Int. Sugar J. 124 (2022) 378–380.

[276] A. Couplet, V. Couplet, S. Schellen, Efficient crystallization: paving the way to 100% electrification in crystallization, Zuckerindustrie 149 (2024) 800–806, https://doi.org/10.36961/si32560.

[277] S. Schellen, V. Couplet, Significant energy savings in the beet sugar industry to reach the decarbonization goals, Sugar Industry Intern. 147 (2022) 616–623, https://doi.org/10.36961/si29263.

[278] P. Starke, C.M. Hoffmann, Dry matter and sugar content as parameters to assess the quality of sugar beet varieties for anaerobic digestion, Zuckerindustrie 139 (2014) 232–240, https://doi.org/10.36961/si15449.

[279] A. Kiskini, A. Vissers, J.P. Vincken, H. Gruppen, P.A. Wierenga, Effect of plant age on the quantity and quality of proteins extracted from sugar beet (*Beta vulgaris* L.) leaves, J. Agric. Food Chem. 64 (2016) 8305–8314, https://doi.org/10.1021/acs.jafc.6b03095.

[280] A. Akyüz, İ. Tekin, Z. Aksoy, S. Ersus, Determination of process parameters and precipitation methods for potential large-scale production of sugar beet leaf protein concentrate, J. Sci. Food Agric. 104 (2024) 3235–3245, https://doi.org/10.1002/jsfa.13210.

[281] A.H. Martin, O. Castellani, G.A.H. de Jong, L. Bovetto, C. Schmitt, Comparison of the functional properties of RuBisCO protein isolate extracted from sugar beet leaves with commercial whey protein and soy protein isolates, J. Sci. Food Agric. 99 (2019) 1568–1576, https://doi.org/10.1002/jsfa.9335.

[282] A. Kiskini, E. Zondervan, P.A. Wierenga, E. Poiesz, H. Gruppen, Using product driven process synthesis in the biorefinery, Comput. Chem. Eng. 91 (2016) 257–268, https://doi.org/10.1016/j.compchemeng.2016.03.030.

[283] P. Ebrahimi, F. Khamirikar, A. Lante, Unlocking the biorefinery approaches to valorize sugar beet leaves (*B. vulgaris* L.) for food industry applications: a critical review, Food Res. Int. 197 (2024) 115145, https://doi.org/10.1016/j.foodres.2024.115145.

[284] A. Tamayo Tenorio, F.K.G. Schreuders, F.K. Zisopoulos, R.M. Boom, A.J. van der Goot, Processing concepts for the use of green leaves as raw materials for the food industry, J. Clean. Prod. 164 (2017) 736–748, https://doi.org/10.1016/j.jclepro.2017.06.248.

[285] A. Tamayo Tenorio, J. Gieteling, C.V. Nikiforidis, R.M. Boom, A.J. van der Goot, Interfacial properties of green leaf cellulosic particles, Food Hydrocoll. 71 (2017) 8–16, https://doi.org/10.1016/j.foodhyd.2017.04.030.

[286] C. vom Berg, M. Carus, M. Stratmann, L. Dammer, Renewable carbon as a guiding principle for sustainable carbon cycles. Renewable Carbon Initiative, nova-Institute, Hürth, Germany, 2022, p. 41. https://renewable-carbon.eu/publications/product/renewable-carbon-as-a-guiding-principle-for-sustainable-carbon-cycles-pdf/.