

# Comprehensive Agronomic and Industrial Guide to Sugar Beet Cultivation and Processing

## Introduction to the Sugar Beet Value Chain

The cultivation and industrial processing of the sugar beet (*Beta vulgaris* L. subsp. *vulgaris*) represent one of the most highly integrated agricultural and chemical engineering value chains in the modern global economy. Originating historically as a forage crop, the modern sugar beet has undergone rigorous genetic and agronomic optimization over the past century to become a premier source of sucrose, currently fulfilling approximately 20% to 25% of the world's sugar demand<sup>1</sup>. Operating primarily within temperate climatic zones, the transition of the sugar beet from a raw agricultural commodity to highly refined crystalline sucrose, liquid sugars, and advanced biochemical co-products demands a profound synthesis of pedology, phytopathology, thermodynamics, and fluid dynamics.

As global agricultural systems face escalating pressures from anthropogenic climate change, shifting pedoclimatic zones, and stringent regulatory frameworks—such as the European Union's severe restrictions on synthetic agrochemicals—the agronomic and industrial paradigms governing sugar beet production are undergoing rapid transformation<sup>3</sup>. Agronomically, maximizing the yield of extractable white sugar requires precise modulation of soil organic carbon, strict nutrient balancing to minimize molassigenic impurities, and the deployment of advanced integrated pest management (IPM) strategies to compensate for the loss of vital insecticidal seed coatings<sup>4</sup>.

Industrially, the imperative for energy efficiency and decarbonization has catalyzed the adoption of novel technologies. Facilities are moving away from entirely thermal-dependent processes, integrating Pulsed Electric Field (PEF) extraction, simulated moving bed (SMB) chromatography, and mechanical vapor recompression (MVR) to create zero-waste, cascading biorefineries<sup>7</sup>. This report provides an exhaustive, expert-level examination of the entire sugar beet lifecycle. It details the precise agronomic conditions required for optimal cultivation, navigates the complexities of the harvest and storage phases, and thoroughly dissects the thermochemical and mechanical unit operations required to transform raw beet roots into high-purity commercial sucrose and value-added derivatives.

## Agronomic Principles and Cultivation Dynamics

### Geo-Climatic Parameters and Pedological Constraints

The architectural design of a high-yielding sugar beet crop must be inextricably linked to the localized climatic boundaries and pedological realities of the target geography. Traditionally a crop of temperate climates, sugar beet is highly responsive to the accumulation of thermal energy, quantified as Growing Degree Days (GDD), utilizing a base temperature threshold of

$10^{\circ}\text{C}$  and an upper limit of  $30^{\circ}\text{C}$ <sup>1</sup>. The operational growing season, which typically spans five to six months, is strictly dictated by absolute frost dates. For example, historical meteorological data in prime European growing regions, such as the Berlin-Brandenburg climate (USDA Hardiness Zone 7b), delineates a reliable frost-free window of approximately 136 to 137 days, though modern cold-hardy cultivars and protective measures can extend the functional season to up to 163 days<sup>11</sup>.

While historically constrained to temperate zones, advanced breeding programs have enabled the expansion of sugar beet cultivation into tropical and subtropical regions. In these warmer climates, sugar beet exhibits distinct physiological advantages over sugarcane, including a halving of the required growing duration (5 to 6 months versus 12 to 18 months) and a 30% to 40% reduction in overall water and fertilizer demand<sup>1</sup>. Furthermore, *Beta vulgaris* exhibits an exceptional tolerance to saline-sodic soils, capable of remaining viable in high salt concentrations (up to 500 mM) for extended periods, allowing for the utilization of marginal agricultural lands that would otherwise remain fallow<sup>1</sup>.

The defining limitation of yield potential, however, remains pedology. In regions dominated by Pleistocene-derived glacial sands and sandy loams (Arenosols), agricultural yield indices (Bodenpunkte) are frequently categorized as low, ranging between 25 and 40<sup>11</sup>. These coarse-textured soils boast an abundance of macropores, ensuring excellent aeration and ease of mechanical cultivation, but suffer from an exceptionally low Available Water Capacity (AWC)<sup>11</sup>. Consequently, they are highly susceptible to acute drought stress during summer months and severe downward leaching of water-soluble macronutrients—particularly nitrate ( $\text{NO}_3^-$ ) and potassium ( $\text{K}^+$ )—during winter precipitation events<sup>11</sup>.

## Soil Organic Carbon (SOC) and the Humus Balance

Sugar beet cultivation inflicts severe structural and biochemical demands on the soil matrix. The crop is a heavy feeder, and the mechanical intensity required for its harvest results in significant soil aggregate disruption. Long-term studies evaluating the impact of sugar beet on Soil Organic Carbon (SOC) reveal nuanced dynamics. Historical data across German agricultural inventories indicated that sugar beet sites suffered SOC depletion (approximately -4.6% relative to non-beet sites) due to the remarkably low carbon input from belowground residues, which average 2.0 to 2.7 Mg ha<sup>-1</sup> year<sup>-1</sup> compared to 3.6 to 5.8 Mg ha<sup>-1</sup> year<sup>-1</sup> for winter wheat<sup>14</sup>.

To achieve agronomic stability, nitrogen self-sufficiency, and the preservation of SOC, cultivation must be embedded within a rigorously structured crop rotation, frequently assessed using the Humus Balance framework established by the Association of German Agricultural Analytic and Research Institutes (VDLUFA)<sup>11</sup>. Root crop cultivation generally operates at a severe humus deficit of approximately -760 kg Humus-C/ha<sup>11</sup>. However, long-term empirical analyses indicate that simple humus balance calculators (like VDLUFA and STAND) occasionally overestimate the actual organic matter demand, particularly when organic fertilization such as farmyard manure or compost is heavily integrated into the rotation<sup>15</sup>.

To counteract depletion, contemporary rotations alternate sugar beet with deep-rooting, nitrogen-fixing leguminous species (such as *Lupinus angustifolius*) and multi-species green

manures<sup>11</sup>. Modern lupin cultivars, such as 'Haags Blaue' or 'Probor', can generate between 7,632 and 10,200 kg of dry matter per hectare and fix up to 180 kg N/ha, providing a massive organic influx prior to the beet phase<sup>11</sup>.

| Crop Functional Group             | VDLUFA Humus Balance Coefficient (kg Humus-C/ha) | Agronomic Impact and Rotational Implication                                                       |
|-----------------------------------|--------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Root Crops (Sugar Beet, Potatoes) | -760                                             | Severe humus depletion; destroys aggregate stability; requires preceding green manure or biochar. |
| Winter Cereals (Rye, Wheat)       | -280                                             | Moderate depletion; root exudates provide structural recovery; mitigated by straw retention.      |
| Grain Legumes (Lupins, Peas)      | +160                                             | Humus addition; contributes stable organic nitrogen via root nodules.                             |
| Perennial Forage / Clover-Grass   | +600 to +1400                                    | Massive humus contribution; essential for long-term SOC recovery and pathogen break.              |

Beyond nutrient cycling, strict rotational intervals of three to five years are mandated to disrupt the life cycles of devastating soil-borne pathogens<sup>11</sup>. Pathogens such as *Rhizoctonia solani* (which induces crown and root rot, particularly anastomosis groups AG 2-2 IIIB and IV) and beet cyst nematodes (*Heterodera schachtii*) rely on unbroken host availability to multiply resilient resting spores<sup>11</sup>. Rotations integrating non-host species physically starve the inoculum reservoir, safeguarding the subsequent sugar beet crop.

## Nutritional Management and Molassigenic Impurities

The primary objective of sugar beet agronomy is not merely maximizing total root biomass, but optimizing the yield of extractable white sugar. This requires a delicate, mathematically precise equilibrium in plant nutrition.

Nitrogen (N) is the most critical and complex variable. Nitrogen drives vegetative canopy expansion, maximizing the Leaf Area Index (LAI) required for photosynthetic sucrose synthesis. However, sugar beet exhibits a highly sensitive response curve to N application. While elevated

N increases total root tonnage, it simultaneously depresses the overall sucrose concentration and drastically elevates the accumulation of soluble nitrogenous compounds in the

root—specifically  $\alpha$ -amino nitrogen, amides (such as glutamine), and the osmoprotectant betaine<sup>1</sup>.

These soluble nitrogen compounds, alongside the alkali metals Potassium ( $K^+$ ) and Sodium ( $Na^+$ ), act as potent molassigenic impurities<sup>6</sup>. During the industrial crystallization phase, these impurities exert colligative properties that retard sucrose crystallization, effectively locking up to 50% of available sucrose into the non-crystallizable liquid molasses fraction<sup>19</sup>. Therefore,

precise N-mineralization estimates ( $N_{min}$ ) prior to sowing are mandatory, and split N applications are utilized to prevent luxury consumption during the late vegetative stages<sup>1</sup>.

Phosphorus (P) and Potassium (K) must also be balanced. Phosphorus is an integral component of nucleic acids and lipids, driving the phosphorylation reactions essential for glycolysis and sucrose transport<sup>1</sup>. Potassium functions as the primary osmoticum regulating stomatal conductance and phloem loading; however, excessive soil K luxury uptake directly elevates the root's K content, exacerbating the aforementioned molasses losses<sup>6</sup>.

Micro-nutritional management is equally critical, specifically concerning Boron (B) and Manganese (Mn). Sugar beet has an exceptionally high boron requirement, demanding up to 10 to 35 parts per million (ppm) in healthy tissues to facilitate the cross-linking of rhamnogalacturonan II in primary cell walls<sup>23</sup>. Deficiencies rapidly induce necrosis of the apical meristem, leading to heart rot and dry rot, which devastates commercial yields<sup>23</sup>. Supplemental foliar applications of boron, manganese, and silicon are frequently deployed to mitigate environmental stressors (e.g., drought, cold) that restrict nutrient bioavailability<sup>24</sup>.

## Weed Control and the Transition to Organic Cultivation

Effective weed management remains one of the most critical operational hurdles in sugar beet production. The crop suffers from slow early-stage canopy closure, making it highly susceptible to competition for solar radiation, moisture, and nutrients. Conventional chemical weed control relies heavily on the implementation of three to five post-emergence herbicide applications targeting the cotyledonous stage of the weeds, utilizing active ingredients such as metamitron, phenmedipham, and ethofumesate<sup>25</sup>.

However, regulatory bodies are increasingly restricting herbicide applications to mitigate environmental externalities. In the European Union, frameworks such as the European Green Deal and France's Ecophyto Plan II aim to drastically curtail pesticide usage by 2025<sup>25</sup>.

Consequently, integrated weed management (IWM) strategies are gaining prominence. Field trials demonstrate that combining mechanical weed control (MWC) with targeted hoeing weed control (HWC) can achieve Weed Control Efficacy (WCE) rates that rival chemical interventions, occasionally increasing root yields up to 56.48 t ha<sup>-1</sup> compared to baseline treatments<sup>25</sup>.

The push toward organic sugar beet cultivation introduces further complexities. Currently, organic sugar beet accounts for a negligible fraction of cultivated areas (e.g., approximately

0.3% in the EU) due to high field labor costs for manual weeding and extreme vulnerability to pest pressures<sup>27</sup>. Furthermore, organic production necessitates parallel, segregated processing campaigns at the factory level to ensure non-organic cross-contamination does not occur, compounding logistical overhead<sup>27</sup>.

## **Phytosanitary Pressures and the Neonicotinoid Ban**

The phytosanitary landscape of sugar beet cultivation has been fundamentally upended by shifting regulatory frameworks, most notably the outright prohibition of neonicotinoid insecticides. Historically, neonicotinoids (e.g., thiamethoxam, imidacloprid, clothianidin) applied as seed coatings provided unparalleled, systemic protection against early-season insect pests—such as the sugar beet weevil (*Asproparthenis punctiventris*) and wireworms (*Agriotes* spp.)—for up to ten weeks post-emergence<sup>4</sup>.

The primary target of these insecticides is the green peach aphid (*Myzus persicae*) and the black bean aphid (*Aphis fabae*), the principal vectors for the Virus Yellows complex. This complex, comprising Beet Yellows Virus (BYV), Beet Mild Yellowing Virus (BMV), and Beet Chlorosis Virus (BChV), represents a catastrophic phytopathological threat<sup>4</sup>. Viral infections disrupt phloem transport and chlorophyll synthesis, severely stunting the plant and reducing extractable sugar yields by up to 31% to 50%<sup>4</sup>.

Due to mounting scientific evidence linking neonicotinoids to the chronic, sublethal decline of non-target pollinator populations (e.g., *Bombus terrestris* and *Apis mellifera*), the European Union enacted a moratorium on their outdoor use in 2018<sup>4</sup>. Initially, many Member States utilized Article 53 of the EU Plant Protection Products Regulation to grant routine emergency authorizations (derogations) for neonicotinoid-treated beet seeds, arguing that the threat of Virus Yellows could not be contained by alternative means<sup>4</sup>.

However, on January 19, 2023, the Court of Justice of the European Union (CJEU) delivered a landmark ruling that expressly prohibited Member States from issuing further emergency derogations for seeds treated with banned neonicotinoids, affirming the primacy of the precautionary principle over agricultural output<sup>4</sup>. This ruling immediately exposed millions of hectares of sugar beet to unmitigated aphid predation, triggering significant yield variability across prime growing regions in France and Germany<sup>33</sup>.

The cessation of neonicotinoid use necessitates an urgent pivot toward alternative, multi-component Integrated Pest Management (IPM) strategies. In the short term, growers are forced to rely on foliar applications of contact insecticides (e.g., pyrethroids, spiromesifen, flonicamid) or alternative seed treatments like chlorantraniliprole and spinosad<sup>5</sup>. However, these lack the systemic longevity of neonicotinoids and face rising resistance in aphid populations<sup>29</sup>. Longer-term interventions require the acceleration of breeding programs to develop genetically tolerant varieties, the application of elicitors to induce systemic acquired resistance (SAR), and the utilization of biological control vectors, such as entomopathogenic fungi and plant-growth-promoting rhizobacteria (PGPR)<sup>34</sup>.

## **Harvest and Long-Term Storage Physiology**

### **Post-Harvest Respiration and Deterioration Kinetics**

The harvesting of sugar beet typically commences in late autumn (September through November), precisely when the root has accumulated maximum sucrose reserves (generally 16% to 20% of its fresh weight)<sup>13</sup>. Because industrial processing capacities cannot match the rapid pace of modern mechanical harvesting, massive quantities of beet must be stockpiled in clamps (large outdoor piles) for several weeks to months before entering the factory<sup>35</sup>. During this extended storage phase, the beet root remains a living, respiring biological entity. Post-harvest physiology is defined by continuous metabolic activity that consumes stored sucrose to sustain basal cellular functions. Under near-ideal storage conditions (e.g.,  $5^{\circ}\text{C}$ ), respiration accounts for the vast majority of sugar depletion. Empirical studies demonstrate that over a 130-day storage period, a single ton of beets can lose approximately 26 lbs of total sucrose, with 21.1 lbs (over 80%) directly consumed by respiration<sup>36</sup>. Furthermore, endogenous invertase enzymes hydrolyze a portion of the remaining sucrose into the reducing monosaccharides glucose and fructose (invert sugar), which represent a permanent loss of crystallizable product<sup>36</sup>.

Temperature regulation within the clamp is the paramount parameter for mitigating loss. If clamp temperatures elevate into the mid- $20^{\circ}\text{C}$  (mid- $60^{\circ}\text{F}$ ) range, respiration rates accelerate exponentially. If beets are allowed to reach  $70^{\circ}\text{F}$ , between 25% and 35% of the total sucrose can be lost in just 40 days<sup>18</sup>. Conversely, acute freezing events (e.g., exposure to  $-10^{\circ}\text{C}$  /  $14^{\circ}\text{F}$  for a single day) inflict catastrophic cellular lysis, damaging up to 50% of the beets<sup>18</sup>. Upon thawing, the ruptured cell walls release nutrient-rich vacuolar fluids, triggering rampant microbial fermentation (often dominated by *Leuconostoc mesenteroides*), which synthesizes highly viscous dextran polymers that severely impede factory filtration systems<sup>18</sup>.

## Initial Processing: Washing, Slicing, and Diffusion

### Fluming and Mechanical Preparation

Upon arrival at the factory, the beets undergo a rigorous sequence of mechanical preparation. They are flumed in water, which simultaneously transports the beets and removes adhering field soil, stones, and vegetative debris (weeds and beet tails)<sup>35</sup>.

Following washing, the beets are elevated into slicing machines where they are cut into long, thin, V-shaped or rhomboid strips known as "cossettes." The geometry of the cossette is engineered to maximize the specific surface area available for aqueous diffusion while maintaining sufficient structural rigidity to prevent the collapse of the deep extraction bed<sup>37</sup>.

The physical quality of the cossettes is meticulously monitored using two primary metrics:

1. **The Silin Number:** Defined as the total length, expressed in meters, of 100 grams of cossettes placed end-to-end. An optimal Silin number ranges between 10 and 18 meters<sup>40</sup>.
2. **The Swedish Number:** A ratio representing the mass of cossettes longer than 50 mm compared to those longer than 10 mm. A higher Swedish number indicates longer, more

uniform continuous strips<sup>39</sup>.

Modern slicing equipment relies on precision-milled blades, such as Königsfelder knives with profile angles of  $75^\circ$  and 8.25 mm increments<sup>38</sup>. Dull knives or improper blade alignment shatter the cellular matrix rather than slicing it, producing excessive "mush" (particles smaller than 1 cm). High mush content critically restricts fluid permeability in the downstream extraction tower, leading to channeling, severe efficiency losses, and elevated microbial infection risks<sup>41</sup>.

| Cossette Metric | Definition                               | Target Range | Industrial Implication                                               |
|-----------------|------------------------------------------|--------------|----------------------------------------------------------------------|
| Silin Number    | Length (m) of 100g of cossettes          | 10 – 18 m    | Ensures optimal surface-area-to-mass ratio for rapid diffusion.      |
| Swedish Number  | Mass ratio of cossettes > 50mm to > 10mm | High         | Indicates structural integrity and prevents extraction bed collapse. |
| Mush Content    | Percentage of mass < 1cm length          | < 5%         | Prevents flow-channeling and localized blockages in the diffuser.    |

## Thermal Diffusion Extraction

The extraction of sucrose from the solid cossette matrix into an aqueous solution is governed by the principles of mass transfer and cellular permeabilization. Traditionally, this is achieved via thermal diffusion in massive, continuous counter-current extraction towers (e.g., BMA towers)<sup>42</sup>. In the conventional process, cossettes are fed into the bottom of the extraction tower and transported upward by rotating helical screws, while fresh, heated extraction water is injected at the top, flowing downward under gravity<sup>42</sup>. To allow the large sucrose molecules to pass through the semi-permeable tonoplast and plasma membranes of the beet cells, the tissue must be thermally denatured. This is accomplished by maintaining the extraction fluid at elevated temperatures between  $65^\circ C$  and  $75^\circ C$ <sup>45</sup>.

Operating temperature is a highly sensitive and dangerous variable. Temperatures must be high enough to rapidly kill the plant cells and halt biological sucrose inversion, but if temperatures exceed  $75^\circ C$ , the pectic substances binding the primary cell walls undergo extensive

hydrolytic breakdown<sup>47</sup>. The dissolution of pectin releases massive quantities of colloidal macromolecules into the raw juice, which exponentially increases viscosity and catastrophically impairs the subsequent filtration stages<sup>47</sup>. The resulting sucrose-depleted cellular matrix, exiting the top of the tower, is pressed and dried as beet pulp for animal feed or biorefinery feedstock, while the sucrose-rich "raw juice" (or diffusion juice) exits the base<sup>49</sup>.

## **Pulsed Electric Field (PEF) Extraction**

To circumvent the immense energy expenditure and the risk of pectin degradation associated with thermal diffusion, the industry is increasingly adopting Pulsed Electric Field (PEF) technology as a non-thermal pretreatment<sup>7</sup>. PEF operates by subjecting the cossettes to high-voltage, short-duration electrical pulses (e.g., 1.0 to 5.0 kV/cm for microseconds) as they pass between two electrodes<sup>52</sup>.

This electrical stress induces an accumulation of charges across the phospholipid bilayer of the cell membrane. Once the transmembrane potential exceeds a critical threshold, electro-compression causes the spontaneous formation of transient or permanent pores—a phenomenon known as electroporation<sup>7</sup>.

Electroporation profoundly alters the extraction thermodynamics. Because the cell membranes are physically ruptured by the electric field rather than by heat, the extraction of sucrose can

proceed efficiently at significantly lower "cold" temperatures ( $35^{\circ}C$  to  $50^{\circ}C$ )<sup>46</sup>. This "cold extraction" delivers profound industrial advantages:

1. **Energy Efficiency:** PEF drastically reduces the specific thermal energy required to heat massive volumes of water. The specific energy input of the PEF treatment itself is remarkably low, typically ranging from only 0.5 to 4.0 kJ/kg of beet tissue<sup>52</sup>.
2. **Juice Purity:** Because the extraction occurs well below the thermal threshold for pectin hydrolysis, the high-molecular-weight pectins remain locked within the cellular matrix<sup>48</sup>. The resulting raw juice exhibits drastically lower colloidal impurities, lower coloration, and superior downstream filterability, routinely achieving purities above 95% straight from the press<sup>48</sup>.
3. **Pulp Dewatering:** PEF-treated pulp retains its structural integrity but loses cellular turgor, allowing mechanical screw presses to expel significantly more moisture prior to thermal drying. A PEF-assisted belt press can increase juice yield to roughly 80% prior to any washing, generating cascading energy savings across the plant's CAPEX and OPEX profiles<sup>46</sup>.

## **Juice Purification and Decolorization**

### **Carbonatation: The Lime Kiln, Preliming, and Main Liming**

The raw juice emerging from the diffuser is a dark, turbid liquid containing 12% to 18% sucrose alongside a complex matrix of non-sucrose impurities, including proteins, amino acids, organic acids, saponins, and dissolved pectins<sup>45</sup>. If not removed, these impurities will prevent sucrose crystallization. The universal method for purifying beet juice is the lime-carbon dioxide process, universally known as carbonatation<sup>45</sup>.

The active reagents—quicklime ( $CaO$ ) and carbon dioxide ( $CO_2$ )—are generated simultaneously on-site via the thermal calcination of limestone ( $CaCO_3$ ) in a dedicated, energy-intensive lime kiln<sup>57</sup>. Lime manufacturing requires significant energy, with the endothermic calcination reaction consuming roughly 3.6 GJ/t of energy and emitting 0.96  $tCO_2/t$ <sup>59</sup>. The chemical equation for this decomposition is:

$CaCO_3(s) + \text{heat} \rightleftharpoons CaO(s) + CO_2(g)$ <sup>58</sup>. The generated quicklime must meet strict purity standards ( $\geq 90\%CaO$ ) and exhibit high reactivity (a low  $t_{60}$  slaking time) before being slaked with water to form milk of lime ( $Ca(OH)_2$ )<sup>57</sup>.

The purification of the juice is executed in tightly controlled phases:

1. **Preliming:** Milk of lime is added gradually to the raw juice (which initially rests at a pH of ~5.8 to 6.2) to raise the alkalinity progressively to a pH of approximately 11.4 to 11.5<sup>45</sup>. This gradual pH gradient, often facilitated by multi-chambered Brieghel-Müller preliners, is critical. It promotes the isoelectric precipitation of proteins and the controlled denaturation of colloidal pectins, forming dense, compact flocs<sup>57</sup>.
2. **Main Liming (Cold and Hot):** A massive excess of lime (typically 1.5% to 2.5% by weight of beet) is added to establish an aggressively alkaline environment<sup>57</sup>. At elevated temperatures (up to  $85^\circ C$  to  $95^\circ C$ ), this energetic liming triggers the chemical destruction of heat-sensitive impurities. Crucially, it saponifies amides like glutamine into ammonia and entirely degrades invert sugars (glucose and fructose) into stable organic acids<sup>62</sup>. Destroying invert sugar at this stage is vital, as its presence during downstream high-temperature evaporation would trigger severe Maillard browning reactions, irreparably darkening the final sugar<sup>20</sup>.
3. **First and Second Carbonatation:** The highly alkaline juice is then saturated with the  $CO_2$  gas recovered from the lime kiln<sup>57</sup>. The  $CO_2$  reacts with the dissolved calcium hydroxide to precipitate nascent microcrystalline calcium carbonate ( $CaCO_3$ )<sup>63</sup>. As these massive  $CaCO_3$  flocs precipitate out of solution, they act as an intense physical adsorbent, sweeping suspended colloids, colorants, and precipitated lime salts out of the juice<sup>63</sup>.

The resulting slurry is filtered, producing a clear, purified "thin juice." The retained solid byproduct, known as carbonatation mud or *Carbokalk*, possesses high agronomic value.

Containing precipitated microcrystalline  $CaCO_3$ , residual organic matter, and trace phosphates, *Carbokalk* is widely redistributed to agricultural fields as a potent soil amendment<sup>63</sup>. Beyond agriculture, *Carbokalk* has demonstrated exceptional utility in advanced ecological remediation; for instance, applying *Carbokalk* to acidic pit mine lakes (e.g., Lake 111 in

Germany) successfully neutralizes the water column by stimulating microbial sulfate and iron reduction at the sediment-water interface<sup>66</sup>.

## Thin Juice Softening and Sulfitation

Despite double carbonatation, the thin juice often retains residual soluble calcium salts (hardness) that escaped precipitation. If introduced into the high-temperature evaporators, these calcium ions will aggressively precipitate onto the heat exchange tubes as hard scale, drastically reducing thermodynamic efficiency and forcing costly factory shutdowns for acid cleaning<sup>68</sup>.

To mitigate this, modern refineries employ Weak Acid Cation (WAC) exchange resins (e.g., Lewatit S 8528) to actively soften the juice. Utilizing advanced Fractal Fluid Distribution technology to maximize resin kinetics and minimize equipment footprint, the thin juice is

percolated through the resin beds where calcium ( $Ca^{2+}$ ) is exchanged for benign sodium ( $Na^{+}$ ) or hydrogen ( $H^{+}$ ) ions<sup>68</sup>. The operational breakthrough point for these weak resins in  $H^{+}$  form is exceptionally high, capable of treating up to 700 bed volumes before regeneration is required, compared to a mere 300 bed volumes for older strong acid resins like Amberlite<sup>70</sup>. This decalcification guarantees scale-free evaporator performance and improves the ultimate crystallization rate<sup>68</sup>.

Following filtration and softening, the juice is frequently subjected to sulfitation—the controlled

injection of sulfur dioxide gas ( $SO_2$ )<sup>71</sup>.  $SO_2$  serves a dual function: it acts as a potent reducing agent that blocks the aldehyde and ketone groups of residual reducing sugars, profoundly inhibiting subsequent Maillard color formation, and it sharply reduces juice

viscosity<sup>71</sup>. Experimental analyses confirm that a double treatment of  $SO_2$  (applied at both raw juice extraction and just prior to evaporation) can reduce the color of the resulting thick juice by up to 38.37%<sup>72</sup>.

## Concentration, Storage, and Crystallization

### Multi-Effect Evaporation and Decarbonization

The purified thin juice (containing approximately 15% dry substance) must be concentrated into a heavy syrup known as "thick juice" (68% to 70% dry substance) prior to crystallization. This massive dehydration is achieved in a multi-effect falling film evaporator station<sup>73</sup>. In a multi-effect system, the vapor boiled off from the juice in the first vessel is utilized as the heating medium for the second vessel, which operates at a slightly lower pressure and temperature. This cascade repeats across five to six effects to absolutely maximize steam economy<sup>75</sup>. Because the evaporation of water requires an immense input of latent heat, the sugar industry is under intense regulatory and economic pressure (e.g., the tightening free-allocation schedule of the EU Emissions Trading System) to decarbonize this unit operation<sup>33</sup>. Consequently, major producers such as Südzucker and Nordzucker are committing nine-figure capital investments to transition away from fossil-fuel-fired steam boilers toward electrification via Mechanical Vapor

Recompression (MVR)<sup>33</sup>.

In an MVR system, the low-pressure, low-temperature vapor exiting the final evaporator effect is not discarded to a condenser. Instead, it is routed into a massive mechanical compressor powered by renewable electricity<sup>77</sup>. The compressor actively shrinks the vapor's volume, exponentially increasing its pressure and saturation temperature, allowing it to be recycled directly back into the first evaporator effect as primary heating steam. This closed-loop thermodynamic recovery slashes the factory's primary thermal energy usage and drastically cuts absolute carbon emissions<sup>80</sup>.

## Thick Juice Storage Microbiota

A unique operational advantage of beet sugar processing is the ability to sever the extraction phase from the crystallization phase via the long-term storage of thick juice<sup>82</sup>. By storing millions of gallons of 69 Brix thick juice in colossal aseptic tanks, factories can operate their energy-intensive crystallization infrastructure year-round, long after the beet harvest has concluded<sup>82</sup>.

However, maintaining the biochemical stability of thick juice over 180 days is challenging.

Despite the low water activity ( $a_w \approx 0.80$ ) induced by the extreme sucrose concentration, specific extremophilic microorganisms can proliferate<sup>82</sup>. Extreme xerophilic filamentous fungi (e.g., *Acremonium strictum*, *Aspergillus niger*, and *Penicillium aurantiogriseum*) can colonize the liquid surface<sup>82</sup>. Below the surface, in the anaerobic bulk, mesophilic "fastidious bacteria" (such as *Tetragenococcus halophilus* and various *Bacillus* species including *B. licheniformis*) can survive and multiply<sup>82</sup>.

Proliferation of these organisms triggers catastrophic degradation: the lactic acid generated by bacterial metabolism forces the pH to plummet from an optimal 9.0 down to 5.0, inducing the spontaneous acid hydrolysis of sucrose into invert sugar<sup>82</sup>. To suppress this, meticulous storage

protocols dictate chilling the juice to an optimal  $15^{\circ}\text{C}$  and applying specialized biocides, such as Hop  $\beta$ -acids (at 40 ppm) or sodium dimethyldithiocarbamate, which effectively disrupt the bacterial transmembrane proton gradient<sup>82</sup>.

## Vacuum Pan Boiling and Centrifugation

The transformation of thick juice into white, crystalline sucrose is executed in the sugar house. The heavy syrup is drawn into massive, low-pressure vessels known as vacuum pans—either traditional batch pans or modern Continuous Vacuum Pans (VKT)<sup>73</sup>. By operating under a deep vacuum, the boiling point of the syrup is artificially depressed to approximately  $70^{\circ}\text{C}$  to  $75^{\circ}\text{C}$ , preventing the thermal caramelization of the sucrose<sup>86</sup>.

As water boils off, the solution crosses the boundary of supersaturation. The pan boiler introduces a finely milled slurry of sucrose "seed" crystals to provide nucleation sites. The sucrose molecules precipitate out of the supersaturated liquid phase and deposit onto the exact lattice structure of the growing seeds. The resulting dense mixture of distinct sugar crystals

suspended in a thick, exhausted mother liquor is termed "massecuite"<sup>86</sup>.

The separation of the pure crystals from the dark mother liquor relies entirely on centrifugal force. The massecuite is discharged into massive centrifugals, which can operate in batch or continuous modes<sup>89</sup>. As the centrifugal basket accelerates, the generated G-force drives the heavy molasses outward through a perforated stainless-steel screen, while retaining the solid sucrose crystals<sup>89</sup>.

To ensure the final sugar achieves the brilliant white color characteristic of refined sucrose, a brief, highly calibrated pulse of superheated wash water (or steam) is sprayed onto the spinning crystal wall<sup>88</sup>. This wash aggressively scours the microscopic film of residual molasses from the crystal surfaces. Modern batch centrifugals automate this wash water volume precisely; excessive washing dissolves the actual sugar crystal, slashing yield, while insufficient washing leaves the sugar burdened with high ICUMSA color values and elevated ash content<sup>88</sup>. The purged, pristine white sugar is discharged, dried in rotary granulators, cooled, and conveyed to climate-controlled silos for bulk distribution<sup>35</sup>.

For specific markets, particularly those catering to strict vegan or organic demographics, the final purification steps are critical. While cane sugar refineries historically relied on cattle bone char as a decolorizing filter—rendering the sugar non-vegan—beet sugar processing achieves pristine coloration entirely through the carbonatation and ion exchange processes outlined above, inherently bypassing animal-derived filtration media<sup>92</sup>.

## Advanced Biorefinery and Co-Product Valorization

### The Reinefeld Formula and Molasses Yield

The dark syrup spun off by the centrifugals is returned to subsequent, lower-purity vacuum pans to extract secondary and tertiary crops of crystals<sup>35</sup>. Eventually, the concentration of accumulated non-sucrose impurities—specifically the molassigenic agents discussed in the agronomy section—becomes so overwhelmingly high that the remaining sucrose is thermodynamically blocked from crystallizing, regardless of further boiling<sup>19</sup>. This final, exhausted, viscous liquid is molasses.

The efficiency of a factory's operation and the technological quality of the initial beet crop are mathematically evaluated using standardized algorithms that predict this inevitable sugar loss. In the European industry, the predominant metric is the Reinefeld Formula, which calculates the

Standard Molasses Loss ( $S_m$ ) based on the precise concentration of alkali metals and nitrogenous compounds in the raw beet<sup>94</sup>.

The classical Reinefeld derivation is expressed as:

$$S_m = 0.0343(K + Na) + 0.0094(\alpha\text{-amino } N) + 0.29 \quad \text{Where } K$$

(Potassium),  $Na$  (Sodium), and  $\alpha$ -amino  $N$  are quantified in millimoles per 100 grams of beet<sup>95</sup>. This formula explicitly demonstrates that for every unit of potassium or sodium absorbed by the beet from the soil, a mathematically predictable fraction of the farmer's sucrose yield is destined to be lost to the molasses stream, underscoring the absolute necessity of precision

fertilization at the field level<sup>95</sup>.

## **Molasses Desugarization (MDS) via Simulated Moving Bed Chromatography**

In the modern circular economy, molasses is no longer viewed merely as a low-value agricultural byproduct suited only for animal feed<sup>9</sup>. Advanced refineries have integrated sophisticated downstream processing to capture every fraction of available biochemical value<sup>98</sup>. The most prominent advancement is Molasses Desugarization (MDS), predominantly achieved via Simulated Moving Bed (SMB) chromatography<sup>8</sup>. An SMB system comprises a massive array of columns packed with highly specialized, monodisperse strong-acid cation exchange resins<sup>100</sup>. As the molasses and an eluent (water) flow continuously through the system, internal port valves switch sequentially to simulate a continuous counter-current movement of the solid resin bed against the liquid flow<sup>100</sup>.

The resin matrix physically retards the progression of larger non-sugar molecules and salts, while the smaller sucrose molecules migrate through the interstitial spaces at a different velocity. This chromatic separation reliably recovers between 81% and 88% of the "lost" sucrose from the molasses as a high-purity extract fraction<sup>8</sup>. This extract is recycled back into the main crystallization loop, drastically elevating the factory's overall yield (quantified industrially as the Z-factor)<sup>8</sup>.

## **Betaine and Pectin Extraction**

Simultaneously, coupled-loop or multi-component SMB systems isolate a distinct, high-value biochemical fraction: Betaine (trimethylglycine)<sup>98</sup>. Betaine is a powerful zwitterionic osmoprotectant and biological methyl donor, commanding significant premiums in the pharmaceutical, cosmetic, and advanced aquaculture feed industries<sup>98</sup>. Facilities utilizing this technology can isolate a purified betaine-rich stream, converting a former waste liability into a highly lucrative secondary revenue channel<sup>105</sup>. Alternatively, emerging reactive extraction techniques utilizing agents like dinonylnaphthalenedisulfonic acid (DNNDsA) dissolved in toluene offer future pathways for isolating betaine directly from vinasse and molasses, achieving extraction efficiencies over 71% without the massive capital expenditure required for SMB arrays<sup>104</sup>.

Beyond molasses, the solid, fibrous beet pulp expelled from the diffusion towers represents an immense reservoir of complex polysaccharides. Rather than merely drying the pulp for ruminant forage, integrated biorefineries are pioneering the isolation of high-methoxyl pectins directly from the pulp matrix<sup>97</sup>. Utilizing eco-friendly citric acid hydrolysis at elevated temperatures, or specialized enzymatic degradation, the rigid cell wall architecture is disassembled to yield purified pectin<sup>97</sup>. Differential Scanning Calorimetry (DSC) analyses of these pectins reveal

stable endothermic peaks between  $156^{\circ}\text{C}$  and  $160^{\circ}\text{C}$ , indicating robust thermal stability<sup>108</sup>.

This beet-derived pectin exhibits extraordinary water-binding capacities—absorbing up to eight times its dry weight—positioning it as a premier texturizer, emulsifier, and structural fiber in the global food ingredients market<sup>98</sup>. The residual, pectin-free lignocellulosic biomass can subsequently undergo thermal torrefaction to yield high-density solid biofuels, perfectly closing

the thermodynamic loop of the facility through a strategy of cascading utilization<sup>97</sup>.

## Conclusion

The lifecycle of the sugar beet is a definitive testament to the synthesis of highly technical agronomic stewardship and advanced industrial engineering. The successful cultivation of the crop demands an uncompromising adherence to biogeochemical parameters—balancing organic carbon reserves, optimizing complex crop rotations to suppress virulent phytopathogens like *Rhizoctonia solani*, and managing trace nutrient kinetics to suppress molassigenic impurities in the face of dwindling agrochemical toolsets and explicit regulatory bans on neonicotinoids.

Following harvest, the industrial extraction and purification of sucrose transcend simple agriculture, operating as a sophisticated, continuous-flow chemical enterprise. As the industry pivots toward the demands of a decarbonized, circular economy, traditional thermal diffusion and fossil-fired evaporation are rapidly giving way to advanced electro-permeabilization, mechanical vapor recompression, and continuous SMB chromatography. By systematically fracturing the biological matrix of the sugar beet into highly purified sucrose, active betaine, specialized pectins, and restorative *Carbokalk* fertilizers, the modern beet sugar factory operates not merely as a processing plant, but as a fully optimized, zero-waste biorefinery.

## Works cited

1. Sugar Beet Cultivation in the Tropics and Subtropics - MDPI, <https://www.mdpi.com/2073-4395/13/5/1213>
2. DROUGHT ADAPTIVE TRAITS FOR SUGAR BEET IMPROVEMENT, <http://publicationslist.org/data/stevanato/ref-23/Stevanato%20et%20al%202010%20NOVA%20PUBLISHER.pdf>
3. Effect of Sugar Beet Genotype, Planting and Harvesting Dates and, <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2018.01041/full>
4. Neonicotinoid ban to drive sugar prices up, <https://www.ragus.co.uk/ongoing-neonicotinoid-ban-to-drive-future-sugar-beet-yield-down-and-prices-up/>
5. Seed Treatment Alternatives with Improved Ecological Profiles for, <https://www.mdpi.com/2223-7747/15/10/1488>
6. (PDF) Sugar beet response to balanced nitrogen fertilization with, [https://www.researchgate.net/publication/286139013\\_Sugar\\_beet\\_response\\_to\\_balanced\\_nitrogen\\_fertilization\\_with\\_phosphorus\\_and\\_potassium\\_Part\\_II\\_dynamics\\_of\\_beet\\_quality](https://www.researchgate.net/publication/286139013_Sugar_beet_response_to_balanced_nitrogen_fertilization_with_phosphorus_and_potassium_Part_II_dynamics_of_beet_quality)
7. Pulsed electric field technology as a promising pre-treatment for, <https://pubs.rsc.org/ra/article/14/3/2116/825885/Pulsed-electric-field-technology-as-a-promising>
8. Molasses Desugarization in the US Beet Sugar Industry, <https://arifractal.net/wp-content/uploads/2019/06/Molasses-Desugarization-in-the-US-Beet-Sugar-Industry-Recent-Update.pdf>
9. Circular Bio-economy—Paradigm for the Future: Systematic Review,

- <https://d-nb.info/1244694002/34>
10. Energy and cost efficiency in the sugar house: combining proven,  
[https://www.bma-worldwide.com/fileadmin/Content/publications/Energy\\_and\\_cost\\_efficiency\\_in\\_the\\_sugar\\_house.pdf](https://www.bma-worldwide.com/fileadmin/Content/publications/Energy_and_cost_efficiency_in_the_sugar_house.pdf)
  11. 24 Berlin Crop Rotation Schedule.pdf
  12. Genome-wide Identification and Expression Analysis of ERF,  
<http://rootspress.org/journals/pbiotech/article/download/1458/1443/9417>
  13. Sugarbeet,  
<https://sugarbeets.ucdavis.edu/sites/g/files/dgvnsk14561/files/inline-files/224143.pdf>
  14. Effect of sugar beet (Beta vulgaris L.) cultivation on soil organic,  
[https://www.researchgate.net/publication/388968667\\_Effect\\_of\\_sugar\\_beet\\_Beta\\_vulgaris\\_L\\_cultivation\\_on\\_soil\\_organic\\_carbon\\_stocks\\_in\\_Germany](https://www.researchgate.net/publication/388968667_Effect_of_sugar_beet_Beta_vulgaris_L_cultivation_on_soil_organic_carbon_stocks_in_Germany)
  15. Sugar beet rotation effects on soil organic matter and calculated,  
[https://www.researchgate.net/publication/287332572\\_Sugar\\_beet\\_rotation\\_effects\\_on\\_soil\\_organic\\_matter\\_and\\_calculated\\_humus\\_balance\\_in\\_Central\\_Germany](https://www.researchgate.net/publication/287332572_Sugar_beet_rotation_effects_on_soil_organic_matter_and_calculated_humus_balance_in_Central_Germany)
  16. Compost as an Option for Sustainable Crop Production at Low,  
<https://www.mdpi.com/2073-4395/11/6/1078>
  17. Crop Rotational Effects on Yield Formation in Current Sugar Beet,  
<https://pmc.ncbi.nlm.nih.gov/articles/PMC5839237/>
  18. Journal of Sugar Beet Research - CABI Digital Library,  
<https://www.cabidigitallibrary.org/doi/pdf/10.5555/20153443336>
  19. Composition of harmful nitrogen in sugar beet (Beta vulgaris L.),  
[https://www.researchgate.net/publication/251661407\\_Composition\\_of\\_harmful\\_nitrogen\\_in\\_sugar\\_beet\\_Beta\\_vulgaris\\_L\\_-\\_Amino\\_acids\\_betaine\\_nitrate\\_-\\_As\\_affected\\_by\\_genotype\\_and\\_environment](https://www.researchgate.net/publication/251661407_Composition_of_harmful_nitrogen_in_sugar_beet_Beta_vulgaris_L_-_Amino_acids_betaine_nitrate_-_As_affected_by_genotype_and_environment)
  20. foliar treatments response of sugar beet (beta vulgaris l.),  
[https://protmed.uoradea.ro/facultate/anale/protectia\\_mediului/2007/Agronomy/Ungai%20Diana.pdf](https://protmed.uoradea.ro/facultate/anale/protectia_mediului/2007/Agronomy/Ungai%20Diana.pdf)
  21. Sugar Beet N Fertilization Management - Encyclopedia.pub,  
<https://encyclopedia.pub/entry/22468>
  22. Root Quality and Processing - ResearchGate,  
[https://www.researchgate.net/publication/228025838\\_Root\\_Quality\\_and\\_Processing](https://www.researchgate.net/publication/228025838_Root_Quality_and_Processing)
  23. Boron Tolerance of Sugar Beets in Relation to the Growth and Boron,  
<https://assbt.org/wp-content/uploads/2024/02/JSBRVol17No3P280to288BoronToleranceofSugarBeetsinRelationtotheGrowthandBoronContentofTissues.pdf>
  24. Foliar fertilisation in sugar beet - Lebosol® Dünger GmbH,  
<https://www.lebosol.de/en/crops/arable-farming/sugar-beet>
  25. Mechanical Weed Control: Sensor-Based Inter-Row Hoeing ... - MDPI,  
<https://www.mdpi.com/2073-4395/14/1/176>
  26. Europe Sugar Market Size, Share & Analysis, 2034,  
<https://www.marketdataforecast.com/market-reports/europe-sugar-market>
  27. THE EU SUGAR INDUSTRY: - CEFS,  
<https://cefs.org/wp-content/uploads/2019/09/CEFS-5-Year-Vision-Report-Digital-S>

[preads.pdf](#)

28. Plant protection consequences in Hungary of the withdrawal of,  
<https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2024.1363950/full>
29. Landscape-scale drivers of insect pest regulation in sugar beet,  
[https://www.researchgate.net/publication/396303708\\_Landscape-scale\\_drivers\\_of\\_insect\\_pest\\_regulation\\_in\\_sugar\\_beet](https://www.researchgate.net/publication/396303708_Landscape-scale_drivers_of_insect_pest_regulation_in_sugar_beet)
30. EU Court to rule on banned pesticide use - ResearchGate,  
[https://www.researchgate.net/publication/353275782\\_EU\\_Court\\_to\\_rule\\_on\\_banned\\_pesticide\\_use](https://www.researchgate.net/publication/353275782_EU_Court_to_rule_on_banned_pesticide_use)
31. member states' discretion in emergency pesticide authorisations: the,  
<https://journals.lub.lu.se/njel/article/download/27003/24204/73831>
32. EU Court of Justice: no more derogations for the use of bee-toxic,  
<https://www.pan-europe.info/press-releases/2023/01/eu-court-justice-no-more-derogations-use-bee-toxic-neonicotinoids>
33. Industrial Sugar Market Growth, Trends, and Outlook by 2035,  
<https://www.marketresearchfuture.com/reports/industrial-sugar-market-2371>
34. (PDF) Plant protection consequences in Hungary of the withdrawal,  
[https://www.researchgate.net/publication/379734864\\_Plant\\_protection\\_consequences\\_in\\_Hungary\\_of\\_the\\_withdrawal\\_of\\_systemic\\_active\\_substances\\_from\\_sugar\\_beet\\_seed\\_treatment](https://www.researchgate.net/publication/379734864_Plant_protection_consequences_in_Hungary_of_the_withdrawal_of_systemic_active_substances_from_sugar_beet_seed_treatment)
35. (PDF) Sugar Beet Processing to Sugars - ResearchGate,  
[https://www.researchgate.net/publication/362832737\\_Sugar\\_Beet\\_Processing\\_to\\_Sugars](https://www.researchgate.net/publication/362832737_Sugar_Beet_Processing_to_Sugars)
36. General Postharvest Physiology of the Sugarbeet Root,  
<https://bsdf-assbt.org/wp-content/uploads/2018/01/GeneralPostharvestPhysiologyoftheSugarbeetRoot.pdf>
37. Beet Diffusion Extraction Training Guide | PDF - Scribd,  
<https://www.scribd.com/document/893391642/Beet-Diffusion-Manual>
38. Comparative analysis of beet cossettes extraction of different profiles,  
<https://www.cabidigitallibrary.org/doi/pdf/10.5555/20153321087>
39. STRAIGHT EDGE KNIFE SHARPNESS DETERIORATION MODEL,  
[https://fse.studenttheses.ub.rug.nl/17934/1/%21MscThesis\\_IEM\\_Pieter\\_Tjabbes\\_2018\\_FINAL.pdf](https://fse.studenttheses.ub.rug.nl/17934/1/%21MscThesis_IEM_Pieter_Tjabbes_2018_FINAL.pdf)
40. The Effects of Mixing Syrups from Beet and Cane Origin on Sugar,  
[https://www.researchgate.net/profile/Karl-Schlumbach/publication/328886731\\_The\\_effects\\_of\\_mixing\\_syrups\\_from\\_beet\\_and\\_cane\\_origin\\_on\\_sugar\\_quality/links/61f42fc14393577abef7a597/The-effects-of-mixing-syrups-from-beet-and-cane-origin-on-sugar-quality.pdf](https://www.researchgate.net/profile/Karl-Schlumbach/publication/328886731_The_effects_of_mixing_syrups_from_beet_and_cane_origin_on_sugar_quality/links/61f42fc14393577abef7a597/The-effects-of-mixing-syrups-from-beet-and-cane-origin-on-sugar-quality.pdf)
41. Beet-Sugar Handbook - PDF Free Download - epdf.pub,  
<https://epdf.pub/beet-sugar-handbook.html>
42. Sugar beet extraction plants - BMA AG,  
<https://www.bma-worldwide.com/extraction-plants-for-sugar-beet-factories.html>
43. Minimizing Loss and Increasing Output - Michigan Sugar,  
<https://www.michigansugar.com/wp-content/uploads/2019/06/Summer-Fall-2018.p>

df

44. (PDF) Extraction of Sugar from Beets - Academia.edu,  
[https://www.academia.edu/35440113/Extraction\\_of\\_Sugar\\_from\\_Beets](https://www.academia.edu/35440113/Extraction_of_Sugar_from_Beets)
45. Raw juice alkalization - WO2008089946A2 - Google Patents,  
<https://patents.google.com/patent/WO2008089946A2/en>
46. Pulsed Electric Field Treatment of Sugar Beet - ResearchGate,  
[https://www.researchgate.net/publication/343049187\\_Pulsed\\_Electric\\_Field\\_Treatment\\_of\\_Sugar\\_Beet](https://www.researchgate.net/publication/343049187_Pulsed_Electric_Field_Treatment_of_Sugar_Beet)
47. EP0649602A2 - Process for making soluble beet fibre,  
<https://patents.google.com/patent/EP0649602A2/en>
48. Quality and filtration characteristics of sugar beet juice obtained by,  
[https://www.researchgate.net/publication/232389412\\_Quality\\_and\\_filtration\\_characteristics\\_of\\_sugar\\_beet\\_juice\\_obtained\\_by\\_cold\\_extraction\\_assisted\\_by\\_pulsed\\_electric\\_field](https://www.researchgate.net/publication/232389412_Quality_and_filtration_characteristics_of_sugar_beet_juice_obtained_by_cold_extraction_assisted_by_pulsed_electric_field)
49. v'yoMing Sugo.r Process Flow - Wyoming Sugar Company,  
<https://wyomingsugar.com/wp-content/uploads/2019/10/Wyoming-Sugar-Company-Process-Flow.pdf>
50. Ultrasonic Extraction of Sugar from Sugar Beet Cosettes -,  
<https://www.hielscher.com/ultrasonic-extraction-of-sugar-from-sugar-beet-cosettes.htm>
51. Processing of sugar beets assisted by pulsed electric fields,  
[https://www.agriculturejournals.cz/artkey/rae-202202-0002\\_processing-of-sugar-beets-assisted-by-pulsed-electric-fields.php](https://www.agriculturejournals.cz/artkey/rae-202202-0002_processing-of-sugar-beets-assisted-by-pulsed-electric-fields.php)
52. The Impact of Pulsed Electric Field Treatment of Beetroots on ... - MDPI,  
<https://www.mdpi.com/2076-3417/15/7/3834>
53. Analysis of pulsed electric field pre-treatment for beet juice extraction,  
<https://cigrjournal.org/index.php/Ejournal/article/download/6465/3633/33189>
54. Application of pulsed electric fields (PEF) in the food industry,  
<https://www.dlg.org/en/mediacenter/dlg-expert-reports/nutrition/dlg-expert-report-02-2024-application-of-pulsed-electric-fields-pef-in-the-food-industry>
55. Pulsed electric field energy calculation to damage red galangal,  
<http://csfarmacie.cz/pdfs/csf/2022/03/03.pdf>
56. A pilot belt press used for PEF-assisted expression from the sugar,  
[https://www.researchgate.net/figure/A-pilot-belt-press-used-for-PEF-assisted-expression-from-the-sugar-beets-With-permission\\_fig4\\_281912677](https://www.researchgate.net/figure/A-pilot-belt-press-used-for-PEF-assisted-expression-from-the-sugar-beets-With-permission_fig4_281912677)
57. Food and Sugar Industry | Vişne Madencilik,  
<https://visnemadencilik.com/en/applications/food-sugar-industry>
58. Reports of Cases - EUR-Lex,  
<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:62012CC0426>
59. (PDF) Optimization of energy transition pathways in the lime industry,  
[https://www.researchgate.net/publication/413568335\\_Optimization\\_of\\_energy\\_transition\\_pathways\\_in\\_the\\_lime\\_industry\\_A\\_superstructure\\_approach](https://www.researchgate.net/publication/413568335_Optimization_of_energy_transition_pathways_in_the_lime_industry_A_superstructure_approach)
60. E529 (CALCIUM OXIDE) - Ataman Chemical,  
[https://www.atamanchemicals.com/e529-calcium-oxide\\_u34247/](https://www.atamanchemicals.com/e529-calcium-oxide_u34247/)
61. Putsch Juice Purification Systems Overview - Sugar Beet - Scribd,

- <https://www.scribd.com/document/406579151/putsh-karbonatlama-pdf>
62. Preliming in Beet Juice Purification | PDF | Alkalinity - Scribd,  
<https://www.scribd.com/document/377800769/2005-Briones-Fundamentals-of-Beet-Juice-Carbonatation>
  63. Filtration principles and troubleshooting - ResearchGate,  
[https://www.researchgate.net/publication/358934675\\_Filtration\\_principles\\_and\\_troubleshooting](https://www.researchgate.net/publication/358934675_Filtration_principles_and_troubleshooting)
  64. (PDF) Carbonation Process in Sugar Refinery - ResearchGate,  
[https://www.researchgate.net/publication/379806929\\_Carbonation\\_Process\\_in\\_Sugar\\_Refinery](https://www.researchgate.net/publication/379806929_Carbonation_Process_in_Sugar_Refinery)
  65. particle size distribution of re-used carbonation mud,  
<https://journal.pan.olsztyn.pl/pdf-97984-30610?filename=30610.pdf>
  66. Processes at the Sediment Water Interface after Addition of Organic,  
<https://pubs.acs.org/doi/abs/10.1021/es0614823>
  67. K. Friese, M. Koschorreck, K. Wendt ... - Proceedings IMWA 2010,  
[https://www.imwa.info/docs/imwa\\_2010/IMWA2010\\_Friese\\_500.pdf](https://www.imwa.info/docs/imwa_2010/IMWA2010_Friese_500.pdf)
  68. ESCON - Purification Technologies, <https://www.escon.com/>
  69. Method for regenerating sugar making decolorized and decalcified,  
<https://patents.google.com/patent/CN102031315A/en>
  70. The use of ion exchange resins for beet sugar juice processing,  
[https://www.researchgate.net/publication/298547007\\_The\\_use\\_of\\_ion\\_exchange\\_resins\\_for\\_beet\\_sugar\\_juice\\_processing](https://www.researchgate.net/publication/298547007_The_use_of_ion_exchange_resins_for_beet_sugar_juice_processing)
  71. US4076552A - Process for decolorizing sugar solutions with peroxide,  
<https://patents.google.com/patent/US4076552A/en>
  72. Comparative evaluation of sugar beet processing intermediates,  
[https://www.researchgate.net/publication/349193724\\_Comparative\\_evaluation\\_of\\_sugar\\_beet\\_processing\\_intermediates\\_color\\_using\\_various\\_treatment\\_methods](https://www.researchgate.net/publication/349193724_Comparative_evaluation_of_sugar_beet_processing_intermediates_color_using_various_treatment_methods)
  73. Vertical continuous pan (VKT),  
<https://www.bma-worldwide.com/crystallisation/vertical-vacuum-pan-vkt.html>
  74. My internship report at esm | PDF - Slideshare,  
<https://www.slideshare.net/slideshow/my-internship-report-at-esm/189613509>
  75. Development of Plate Evaporator Technology, The Market Place,  
[http://w.bdheat.com/bd/references/evaporators/evap\\_d.pdf](http://w.bdheat.com/bd/references/evaporators/evap_d.pdf)
  76. Beet Sugar Evaporator Heat Transfer Coefficients | PDF - Scribd,  
<https://www.scribd.com/document/916847117/JSBRVol13No2P153to169-Evaporator-Heat-Transfer-Coefficients-for-Beet-Sugar-Solution>
  77. SPIRIT Partners - Spirit-Heat, <https://spirit-heat.eu/consortium/>
  78. trial steam production from data center heat recovery - Aaltodoc,  
<https://aaltodoc.aalto.fi/bitstreams/ab88c63c-b6a5-4e5c-8dc4-04c03b548786/download>
  79. Reinventing the Sugar Production - Piller Blowers,  
<https://www.piller.de/news-events/news/article/reinventing-the-sugar-production/>
  80. Turboden will supply a heat electrification solution to Co.Pro.B.,  
<https://www.tecnofoodonline.com/2026/04/08/turboden-will-supply-a-heat-electrification-solution-to-co-pro-b-italia-zuccheri-contributing-to-the-decarbonization-of-ste>

[am-production-in-the-sugar-industry/](#)

81. Energy-efficient systems including mechanical vapor compression,  
<https://patents.google.com/patent/US9925477B2/en>
82. Fungi associated with long-term stored beet thick juice - ResearchGate,  
[https://www.researchgate.net/publication/394517333\\_Fungi\\_associated\\_with\\_long-term\\_stored\\_beet\\_thick\\_juice\\_effect\\_of\\_temperature\\_and\\_biocide\\_treatments](https://www.researchgate.net/publication/394517333_Fungi_associated_with_long-term_stored_beet_thick_juice_effect_of_temperature_and_biocide_treatments)
83. Bacterial biodiversity and optimization of pilot plant-based storage,  
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12084369/>
84. This article appeared in a journal published by Elsevier. The ... - Lirias,  
<https://lirias.kuleuven.be/retrieve/193936>
85. Beet thick juice degradation during storage - ResearchGate,  
[https://www.researchgate.net/publication/290334006\\_Beet\\_thick\\_juice\\_degradation\\_during\\_storage](https://www.researchgate.net/publication/290334006_Beet_thick_juice_degradation_during_storage)
86. The VKT continuous vacuum pan - More than 20 years of experience,  
[https://www.researchgate.net/publication/293528728\\_The\\_VKT\\_continuous\\_vacuum\\_pan\\_-\\_More\\_than\\_20\\_years\\_of\\_experience](https://www.researchgate.net/publication/293528728_The_VKT_continuous_vacuum_pan_-_More_than_20_years_of_experience)
87. Publications for the sugar industry about technical products,  
<https://www.bma-worldwide.com/de/news-and-events/publications-1.html>
88. Batch Centrifugal » SilverWeibull, <https://www.silver-weibull.se/batch-centrifugal/>
89. Types of Sugar Centrifuges: Batch vs. Continuous - Western States,  
<https://www.westernstates.com/batch-vs-continuous-centrifuge/>
90. Batch Centrifugal Machine Capacity and Gravity Factor Calculation,  
<https://www.sugarprocesstech.com/batch-centrifugal-machine-capacity/>
91. Centrifugal Equipment Capacity in Sugar Industry | PDF - Scribd,  
<https://www.scribd.com/document/763144816/Centrifugal-Capacity-Calculation>
92. Sugar: Veg or Non-Veg? Here's the Truth - Book Appointment,  
<https://medicasapp.com/blogs/is-sugar-veg-or-non-veg/>
93. Is Your Sugar Vegan? | Vegetarian Journal,  
[https://www.vrg.org/journal/vj2007issue4/2007\\_issue4\\_sugar.php](https://www.vrg.org/journal/vj2007issue4/2007_issue4_sugar.php)
94. Seed Priming as a Tool for Optimizing Sugar Beet Canopy Traits,  
<https://www.mdpi.com/2077-0472/15/22/2366>
95. Impact of the variety and severity of Cercospora beticola infection on,  
<https://journals.iung.pl/index.php/archpja/article/view/16/6>
96. ELECTRONIC JOURNAL OF POLISH AGRICULTURAL,  
<http://www.ejpau.media.pl/articles/volume4/issue1/agronomy/art-03.pdf>
97. Eco-Friendly Pectin Extraction from Sugar Beet Pulp | PDF - Scribd,  
<https://www.scribd.com/document/841172107/A-Simplified-Biorefinery-Concept-for-the-Valorization-of-Sugar-Beet-Pulp-Ecofriendly-Isolation-of-Pectin-as-a-Step-Preceding-Torrefaction>
98. Sugar Beet Derivatives: Fiber & Betaine Markets - Food Additives Asia,  
<https://www.foodingredientsasia.com/market-insights/sugar-beet-derivatives-beyond-sweeteners-fiber-and-betaine-markets>
99. Process flow of a molasses desugarization system separating two,  
[https://www.researchgate.net/figure/Process-flow-of-a-molasses-desugarization-system-separating-two-components\\_fig1\\_384444654](https://www.researchgate.net/figure/Process-flow-of-a-molasses-desugarization-system-separating-two-components_fig1_384444654)

100. US6663780B2 - Method for the fractionation of molasses,  
<https://patents.google.com/patent/US6663780B2/en>
101. ChemInform Abstract: Simulated Moving-Bed Technology in the,  
[https://www.researchgate.net/publication/250541641\\_ChemInform\\_Abstract\\_Simulated\\_Moving-Bed\\_Technology\\_in\\_the\\_Sweetener\\_Industry](https://www.researchgate.net/publication/250541641_ChemInform_Abstract_Simulated_Moving-Bed_Technology_in_the_Sweetener_Industry)
102. Advances in Chromatographic Sugar Separation | PDF | Ion Exchange,  
<https://www.scribd.com/doc/206401270/cromatografia>
103. Chromatography - Amalgamated Research LLC,  
<https://arifractal.net/applications/chromatography/>
104. Reactive Extraction of Betaine from Sugarbeet Processing Byproducts,  
<https://pubs.acs.org/doi/10.1021/acsomega.2c07845>
105. optimization of betaine recovery in a coupled loop molasses,  
[https://assbt.org/wp-content/uploads/2023/09/Groom20\\_Factory.pdf](https://assbt.org/wp-content/uploads/2023/09/Groom20_Factory.pdf)
106. Reactive Extraction of Betaine from Sugarbeet Processing Byproducts,  
[https://www.researchgate.net/publication/369214526\\_Reactive\\_Extraction\\_of\\_Betaine\\_from\\_Sugarbeet\\_Processing\\_Byproducts](https://www.researchgate.net/publication/369214526_Reactive_Extraction_of_Betaine_from_Sugarbeet_Processing_Byproducts)
107. Structural and Rheological Properties of Pectins Extracted ... - MDPI,  
<https://www.mdpi.com/1420-3049/24/3/392>
108. Greener Pectin Extraction Techniques: Applications and Challenges,  
<https://www.mdpi.com/2297-8739/12/3/65>
109. Business Models, Including Higher Value Products for the New,  
<https://www.frontiersin.org/journals/sustainability/articles/10.3389/frsus.2022.789435/full>