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Taraxacum koksaghyz Rodin as a versatile resource for the production of natural rubber and inulin

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ABSTRACT

The root of *Taraxacum koksaghyz* (*Tk*) represents a promising alternative for sustainable natural rubber (NR) production. It addresses current challenges in NR supply faced by the current world NR producer, the rubber tree (*Hevea brasiliensis*). Such challenges are pathogen vulnerability, sustainability issues, and economic pressure. Moreover, the fossil resource dependency of synthetic rubber (SR) production is of concern. Co-extracted from the roots is inulin, a fructan polymer with great potential as a renewable feedstock for green chemistry. The dual output of NR and inulin positions *Tk* as a multipurpose crop. Its use would support both the development of a biobased economy and reduce reliance on fossil resources for SR production. This review evaluates past accomplishments and recent advances in molecular breeding, omics-driven crop improvement, and bioprocessing technologies. Developments aim to enhance rubber and inulin yields from *Tk*, and focus on insights into the interplay between the metabolisms of both NR and inulin. We discuss the optimization of the entire production chain, from seed to extraction, including agronomic practices and genetic modification/genome editing. Also, the possible valorization of other plant components in industrial and commercial applications is outlined. Collectively, these developments contribute to the productivity and economic viability of *Tk* as a multipurpose crop. Key scientific and technological accomplishments are outlined. We propose

Abbreviations: At, *Arabidopsis thaliana* L.(thale cress); Cas, CRISPR-associated; Ci, *Cichorium intybus* L. var. sativum (root chicory); CPT, cis-prenyl transferase; CPTL, cis-prenyl transferase-like; CRISPR, clustered regularly interspaced short palindromic repeats; CoA, coenzyme A; DMAPP, dimethylallyl pyrophosphate; DOXP, 1-deoxy-D-xylulose 5-phosphate; DP, degree of polymerization; DP_a, average degree of polymerization; EFSA, European Food Safety Authority; EP, European Parliament; EU, European Union; F, fructose; FDA, US Food and Drug Administration; F-1-P, fructose-1-phosphate; 1-FEH, fructan 0 1-exohydrolase; 1-FFT, fructan:fructan 1-fructosyl transferase; FPP, farnesyl diphosphate; FOS, fructo-oligosaccharide; FDCA, 2,5-furan-dicarboxylic acid; G, glucose; G-1-P, glucose-1-phosphate; GE, genome editing; GF, glucose-fructose (=sucrose); GFF, glucose-fructose-fructose) (=1-kestose); GM, genetic modification; GPP, geranyl diphosphate; GRAS, generally recognized as safe; HMF, 5-hydroxymethyl-furfural; Hb, *Hevea brasiliensis* (Willd. Ex A.Juss.) Muell.Arg (rubber tree); ICBN, International Code of Botanical Nomenclature; IPP, isopentenyl pyrophosphate; MEP, methylerythritol phosphate; MVA, mevalonate; MW, weight-average molecular weight; NBT, new breeding techniques; NGT, new genomic techniques; NR, natural rubber; PEF, polyethylene furanoate; PET, polyethylene terephthalate; QTLs, quantitative trait loci; REF, rubber elongation factor; RT, rubber transferase; RTA, rubber transferase activator; RP, rubber particle; SALB, South American leaf blight; SSI, sporophytic self-incompatibility; SR, synthetic rubber; SRPP, small rubber particle protein; 1-SST, sucrose:sucrose 1-fructosyl transferase; t, (metric) tonne(s); Tb, *Taraxacum brevicorniculatum*; Tk, *Taraxacum koksaghyz* (rubber dandelion); Tm, *Taraxacum mongolicum* (Mongolian dandelion); To, *Taraxacum officinale* (common dandelion).

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strategies to accelerate the adoption of *Tk* as a viable, sustainable source of NR and inulin-based green chemicals. Future research directions are defined to target the remaining challenges in upscaling cultivation and integrating *Tk* into sustainable agricultural systems.

1. Introduction

The root of *Taraxacum koksaghyz* Rodin (IPNI, 2025), abbreviated as *Tk*, has long been considered a potential source for natural rubber (NR; Fig. 1A) and inulin (Fig. 1B) (van Beilen and Poirier, 2007a, 2007b). Currently, the primary source of NR is the rubber tree (*Hevea brasiliensis* (Willd. Ex A.Juss.) Muell.Arg. (IPNI, 2025), abbreviated as *Hb*, also known as the para rubber tree. Rubber is a vital chemical commodity in society, essential for transportation (e.g., tires), various industrial applications (e.g., conveyor belts), and everyday use (e.g., condoms, footwear) (Ikeda et al., 2024). Inulin is the primary storage carbohydrate in the root of *Tk*. It is a linear polysaccharide from the class known as fructans (Ni et al., 2024). Its applications include use as a dietary fiber (Qin et al., 2023b), low-calorie sweetener (Tsatsaragkou et al., 2021), or as a fructose source for the production of (bulk) chemicals (Sousa et al., 2015; Zhang et al., 2024a). Over two-thirds of the world's industrial inulin now comes from the roots of root chicory (*Cichorium intybus* L. var. *sativum*), abbreviated as *Ci* (SRD, 2024). Table 1 compares *Tk* with its main plant alternatives, *Hb* for NR, and *Ci* for inulin.

In this review, we examine how to transform *Tk* into a commercially viable alternative for the sustainable production of NR and inulin. We consider advances in breeding, agricultural biotechnology, agronomy, and bioprocessing. We integrate current knowledge and developments to outline the prospects and challenges for the future use of *Tk* as a new crop.

1.1. The security of supply of NR and SR

Global rubber production was 28.8 million metric tons (Mt) in 2023, a slight decrease from 2022 (MRC, 2024). Of this, 51 % was NR (MRC, 2024). Its production volume surpassed oil-based synthetic rubber (SR) for the first time in over half a century. Since the early 1960s, SR production has exceeded NR production (Gent, 2023). Approximately 90 % of the world's NR production is now in Southeast Asia, with Thailand accounting for about one-third (SRD, 2024). The global market size for both NR and SR is forecast to grow (MI, 2024b).

Today, the security of the NR supply may again be at risk, similar to the supply risks the world faced around World War II. From the beginning of its cultivation, *Hb* has been highly susceptible to the fungal leaf blight known as South American leaf blight (SALB) (Kuyper, 1911; Ulu, 1906). SALB is caused by the ascomycete *Pseudocercospora ulei*, formerly *Microcyclus ulei* (da Hora Júnior et al., 2014). It is a close relative of the well-studied wheat pathogen *Zymoseptoria tritici*, formerly *Mycosphaerella graminicola* (Amezrou et al., 2024; Goodwin et al., 2011). Mainly due to SALB (and some other issues), *Hb* disappeared as a plantation crop from its origin in South and Central America at the end of the 19th century. NR production was relocated to Asia. The genetic basis of commercial *Hb* cultivars for resistance against SALB is narrow (Guyot and Guen, 2018; Shitiri and Johar, 2024), creating a situation similar to the case of *Fusarium* wilt (Panama disease) in clonal (Cavendish) banana (*Musa* spp. (Drenth and Kema, 2021)). Data suggests that it may only be a matter of time before Asian *Hb* plantations are also affected by SALB, a scenario considered 'the rubber industry's worst nightmare' for almost three decades now (Davis and Moore, 1997; Guyot and Guen, 2018). Despite similar climatic conditions to those in South America (Roy et al., 2017), the consistent absence of SALB from Asia may demonstrate the efficacy and success of the strict phytosanitary and other biosecurity measures in place (APPPC, 2012). However, continuous vigilance remains essential (Khetarpal et al., 2024). Besides, the high vulnerability of NR production is considered a potential target for bioterrorism (Onokpise and Louime, 2012). Breeding of *Hb* for SALB resistance is progressing but remains challenging and time-consuming (Cardoso et al., 2014; Priyadarshan, 2017; Sterling et al., 2021). In addition to SALB, *Hb* is susceptible to various other diseases that may affect cultivation and yield. These also require attention to safeguard supplies (Chen et al., 2023b; Solpot et al., 2024).

NR is harvested from the bark of *Hb*. The harvesting process is predominantly manual and therefore resource- and labor-intensive. Production costs are rising (SA, 2024) and mechanization is challenging (Shukoor et al., 2024; van Beilen and Poirier, 2007c). Also of

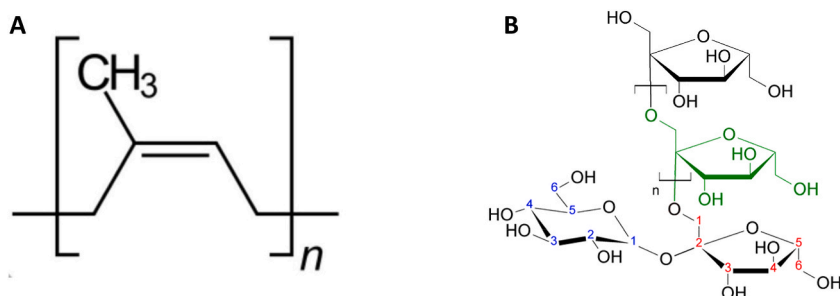


Fig. 1. Chemistry of natural rubber (NR) and inulin from *Tk*. A. Natural rubber (NR). The main component of *Tk* NR is the *cis*-1,4-isoprene unit, or 2-methyl-1,3-butadiene, that comprises over 99 % of the NR molecule with $n = \sim 30,000$; B. Inulin. The characteristic polysaccharide chain consists of $\beta(2-1)$ linked fructose units. In *Tk*, $n = \sim 13$ (DPa ~ 16). See the text for details. Images obtained and adapted from Wiki Commons.

Table 1
Comparison of *T. koksaghyz* with its main competitors in the production of NR and inulin.

Common name	rubber tree	rubber dandelion	root chicory
General			
botanical name (IPNI, 2025)	<i>Hevea brasiliensis</i> (Willd. ex A.Juss.) Müll.Arg.	<i>Taraxacum koksaghyz</i> L.E.Rodin	<i>Cichorium intybus</i> L. (subsp. <i>sativum</i> (Bisch.) Janch. or subsp. <i>intybus</i>) Asteraceae
plant family (IPNI, 2025)	Euphorbiaceae	Asteraceae	Asteraceae
first description (IPNI (2025))	1865	1933	1753 (subsp. <i>sativum</i> 1959)
area of origin (POWO (2024))	South America	Central Asia, Mongolia	Europe, Middle East, Central Asia, North Africa
field appearance	perennial tree Priyadarshan (2017)	annual/biennial rosettes van Dijk et al. (2010)	perennial/biennial/herbaceous (Hilbert and Rambaud, 2023)
Target product	natural rubber		inulin
chemical name	<i>cis</i> -1,4-polyisoprene Ikeda et al. (2024)		(inulin-type) oligo/polyfructan Mensink et al. (2015)
basic structure	(C ₅ H ₈) _n van Beilen and Poirier (2007a)		GFF _n or C _{6n} H _{10n+2} O _{5n+1} (Mensink et al., 2015; Tresina et al., 2022)
MW (kDa)	~1300 (van Beilen and Poirier, 2007a); 1600–2000 (Sengloyluan et al., 2025)	~2200 van Beilen and Poirier (2007a)	~2 (with n = 13)
# units (n)	~18,000 van Beilen and Poirier (2007a)	~32,000 (based on above MW)	~4 (Mensink et al., 2015) (with n = 25)
DPa	n.a.	n.a.	~15–16 (Hahn et al., 2016) ~8–18 (van Arkel et al., 2012)
source (Venkatachalam et al., 2013)	bark	root	root
production location	Southeast Asia Priyadarshan (2017)	worldwide temperate regions (Salehi et al., 2021)	Europe, South Africa, China, India (Gordon et al., 2018)
production area (ha)	~13,575,000 (2023) FAO (2025)	~67,000 (1950-SU) (Venkatachalam et al., 2013); 0 (2024)	~26,500 (2024) ^a
annual production (kt/yr)	~14,757 (2023) FAO (2025)	~3 (1943) (van Beilen and Poirier, 2007a); 0 (2024)	n.a.
productive years	~25–30 (from age ~ 5–7) (Widyarani et al., 2017)	1 Kreuzberger et al. (2016)	~185 (2024) ^a
content (g/g)	~0.36 (An et al., 2015) (FW latex); ~0.85 (Jayanthi and Sankaranarayanan, 2005) (DW latex)	0.05–0.30 (Luo et al., 2018) (DW root)	~0.35 (Hahn et al., 2016) (DW root)
reported yield (kg/ha/yr)	~500–1350 (Priyadarshan, 2017; SRD_2, 2024; van Beilen and Poirier, 2007a)	~200 (Sørensen, 2017); 32–62 (Kreuzberger et al., 2016)	~130–200 Kreuzberger et al. (2016)
suggested potential yield (kg/ha/yr)	~3000 (Priyadarshan, 2017; van Beilen and Poirier, 2007a) - ~ 12,000 (Tang et al., 2016)	~750–1138 (Luo et al., 2018; Sørensen, 2017)	~7000 Sensus (2017)
Genetics/ biotechnology	amphidiploid Priyadarshan (2017)	diploid Luo et al. (2018)	diploid Cadalen et al. (2010)
compatibility	SC/LSI (da Costa et al., 2000; Sedgley, 1994)	SSI Wollenweber et al. (2021)	SSI Cadalen et al. (2010)
Karyotype	2n = 4x = 36 Triwitayakorn et al. (2011)	2n = 2x = 16 Schuchovski et al. (2020)	2n = 2x = 18 Cadalen et al. (2010)
Propagation for production	clones (Masson and Monteuis, 2017; Priyadarshan, 2017)	seed Kreuzberger et al. (2016)	seed Sensus (2017)
GM/GE technology	+ (Blanc et al., 2006; Jayashree et al., 2018)J/+ (Yang et al., 2024b)	+ (Lankitus et al., 2023; Stolze et al., 2017)/+ (Ariyaratne et al., 2023; Iaffaldano et al., 2016)	+ (Maroufi et al., 2018)J/+ (Bernard et al., 2019; Salvagnin et al., 2023)
public genome assembly	+ (Fang et al., 2024; Lau et al., 2016; Tang et al., 2016; Wuyun et al., 2018)	+ (Lin et al., 2018, 2022)	+ (Fan et al., 2022; Shen et al., 2023; Waegneer et al., 2023)
haploid genome size (Gb)	~1.5 Fang et al. (2024)	~1.1 Lin et al. (2022)	~0.9–1.3 (Fan et al., 2022; Shen et al., 2023; Waegneer et al., 2023)

Abbreviations: CR, chicory root; DP_n, average degree of polymerization; DW, dry weight; FW, fresh weight; GE, genome editing; GM, genetic modification; LSI, late-acting self-incompatibility; MW, (weight-average) molecular weight; n.a., information or data not (yet) applicable or available in the public domain; SC, self-compatible; SSI, sporophytic self-incompatible; SU, Soviet Union.

* The 2023 FAOSTAT information on Ci (FAO, 2025) seems incomplete. Estimate based on public domain data of the market size of Ci inulin (72 % of USD 1.8 billion), its bulk wholesale price (USD 7/kg), and average yield (7000 kg/ha).

concern are the environmental impacts of NR production, such as deforestation (Wang et al., 2023a), land use, and its overall sustainability (Ahrends et al., 2015; Marrero Nunes et al., 2025; Verhofste et al., 2024). Due to market dynamics and competition with SR, NR prices are closely linked to fossil oil prices, resulting in their high volatility (Ramli et al., 2019; Sungkaew, 2024). As a result of these factors, palm oil production tends to become more attractive and profitable for (small-scale) farmers than the production of rubber. Therefore, *Hb* plantations are increasingly replaced by oil palm plantations despite the substantial environmental issues of the latter (Jayathilake et al., 2023). Moreover, the number of *Hb* rubber/latex allergy cases is increasing (Gurlek, 2024), justifying the development and use of alternatives with reduced or no allergenic properties relative to *Hb* NR.

In addition to NR, the SR supply also faces future challenges. The production of SR is oil-based and energy-intensive (Batten et al., 2021). Wherever possible, fossil oil use should transition to renewable biobased alternatives. This transition is due to CO₂ emissions related to global warming, climate concerns, and agreed-upon policies (IPCC, 2023). In the process of discouraging the use of petroleum resources, alternatives need to be considered. Also, the costs of SR are expected to rise (Miller and Sorrell, 2014; Wang et al., 2023b).

The lack of NR-based medical gloves in both Europe and the USA during the COVID-19 pandemic (2019–2020) demonstrated the vulnerability of global supply chains. It prompted the development of policies to mitigate such an undesired situation (Aigbogun, 2023). In 2020, the European Union (EU) declared NR a 'critical raw material,' which emphasized its economic importance and highlighted the potential vulnerability of the supply. The EU identified the need for a secure, sustainable, and preferably domestic supply of NR (EC, 2020), in line with earlier such calls (Mooibroek and Cornish, 2000). In the USA, similar concerns are in place (Puskas et al., 2024). A research center called TARDISS (Transformation of American Rubber through Domestic Innovation for Supply Security) recently started at Ohio State University (USA) to focus on securing the local supply of NR for the North American market (TARDISS, 2025). For any local supply, sustainable alternatives for *Hb* NR are warranted.

1.2. Alternative sources for the production of NR

In plants, NR is produced as rubber particles (RPs) in latex, a milky colloidal suspension (emulsion) in water. Over 20,000 plant species in ~40 families can produce latex (Lewinsohn, 1991). It is supposed to offer protection against phytophagous insects by expelling ('bleeding') and coagulation (Huber, 2024). Only a subset of about 1800 (van Beilen and Poirier, 2007b) to 2500 plant species (Mooibroek and Cornish, 2000) have NR in their latex. Although NR's precise biological role is unclear, available data suggest that it reduces insect herbivory and affects the microbial ecosystem around the root (Böttner et al., 2023).

In surveys of NR-producing plant species (Bowers, 1990; Schütz et al., 2006; Ulmann, 1951; Venkatachalam et al., 2013), the shrub guayule (*Parthenium argentatum* A. Grey) and *Tk* were identified as promising alternatives for NR (van Beilen and Poirier, 2007a). In recent years, garden lettuce (*Lactuca sativa* L. (Reyes-Chin-Wo et al., 2017; Tan et al., 2023)) has resurfaced as an alternative after earlier attention to this species (Bushman et al., 2006). The same applies to its close relative, prickly lettuce (*Lactuca serriola* L. (Bell et al., 2015; Yang et al., 2023)). Mountain gum (*Takhtajianantha tau-saghyz*, formerly *Scorzonera tau-saghyz* (Zaika et al., 2020)), has also been put forward as an alternative (Puskas et al., 2024), as was *Taraxacum bicorne* Dahlst (Zeisek et al., 2019). and several more (Rasutis et al., 2015). Before *Hb*, the Panama rubber tree (*Castilla elastica* Cerv.) was used (Metcalf, 1967) and may deserve reevaluation. The hardy rubber tree (*Eucommia ulmoides* Oliv.) produces an NR type chemically distinct from *Hb* and *Tk* NR, commonly referred to as *trans* rubber (Yang et al., 2023), which may complement these for some specialty applications (Liu et al., 2022b; Yang et al., 2023). Further exploration of plant diversity is likely to reveal other interesting candidates for rubber production.

NR has never been detected in prokaryotes (Steinbüchel, 2003), but a few fungal species produce relatively short-chain NR-like compounds (Stewart et al., 1955). Bioreactor technology and biotechnology involve genetically modifying microorganisms such as yeast to produce NR-like polyisoprene. These are in the early stages of development (Liu et al., 2022a). Similarly, technologies and organisms are in place for the production of biobased isoprene as a platform chemical for the chemical production of SR (Isar et al., 2022; Wang and Yang, 2017). Such developments may offer promising alternatives in the future, but will likely require much longer time-to-market efforts.

All options except guayule and *Tk* are currently theoretical or in the early stages of research and development. Their potential contribution to a viable NR supply chain requires further analysis. *Tk* produces NR of a quality equal to or surpassing that of *Hb* rubber (Table 1). Besides, it has more favorable agronomic characteristics than guayule (van Beilen and Poirier, 2007b) and has a history of earlier use. Its cultivation and processing systems offer biotechnological advantages over *Hb* NR production. Therefore, *Tk* is currently the most promising alternative for a commercially viable production of NR (DRIVE4EU, 2018; Salehi et al., 2021; Tan et al., 2023).

1.3. Characteristics of *Tk* as a crop for NR

1.3.1. Biological and biotechnological characteristics

Tk is a species in the genus *Taraxacum*, family Asteraceae (Asteraceae: Chicorieae, sect. *Ceratoidea* (Kirschner et al., 2015)). There are some issues with the names of *Tk*. The botanical name was originally hyphenated as *T. kok-saghyz*. It should be corrected to

T. koksaghyz as orthographic standardization (and not a taxonomic revision) based on Article 60.9 of the International Code of Botanical Nomenclature (ICBN) (van Dijk et al., 2010). However, the hyphenated *T. kok-saghyz* is still widely used (IPNI, 2025). The common name for the plant can be either Kazakh dandelion (the epithet 'kok-saghyz' derives from two Kazakh words) or Russian dandelion (as Kazakhstan was part of Russia at the time of its first description). To avoid any geopolitical sensitivities, the designation 'rubber dandelion' is increasingly being used as a common name, as we do here (Table 1).

The overall taxonomy of the genus *Taraxacum* is complex due to the frequent occurrence of hybridization and considerable morphological plasticity. Also, there is a co-existence of different (sexual and asexual) reproduction strategies. These strategies comprise (a) sporophytic self-incompatibility (SSI) (Tas and Van Dijk, 1999), in which the mother plant determines the mating type of pollen; (b) clonal seed production (apomixis), which is generally diplosporous (i.e., incomplete meiosis); (c) gametophytic (parthenogenic) and (d) autonomous (i.e., endosperm development without pollen) self-incompatibility (Tas and Van Dijk, 1999); as well as (e) different levels of ploidy, notably triploidy ($2n = 3x = 24$) (Iaffaldano et al., 2017; van Dijk et al., 2010);). Within this spectrum of genetics, *Tk* presents a relatively simple case (van Beilen and Poirier, 2007b). It is a perennial diploid ($2n = 2x = 16$), usually growing as an insect-pollinated biennial plant. It has, as far as is known, an exclusively sexual mode of reproduction, in combination with SSI to prevent self-fertilization (Wollenweber et al., 2021). *Tk* has a taproot system, of which the primary root is less prominent than that of its close relative, the well-known garden weed common dandelion, *Taraxacum officinale* (*To*).

The foundation for a systematic improvement of *Tk* by breeding and biotechnology has been firmly established (Kuluev et al., 2023). Progress is based on the availability of proper germplasm, genetic variability, and the use of modern genome biotechnology. Much data, such as whole genome sequences, transcriptome, and differential expression data (Cao et al., 2017; Luo et al., 2017), plastome resources (Zhang et al., 2017), genetic linkage maps (Arias et al., 2016a), quantitative trait loci (QTLs), omics data for traits-of-interest, and various types of (potential) markers (Arias et al., 2016a; McAssey et al., 2016; Nowicki et al., 2019), are available for the analysis of germplasm and the screening of offspring. *Tk* has a reported haploid genome assembly size of about 1.1 Gb, with relatively high repeat content and heterozygosity, likely due to its SSI (Lin et al., 2018, 2022).

In addition, *Tk* is readily amenable to the toolbox of agricultural biotechnology. This toolbox includes tissue culture (Benzle and Cornish, 2017) and genetic modification (GM). The latter involves *Agrobacterium rhizogenes* to produce hairy roots or hairy root-derived transgenic plants (Zhang et al., 2015), or *Agrobacterium tumefaciens* for the production of transgenic plants (Stolze et al., 2017; Yang et al., 2024a). More recently, genome editing (GE) with CRISPR/Cas technology has also become available (Iaffaldano et al., 2016). Comparative genomics with the genomes of related species is giving additional leads for understanding and improving *Tk* (Chen et al., 2023a). Available for comparison are the genomes of *To* (contains inulin but no rubber), a diploid with a haploid genome assembly of about 0.94 Gb (Xiong et al., 2023), and of *Taraxacum mongolicum* (*Tm*, Mongolian dandelion, which contains inulin but no rubber), an agamosperous triploid with a haploid genome assembly of about 0.79 Gb (Lin et al., 2022).

1.3.2. Industrial interest in *Tk* NR

Tk was already cultivated in the Soviet Union, the United States of America, and Western Europe around World War II (~1930–1952). It was used as an alternative crop for NR production due to geopolitical supply risks. After World War II, the interest in *Tk* NR declined because *Hb* NR from Southeast Asia was cheaper. Besides, lower-cost oil-based SR became widely available. As a result, *Tk* research and cultivation programs were discontinued, and knowledge, plant material, and expertise were largely lost. A few older monographs and papers provide access to data from original scientific papers that are sometimes difficult to access. These summarize the knowledge generated up to 1952 (Bonner and Galston, 1947; Polhamus, 1962; Ulmann, 1951; Whaley and Bowen, 1947). Access to literature in the Russian language (e.g., as cited in (van Dijk et al., 2010)) is available through the monograph especially prepared for that purpose (Krotkov, 1945).

An unfortunate setback for the renewed interest in *Tk* as a rubber producer was the finding that *Tk* germplasm used for investigations had been misidentified and contaminated (Kirschner et al., 2013). As a result, a substantial body of research on presumed *Tk* material was performed with *Taraxacum brevicorniculatum* (*Tb*). This close relative is a relatively poor rubber-producing triploid apomict (Kirschner et al., 2013). Therefore, research published on *Tk* until about 2014 may concern *Tb* or mixtures of the two species. Although *Tb* may be a valid model system for rubber biosynthesis (Zhang et al., 2015), its genetic composition differs. It is unclear whether the rubber metabolism in *Tb* is identical to that in *Tk*; subtle species-specific differences may exist (Cornish, 2014). New expeditions into the areas of origin of *Tk*, mainly in Kazakhstan, have reintroduced proper *Tk* material for research and breeding (DRIVE4EU, 2018; van Dijk et al., 2010; Volis et al., 2009). In its centers of origin, it was reported as a relatively common species (van Dijk et al., 2010), despite suggestions to the contrary (Volis et al., 2009). In Kazakhstan, *Tk* is currently considered a rare and endangered species (Akhmetova et al., 2018).

Advances in molecular life sciences, biotechnology, and breeding research have supported the domestication of *Tk*. These advances have helped to develop *Tk* as a crop in both laboratory and field settings. Numerous research groups and private parties in the various temperate zones of the world (Canada, China, EU, Russia, and USA) are currently or have been in the process of redeveloping *Tk* as a crop for NR production (Cornish, 2017; DRIVE4EU, 2018; Gronover and Prüfer, 2010; Salehi et al., 2021; TARDISS, 2025).

2. NR from *Tk*

2.1. Molecular characteristics and uses of NR

NR is a polymer of *cis*-1,4-isoprene units $(C_5H_8)_n$ (Fig. 1A; Table 1), with *n* ranging from 150 to about 2 million. The high quality of *Hb* and *Tk* NR is due to their exceptionally high stereo-regularity (99.99 %), combined with the long length of the poly-isoprene chains:

the *cis*-1,4-polyisoprene contains only two or three monomeric *trans*-1,4-isoprene units, mainly located at the end of the linear chain (Ikeda et al., 2024). This structure can be considered a naturally occurring nanocomposite (Kawahara, 2023). The presence of other organic compounds (proteins, (phospho)lipids) and salts also contributes to the properties and quality of NR (Luo et al., 2025; Wang et al., 2022). To further enhance its longevity, the characteristics of NR, such as robustness, thermal stability, and chemical resilience, are improved through vulcanization. This is a chemical process that involves heating with sulfur to create additional cross-links (Wemyss et al., 2020). Currently, most NR used commercially is vulcanized.

Although *Tk* and *Hb* NR have an identical poly-isoprene backbone structure, subtle chemical differences may occur that can impact processing and end-use properties. Both the weight-average molecular weight (MW) and molecular weight distribution of *Hb* rubber vary considerably among *Hb* clones (Sengloyluan et al., 2025). RP size also impacts its properties (Payungwong et al., 2024). For both species, the particular extraction method used influences the properties of the rubber. Depending on the extraction technology used, *Tk* NR closely resembles *Hb* NR with respect to its mechanical properties and molecular composition, such as molecular weight distribution, crystallinity, and cross-linking network (Naghavi et al., 2023; Zheng et al., 2025). The crystallization and network characteristics are important for high-performance NRs (Kong et al., 2025; Nie et al., 2017). Therefore, the uses and applications of both NRs overlap and concern tires (bicycles, cars, planes), medical, and industrial goods. A notable difference between *Tk* and *Hb* rubber is the lower protein content of *Tk* latex (Liu et al., 2024a). It likely explains the hypoallergenic properties of *Tk* rubber relative to the well-documented allergenicity of *Hb* rubber.

(Gurlek, 2024; Vandenplas and Raulf, 2017). However, *Tk* rubber contains proteins that cross-react with *Hb* allergens that could contribute to allergenicity (Cornish et al., 2015). More research to confirm the relative safety and the actual allergenicity of *Tk* rubber or its intended products is warranted (Dafoe et al., 2017).

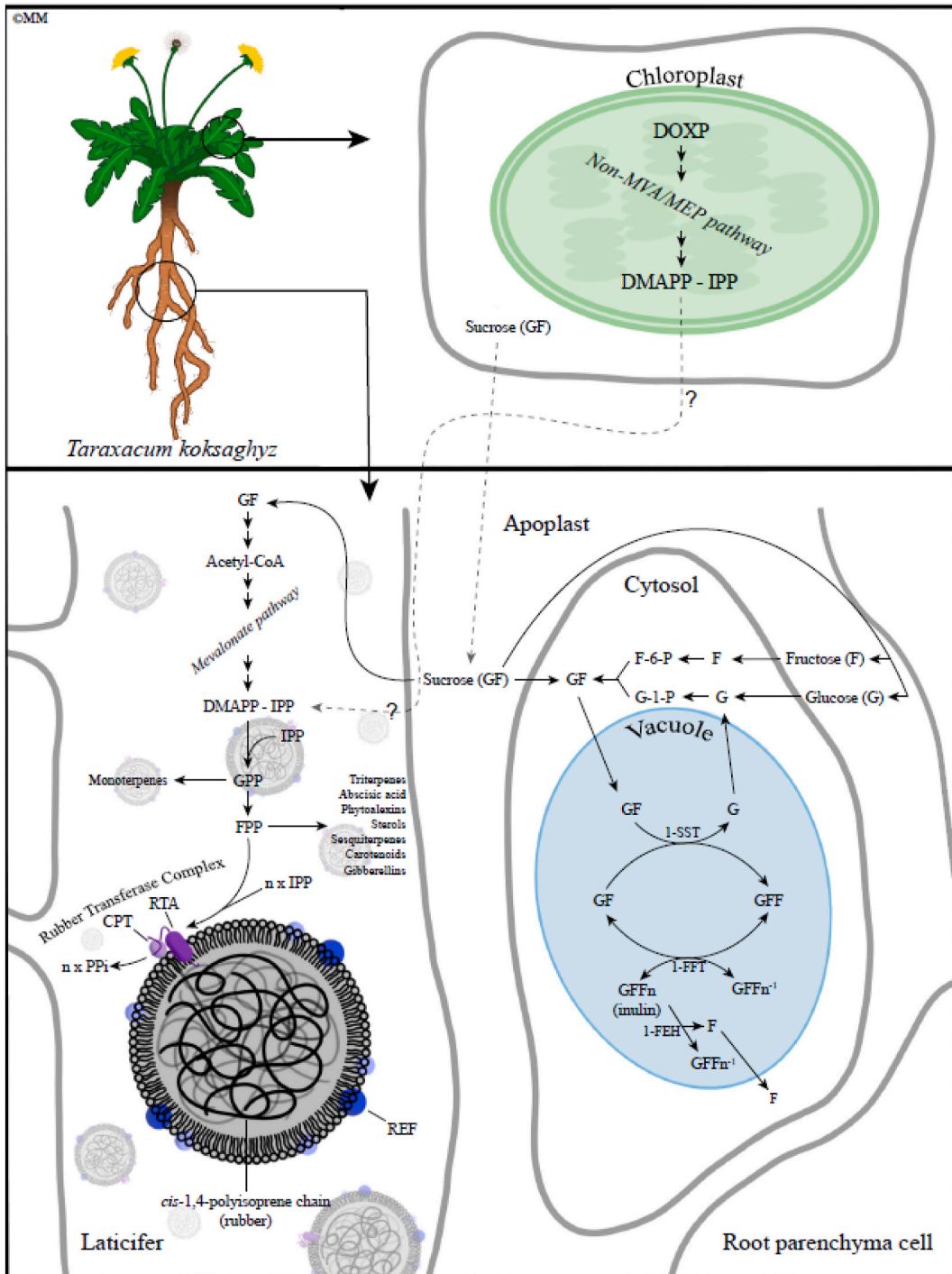
The chemical synthesis of SR has not yet been able to reproduce the high stereoregularity of NR. Approximately 60 different SR types are distinguished based on their chemical composition, comprising eight main groups (ASTM, 2022), such as a random copolymer of styrene and butadiene (Ikeda et al., 2024). Most of these SR types also undergo vulcanization. One SR type, known as polyisoprene or isoprene rubber, comprises the same isoprene units as NR. Still, its stereo-regularity does not exceed 98 % (Ikeda et al., 2024), and it has a seemingly random distribution of *trans*-units. Both characteristics impact its properties (Candau et al., 2016). Relative to this SR, NR has superior quality concerning abrasion, elasticity, heat performance, and other properties, so for many applications, NR cannot be adequately substituted by this particular SR (Ikeda et al., 2024). Other SR types outperform NR in terms of aging due to their better resistance to sunlight, oxygen, high temperatures, or specific chemicals. These SR types are used for specialty applications (Ikeda et al., 2024). Adding nanomaterials to SR preparations may bring the properties of particular SR types and NR closer together (Cruz-Morales et al., 2023).

2.2. Biosynthesis of NR

The biosynthesis of NR in *Tk* is well documented, although some understanding is inferred from analyses of rubber formation in *Hb* (Florez-Velasco et al., 2024; Yamashita and Takahashi, 2020). For more details, we refer to comprehensive summaries of the biochemical aspects (Cherian et al., 2019; Salehi et al., 2021). Like in *Hb*, rubber biosynthesis in *Tk* occurs in specialized cells called laticifers (Fig. 2). Laticifer cells are widely distributed throughout the plant kingdom. They are characterized by their complex anatomy, physiology, and phylogeny (Johnson et al., 2021). The main distinction is between articulated and non-articulated types. Articulated laticifers develop from multiple cells, of which the dividing walls dissolve. Non-articulated laticifers are thought to have a single-cell origin (Johnson et al., 2021). *Tk* contains the articulated type (Benninghaus et al., 2020), as does the mature *Hb* (Tan et al., 2019). Rubber biosynthesis begins with the general central metabolism, involving glycolysis, which converts photosynthesis-derived sugars into pyruvate (Fig. 2). Acetyl-CoA, formed by the pyruvate dehydrogenase complex, is the first building block and enters the cytosolic mevalonate (MVA) pathway (Cornish, 2014). Through a series of enzymatic condensation reactions, the isoprenoid building blocks of isopentenyl pyrophosphate (IPP) and its isomer dimethylallyl pyrophosphate (DMAPP) are formed. These can be quantified and followed (Zhang et al., 2018). All enzymes of the MVA pathway are present in the latex of both *Tk* and *Tb*, and the corresponding genes are cloned (Van Deenen et al., 2012; Wahler et al., 2012).

An alternative pathway for the biosynthesis of the isoprenoid building blocks occurs in the plastid (Fig. 2). This alternative is the methylerythritol phosphate (MEP) or non-MVA pathway (Bergman et al., 2024). Gene expression studies showed that all the genes encoding the enzymes of the MVA pathway are highly expressed in *Tk*, in contrast to most genes of the MEP pathway (Lin et al., 2018), as was also shown to be the case in *Hb* (Makita et al., 2017; Sando et al., 2008). Moreover, RNA interference (RNAi), which down-regulates a key enzyme in rubber synthesis, resulted in the knockdown of a rate-limiting enzyme in the MVA pathway and markedly reduced rubber production (Niephaus et al., 2019). Therefore, the MVA pathway is likely the dominant pathway for rubber production in the *Tk* root tissue. Tracer experiments in *Hb* had earlier indicated that the MVA pathway drives rubber biosynthesis (Bandurski and Teas, 1957). However, cross-talk between the MVA and MEP pathways may also affect rubber biosynthesis. The same is true for contributions of the MEP pathway to DMAPP/IPP synthesis in photosynthesizing tissues, or for other inter-pathway exchanges of intermediates (Cherian et al., 2019; Rodríguez-Concepción and Boronat, 2015; Salehi et al., 2021; Vranová et al., 2013).

In a series of chemical conversions, IPP and DMAPP generate farnesyl diphosphate (FPP; C15), which undergoes iterative rounds of *cis*-1,4 polymerization with IPP (Cornish, 2014) to result in the rubber molecules of NR (Fig. 2). Both the ratio and the concentration of FPP and IPP can promote the synthesis of long-chain rubber. Higher IPP concentrations increase the amount and the length of rubber polymer in both *Hb* and guayule (Cherian et al., 2019; Cornish, 2001b). In *Tk*, a similar regulation may determine the length of the rubber molecule. Isoprenoids, also known as terpenoids, are a versatile class of many (well over 80,000) secondary metabolites in plants (Bergman and Dudareva, 2024; Singh et al., 2024; Zeng et al., 2022). They include the carotenoids and chlorophylls in leaves.



(caption on next page)

Fig. 2. Biosynthesis of natural rubber (NR) and inulin in the root of *Tk*: pathways and pathway cross-talk. In the *Tk* root, NR (*cis*-1,4-polyisoprene) is synthesized in the cytosol of laticifer cells, and inulin (GFF_n) in the vacuole of neighboring root parenchyma cells. The intermediates for the biosynthesis of NR and a wide variety of other terpenoids, DMAPP-IPP, are synthesized in leaf chloroplasts via the non-MVA or MEP pathway and in laticifer cells via the MVA pathway. Transport of DMAPP-IPP from the chloroplast to the laticifer, if any, is unknown, indicated with dashed lines and question marks. Cross-talk between the two metabolisms is hypothesized to be mediated by sucrose. See the text for details. Consecutive arrows indicate the occurrence of multiple enzymatic steps. Modified and extended after (Stolze et al., 2017). Abbreviations: CPT, *cis*-prenyl transferase; CoA, coenzyme A; DMAPP, dimethylallyl pyrophosphate; DOXP, 1-deoxy-D-xylulose 5-phosphate; F, fructose; F-1-P, fructose-1-phosphate; 1-FEH, fructan 1-exohydrolase; 1-FFT, fructan:fructan 1-fructosyl transferase; FPP, farnesyl diphosphate; G, glucose; G-1-P, glucose-1-phosphate; GF, glucose-fructose (=sucrose); GFF, glucose-fructose-fructose (=1-kestose); GFFn, inulin; GPP, geranyl diphosphate; IPP, isopentenyl pyrophosphate; MEP, methylerythritol phosphate; MVA, mevalonate; Ppi, pyrophosphate; REF, rubber elongation factor; 1-SST, sucrose: sucrose 1-fructosyl transferase.

Biosynthesis of any of these may compete for the precursors of rubber synthesis (Bergman et al., 2024; Cao et al., 2017).

Concomitantly with rubber biosynthesis, rubber molecules in the cytoplasm emulsify with lipids to form the RP. These lipids likely originate from the Golgi and endoplasmic reticulum (Cornish, 2001a; Salehi et al., 2021). An RP comprises rubber molecules surrounded by a lipid monolayer (Fig. 2). New rubber molecules are synthesized on the surface of an RP, increasing its size. A large variety of proteins is present in RPs (Salehi et al., 2021), including all the enzymes involved in rubber biosynthesis and proteins that help to stabilize the RP. A mature RP is transported to the laticifer vacuole for storage. This way, NR is considered a dead-end product; it is neither remetabolized nor degraded by plant enzymes (Men et al., 2019). In *Tk*, some RP formation is also seen in laticifer plastids (Ghaffar and Cornish, 2020), but the functional relevance of this formation needs further analysis.

The isoprene polymerization reaction that makes rubber molecules is catalyzed by rubber transferases (RTs). These are members of the large *cis*-prenyltransferase (CPT) family of plant enzymes (Grabińska et al., 2016). For the detailed description of the *cis*-prenyltransferase family in *Tk* we refer to a recent review (Müller et al., 2025). The RTs constitute a protein complex that is considered the core biosynthetic machinery of rubber biosynthesis (Cornish, 2014; Hillebrand et al., 2012; Laibach et al., 2015), similar to *Hb* (Yamashita and Takahashi, 2020). The complex contains additional proteins known as small RP proteins (SRPPs), rubber elongation factors (REFs), and RT activators (RTAs), also referred to as *cis*-prenyltransferase-like (CPTL) proteins (Fig. 2). Both the SRPPs and the structurally related REFs are located in the RP's membrane and are thought to contribute to proper RP architecture (Hillebrand et al., 2012; Laibach et al., 2015).

Proteomics analyses have shown that SRPPs are the most abundant proteins in the latex of *Tb* (Wahler et al., 2012) and *Hb* (Tong et al., 2017). The SRPP genes in *Hb* and *Tk* were shown to belong to different monophyletic groups, suggesting that the mechanism of RP stabilization may have evolved independently (Lin et al., 2018). Comparative analyses of *Tk* and the non-rubber-producing *Tm* showed expansion of the SRPP and CPT-encoding gene families in *Tk* (Lin et al., 2022), in agreement with their importance in rubber biosynthesis. RTAs/CPTLs have a chaperone-like function in the isoprene polymerization reaction (Epping et al., 2015; Lin et al., 2018). Besides, miRNAs are likely to be involved in regulating the expression of rubber synthesis genes (Karimi et al., 2022; Liang et al., 2023). Other family members of the class of regulatory non-coding RNAs may do so as well (Cao et al., 2024). Various suggestions for the detailed molecular sequence of events in rubber polymerization and its regulation, proposed in the literature (Cherian et al., 2019), remain to be experimentally demonstrated before a comprehensive understanding of rubber biosynthesis is achieved.

Over 100 genes were identified as involved in rubber biosynthesis by transcriptomics and proteomics analyses (Xie et al., 2022). Many of these are members of gene families. Family members are likely to play different roles. For example, based on protein and gene expression analyses, three out of nine oxidosqualene cyclase genes in *Tk* were identified as more important for NR biosynthesis than the other six (Wang et al., 2024b). However, these conclusions may need to be reconciled, given that the downregulation of the expression of (all?) oxidosqualene cyclase genes by RNA interference reduced the triterpene content in *Tk* latex but did not affect rubber biosynthesis (Van Deenen et al., 2019).

3. Inulin from *Tk*

For a viable business case for *Tk* as a future crop, concurrent extraction, marketing, and application of inulin may be crucial (Cornish, 2017; DRIVE4EU, 2018). Northern Europe is currently the world leader in *Ci* inulin production; however, production is on the rise in China and India (FAO, 2025). The world production of inulin was approximately 485,000 tons in 2023. This estimate was calculated based on a market value of \$1.75 billion [145] and an average cost of about \$3600 per ton. Similar to the rubber market, the global inulin market is expected to grow considerably (MI, 2024a). Inulin extraction from *Ci* has developed into a smoothly running industrial endeavor. Any forecasted increase in the demand for inulin may be most easily met by expanding the cultivation area of *Ci*. Therefore, *Tk* inulin is likely to cater to other markets.

3.1. Molecular characteristics of inulin

Inulin is a linear fructan-type polysaccharide that consists of $\beta(2-1)$ linked fructose units. It has a terminal glucose moiety ((sucrosyl)-(fructosyl)_n or GFF_n; n = 1~60/~200; Fig. 1B) (Du et al., 2023; Mensink et al., 2015). The number of carbohydrate units in the inulin polymer, i.e., the degree of polymerization (DP), determines its biological activity and application (Ni et al., 2024). The smallest inulin is 1-kestose, having two fructose units (GFF) with a DP of three. So-called short-chain inulin, also known as oligo-fructose, fructo-oligosaccharide (FOS), or readily fermentable inulin, contains up to ten fructose units (DP \leq 11). Due to synthesis and

degradation, a range of DPs is found within any plant inulin resource. Therefore, a second parameter of use is the average degree of polymerization (DPa) based on the average number of fructose units in a given inulin batch or crop (Mensink et al., 2015).

Over 36,000 plant species have been estimated to contain inulin (Hendry, 1987). It is a storage carbohydrate in stems, tubers, or taproots, but also functions as an osmoregulatory protection against drought, salt, or cold stress (Du et al., 2023; van Arkel et al., 2013). Next to *Ci*, Jerusalem artichoke (*Helianthus tuberosus* L.) and various species of *Agave* contribute to industrial inulin production. Up to 80 % of the dry weight of the chicory root, which is about 20 % of the fresh weight, can be inulin (Puhmann and de Vos, 2020; Vergauwen et al., 2003). *Ci* is a member of the *Asteraceae*, just like *Tk*. *Ci* inulin has a DPa of about 8–18, depending strongly on field conditions and cultivar (Du et al., 2023; van Arkel et al., 2012). In comparison, the inulin of *Tk* has a DPa of about 16 (Hahn et al., 2016), and up to 40 % of the dry weight of the *Tk* root can be inulin (Kreuzberger et al., 2016).

Inulin has various food and non-food applications, associated with multiple health claims, bioactivities, and uses. These are reviewed in detail elsewhere (Correa et al., 2024; Du et al., 2023; Hilbert and Rambaud, 2023; Jackson et al., 2023; Ni et al., 2024; Qin et al., 2023b; Zhang et al., 2024b). For example, due to the β (2-1) linkages between the fructosyl moieties (Fig. 1B), inulin is not metabolized by enzymes in the human upper gastrointestinal tract. It is fermented by the microflora in the colon. This fermentation has promoted its use as a health-promoting dietary fiber (Niness, 1999; Qin et al., 2023b; Riva et al., 2023). Due to its reduced caloric value compared to table sugar (sucrose), while retaining sweetness, inulin is used as a low-calorie sweetener (Tsatsaragkou et al., 2021).

Ci inulin is 'generally recognized as safe' (GRAS) by the US Food and Drug Administration (FDA; GRAS notice 118 (FDA, 2025; Ingredient, 2024)). In Europe, so far, only two health-related claims have been approved for inulin by the European Food Safety Authority (EFSA). These involve the claim that consumption of foods or drinks that contain non-digestible carbohydrates, such as the fructo-oligosaccharides from inulin, reduces the glycemic response after consumption (post-prandial) as compared to sugar-containing foods or drinks (EFSA, 2014). The second claim is that inulin from *Ci* contributes to the maintenance of normal defecation by increasing stool frequency, supporting digestive health (EFSA, 2015). Other health claims await demonstration and approval by the regulatory authorities.

Although *Tk* inulin could be used similarly, its future application in food will have to be evaluated by the EFSA in Europe as 'novel food' and by the FDA in the USA as 'new ingredient.' These evaluations will be independent from the results and conclusions obtained with *Ci* inulin, until inulin gets a more general exemption. Non-food applications may, therefore, present a more straightforward use for *Tk* inulin.

Non-food applications of inulin are generally based on the fructose obtained after inulin hydrolysis (Stökle et al., 2023). It can be converted into a range of high-value products (Tsigoriyna et al., 2024). For example, fructose can be converted relatively easily into 5-hydroxymethylfurfural (HMF) (Liu and Kerton, 2021). HMF is a versatile platform chemical that can be used to generate 2,5-furandicarboxylic acid (FDCA) (Aranha and Bogate, 2023; Sousa et al., 2015; Zhang et al., 2024a). FDCA is a substitute for petroleum (xylene)-based terephthalic acid (1,4-benzene-dicarboxylic acid) that is the precursor for plastic polymers, such as polyethylene terephthalate (PET) (Marshall et al., 2022). Substituting terephthalic acid with FDCA to produce polyethylene furanoate (PEF) yields a better plastic and reduces the greenhouse gas emissions of PET production by more than half (Eerhart et al., 2012). Inulin is also a potential source of polyhydroxyalkanoates (Corrado et al., 2024). This way, *Tk* inulin-derived fructose may become a valuable feedstock for the production of (bulk) chemicals in future biobased green chemistry (Ncube et al., 2023; Sousa et al., 2015).

3.2. Biosynthesis of inulin

The metabolism of inulin in *Tk* is presented in Fig. 2. Its metabolism is highly similar (if not identical) to that in *Ci* (Shen et al., 2023; Stolze et al., 2017; van Arkel et al., 2012) or Jerusalem artichoke (Rubel et al., 2021; van der Meer et al., 1998; Wang et al., 2024a).

First, 1-kestose is made by the enzyme 1-SST (sucrose:sucrose 1-fructosyl transferase) from two molecules of photosynthesis-derived sucrose. The 1-kestose molecule is iteratively used as a fructosyl donor by the enzyme 1-FFT (fructan:fructan 1-fructosyl transferase) for the transfer of fructosyl units to either a second 1-kestose molecule or an already longer molecule. This transfer increases in either case the DP of the recipient molecule by one. The molecular mechanisms that limit or terminate the growth of an inulin molecule are poorly understood, but a dynamic balance between synthesis and degradation is likely at play. Inulin is degraded by the enzyme 1-FEH (fructan 1-exohydrolase) by iteratively hydrolyzing the terminal fructosyl unit (Fig. 2). The DPa is reduced, and inulin is degraded when the plant needs the stored carbohydrates for (re)growth or experiences environmental stress (e.g., cold, heat, water stress, damage, herbivory) (Draga et al., 2023; Mathieu et al., 2018; Vandoorne et al., 2012). In all species considered, multiple genes are present for the biosynthetic and catabolic enzymes involved in inulin metabolism (Lin et al., 2018; Shen et al., 2023; Wang et al., 2024a), suggesting additional layers of complexity in its metabolic regulation.

4. *Tk* products beyond rubber and inulin

Similar to the additional value of inulin, other uses of *Tk* should be considered and may contribute to a (more) positive business case. Multi-use coproduct valorization fits well in the overall concept of modern biorefinery (Kumar and Verma, 2021). The various potential applications documented for the genus *Taraxacum* are summarized in Table 2. Flowers, leaves, and roots, or extracts of these parts, of *To* are associated with pharmaceutical/medicinal uses all over the world. Also, other applications for human well-being are considered (Fan et al., 2023; Martinez et al., 2015; Wu et al., 2024a). Molecular breeding of *To* is feasible (Dinkeloo et al., 2021). Besides, *Tm* is well-known in traditional Chinese medicine, as are various other members of the genus *Taraxacum* (Wu et al., 2024a). Moreover, *Tk* plant material may be a source of valuable proteins or non-proteinaceous chemicals, such as sesquiterpene lactones, polyphenols, and many others. Such use is documented in detail elsewhere (Piccolella et al., 2023; Ramirez-Cadavid et al., 2017).

Other options for *Tk* material are direct use as food or feed (Table 2). Using dandelion material as animal feed is reported to have positive effects (Dong et al., 2024; Mostafavi et al., 2022; Zhang et al., 2024c). *To* could be considered a 'forgotten vegetable' or an underestimated wild edible plant (Shikov et al., 2017; Turner et al., 2011). Its leaves, especially when etiolated, are considered a delicacy in a salad. In the Netherlands, such leaves are known as 'molsla' (Sterk et al., 1987), literally 'mole lettuce.' The culinary value of *Tk* as 'dandelion green' (Alrawajfeh et al., 2017) warrants further examination.

5. Development of *Tk* as a commercial crop

The critical parameter for successfully commercializing *Tk* is consistent yield. Here, yield is defined as the amount of NR, inulin, and any other product available for (industrial) use. In addition to yield, the quality of the product is important, particularly for specialty applications. In addition, health issues may play a role. Hypoallergenic products from *Tk* NR are likely to have added value if the hypoallergenicity is confirmed (Dafoe et al., 2017).

5.1. Target: rubber yield

Breeding of *Tk* aims to generate crop material suited for large-scale cultivation with optimal yield. Over several decades, yields reported for rubber from *Tk* plant material have been highly variable. In guayule, rubber concentration does not correlate well with final rubber yield (Ray et al., 2005), indicating that valid and validated standardized yield assessments must be used. Based on transcript and transcriptome analyses, rubber yield in *Tk* is thought to be largely transcriptionally regulated (Panara et al., 2018), as is the case in *Hb* (Wu et al., 2018). Rubber yield, expressed as the percentage of the root dry weight, varies from 0.5 % to 30 % (Arias et al., 2016c; Buranov and Elmuradov, 2010; Kreuzberger et al., 2016; Luo et al., 2018; Ramirez-Cadavid et al., 2017). Rubber yield expressed as quantity per area, as reported from or inferred for field trials, ranges from approximately 7 to 750 kg/ha (Arias et al.,

Table 2
Alternative uses of *T. koksaghyz* plant material after rubber and inulin extraction.

Material	possible application	Documented in ^a
whole plant	soil improvement	Kabir and Koide (2000)
	biomonitoring (pollution)	(Kuleff and Djingova, 1984; Respondek et al., 2024)
	phytoremediation	Yu et al. (2023)
	bee/bumblebee abundance	(Campbell et al., 2017; Jaiswal and Joseph, 2024; Nichols et al., 2023)
	crop rotation	Guo et al. (2024)
	intercropping	Li et al. (2023)
Above ground leaf/stem	fertilizer amelioration	Mehmood et al. (2022)
	chemicals (various)	Tan et al. (2025)
	food (fresh; processed)	(Nirmala et al., 2022; Shikov et al., 2017)
	feed (various livestock)	(Mao et al., 2022; Qureshi et al., 2017; Zhang et al., 2024c)
	veterinary use	Liang et al. (2021)
	antimicrobial use	Díaz et al. (2018)
	(folk) medicine/health ^b	(Cheng et al., 2024; Mopuri and Islam, 2017)
	cosmetics	(Tetty et al., 2012; Xie et al., 2018)
	bioprotection	Gatto et al. (2011)
	germination inhibitor	Gyenes and Béres (2006)
	biochar production	Mehmood et al. (2022)
flower	biofortification	Cheng et al. (2024)
	polysaccharides	Liu et al. (2024b)
	chemicals (various)	Molinu et al. (2019)
	food	Nirmala et al. (2022)
	(folk) medicine/health ^b	Keller (2001)
	dandelion wine	(Otunola and Afolayan, 2023; Wright et al., 2007)
	medicine	(Hu and Kitts, 2004, 2005)
	glycopeptides	Astafieva et al. (2015)
	polysaccharides	Liu et al. (2024b)
	cosmetics	Lee et al. (2020)
seed	Milovanovic et al. (2022)	
Below ground root	chemicals (various)	
	protein	Ramirez-Cadavid et al. (2017)
	chemicals (various)	(Petkova et al., 2017; Ramirez-Cadavid et al., 2017; Tan et al., 2025)
	antimicrobial	Kenny et al. (2015)
	antifungal	Zang et al. (2025)
	biogas	van Beilen and Poirier (2007b)
	tea	Dinkeloo et al. (2021)
	feed	Yu et al. (2022)
	cosmetics	Herman and Herman (2023)

^a not exhaustive.

^b Including traditional medicine (Chinese; other).

2016c; Bonner and Galston, 1947; Cornish et al., 2016; Kreuzberger et al., 2016; Kupzow, 1980; Sørensen, 2017). This considerable variation in yield is likely due to many reasons or combinations thereof: predominantly the crop material, but also agronomic practices, and climate may have played a role. Well-documented field trials in 2015 reported (disappointing) yields: 32–62 kg rubber/ha from 1.3 to 3.7 t/ha fresh roots (Kreuzberger et al., 2016). Some (high) yield data till about 1953 are considered suspect because the infamous Lysenko was involved (Caspari and Marshak, 1965), as documented elsewhere (Bonner and Galston, 1947; Sterk et al., 1987). In individual greenhouse-grown plants with only 5–6 % rubber, yields up to 1138 kg/ha have been inferred, but such yields await realization in the field (Luo et al., 2018). If confirmed, this would indicate that increasing the rubber content to 15 % would generate very acceptable rubber yields. The variability in yield is likely primarily due to genetic differences rather than environmental factors. If so, there is room for yield improvement by selection and subsequent breeding.

5.1.1. Conventional breeding

Breeding strategies to increase the yield of rubber from *Tk* are manifold. Self-compatibility will facilitate the breeding of *Tk* and ease seed multiplication. Approaches to overcoming SSI are reviewed elsewhere (Bala et al., 2023). Successful strategies have been presented for potato (*Solanum tuberosum*) and oilseed rape (*Brassica napus*) (Abhinandan et al., 2023; Eggers et al., 2021), but these strategies must be assessed for practical use in *Tk*. The traditional strategy of open-pollinated polycrosses was reported to nearly double the yield of rubber and root mass (Tysdale and Rands, 1953). This approach suggests that the generic variability for yield has not yet been exhausted. Moreover, recurrent selection increased rubber yield by 47 % without affecting root mass (Hodgson-Kratky et al., 2017), indicating that further yield increases may be feasible with increased root mass. The timing of flowering may affect rubber yield (Hodgson-Kratky and Wolyn, 2015). Better control of flowering time may help generate vernalization-insensitive varieties with a shorter (one-season?) life cycle and more efficient seed production. However, no apparent differences were observed between the yield of the roots of greenhouse-grown early and late flowering genotypes (Roelfs et al., 2024). A selection of high-yielding *Tk* germplasm resulted in improved *Tk* material, branded as Flexilis®Plus (Sørensen, 2017). Such material would allow for the economic exploitation of *Tk* rubber (Fraunhofer, 2013). However, detailed data on agronomic characteristics, yield, and performance are yet to be presented in the public domain.

Increased root biomass is a prime and long-standing target for higher rubber yields (Kuluev et al., 2023; Salehi et al., 2021; van Beilen and Poirier, 2007b; Whaley and Bowen, 1947). The root biomass of individual *Tk* plants is highly variable (Arias et al., 2016c). The selection of individuals based on root size resulted in increased root mass (a 27 % increase) and rubber yield (a 38 % increase) (Kupzow, 1980). Dense sowing may inhibit root branching and promote taproot development (Munt et al., 2012). Engineering the taproot architecture would possibly be advantageous. Knowledge of lateral root development may outline strategies for accomplishing higher-yielding root architecture (Yalamanchili et al., 2024). Root shape is reported to be important, as roots with a top diameter of more than 2.5 cm exhibit a negative correlation between root biomass and rubber content (Kupzow, 1980). Such correlations need confirmation with modern germplasm.

Rather than targeting root biomass directly, higher yield can also be realized by increasing overall plant vigor. Strategies to increase resistance to biotic (*i.e.*, pathogens) and abiotic (*i.e.*, environmental) stresses are part of such an approach. Numerous insects, nematodes, bacteria, and fungi are known to feed on dandelion species (Sterk et al., 1987) and are or may develop into pests for *Tk*. Proper pest resistance, as part of plant vigor, should receive ample attention in *Tk* breeding. Several intermediates in rubber biosynthesis are also intermediates for components that may help plants fend off pests (Bach and Rohmer, 2013). Breeding for increased rubber yield may affect such natural resistance mechanisms, and these need attention and testing. Moreover, *Tk* cultivation is likely to face environmental stresses, including drought, waterlogging, and heat, which will decrease rubber yield. In general, breeding for plants that can cope with variable, changing, and unpredictable cultivation conditions (a concept known as 'resilience') is a major challenge for plant breeding (Cooper and Messina, 2023; Janni et al., 2020).

Besides, targeted strategies for enhancing plant vigor are feasible. The common dandelion (*To*) has a more prominent taproot and is much more vigorous than the dandelion in different environments. Therefore, crossing *Tk* with *To* and selecting for the presence of the *Tk* genes for rubber biosynthesis could generate plant material with higher yields (van Beilen and Poirier, 2007b). This strategy has resulted in interspecific hybrid materials with supposedly higher yields (Kultevat, 2016; Sørensen, 2017; van Dijk and Sørensen, 2016). Tools for continued breeding of *Tk* and *To* seem worthwhile (Kaiser et al., 2025). The commercial designation for this material is Flexilis®Hybrid. Increased vigor is also achieved by polyploidization. Triploid *Tb* is a potential source of vigor (Zhang et al., 2015). Tetraploid *Tk* plants generally have larger and more robust roots than diploids (Bannan, 1948). Polyploidy resulted in over four times more rubber than in the corresponding diploid plants (Warmke, 1945), depending on the conditions used for growth. In more recent trials, about two-fold higher rubber concentrations were observed in first-generation colchicine-induced tetraploid plant material at the expense of inulin yield (Luo et al., 2018). It indicates the promise of polyploid breeding (Salehi et al., 2021). However, the root system of these *Tk* polyploids was severely affected, compromising overall rubber yield. Whether tetraploids with a more robust root system can be identified remains to be investigated.

5.1.2. Molecular breeding

Various GM studies in *Tk* have shown either a reduced rubber yield or no effect. These studies were generally based on the down-regulation of gene expression, aiming to elucidate steps in rubber metabolism. So far, only a few GM or GE results have demonstrated a rubber yield higher than that of unmodified control plants. Emerging GM/GE strategies for enhancing overall plant growth and increasing *Tk* root biomass by modifying photosynthetic performance (Croce et al., 2024; Matthews and Burgess, 2024) could promote rubber yield in *Tk*. Likely, the genetic variation in the *Tk* germplasm for improving photosynthetic performance and enhancing overall plant growth to generate more biomass has not been fully exploited, as was recently shown for *Arabidopsis thaliana* (*At*; thale cress)

(Theeuwens et al., 2024).

A root transcriptome comparing *Tk* lines with high and low rubber yield identified over 150 differentially expressed transcripts that may contribute to differences found in yield; further analyses may establish targets for yield improvement (Luo et al., 2018). Overexpression of genes encoding enzymes of the MVA pathway in *Tk* may overcome the rate-limiting enzymatic steps in this pathway. Constitutive overexpression of *At* genes encoding enzymes of the MVA pathway in *Tk* resulted in higher precursor *cis*-isoprene levels. However, it did not lead to higher rubber content (Pütter et al., 2017), indicating the complex regulation of the MVA pathway. These results also suggest that the rate-limiting step in rubber biosynthesis, which needs to be targeted by GM to increase yield, may be the formation of RPs. Similar analyses of the equivalent *Tk* genes should be conducted to exclude subtle regulatory differences between the genes or enzymes from *At* and *Tk*.

Overexpression of the *TbSRPP* gene resulted in about 30 % higher rubber concentration compared to the control (Collins-Silva et al., 2012), albeit at very low rubber levels. Possibly, this increase is due to the material being from *Tb* rather than *Tk* (see above). This result appears somewhat underrated. It is, to our knowledge, the only example of higher rubber content resulting from the overexpression of a single gene encoding a protein involved in rubber biosynthesis. Remarkably, no other direct overexpression studies in *Tk* have been reported in the literature. More detailed evaluations of preferably properly laticifer-localized overexpression of RTase and RP constituents should be feasible and informative (Post et al., 2014).

MYC2 is a helix-loop-helix transcription factor involved in the jasmonic acid (JA) signaling pathway (Luo et al., 2023), which regulates the expression of SRPP in *Hb* (Deng et al., 2018), among other activities. Overexpression of *TkMYC2* in *Tk* promoted root growth and increased rubber production, showing upregulation of *TkSRPP* gene expression (Wu et al., 2024b). The result of *TkMYC2* overexpression may be interpreted as indirect confirmation of the higher rubber yield observed with *TbSRPP* overexpression. However, MYC2 may have influenced more genes simultaneously. The expression of other transcription factors may also influence NR synthesis, such as members of the MADS-box genes (Chen et al., 2023a). The apparent role of jasmonate signaling in rubber biosynthesis and accumulation may give other future targets for higher rubber yields (Dong et al., 2023; Long et al., 2021). Potential candidates are the WRKY transcription factors (Wu et al., 2024c). The effects of the plant hormones ethylene (Du et al., 2024) and abscisic acid (Fricke et al., 2013) may indicate the involvement of other transcription factors.

Less direct approaches to increase rubber production in *Tk* are worth examining in greater detail. For example, overexpression of chloroplast-localized isoprenoid biosynthesis genes from the non-MVA pathway should be considered (Tata et al., 2016). In *Hb*, particular transcription factors likely related to the laticifer-specific (over)expression of genes are involved in the regulation of rubber biosynthesis (Fricke et al., 2013; Makita et al., 2017). These, either heterologous or available from *Tk*, could present new targets to increase NR production in *Tk*. Likewise, speeding up the TCA cycle by overexpressing, for example, a mitochondrial citrate synthase (Qin et al., 2023a) or adjusting miRNA metabolism (Liang et al., 2023) may promote rubber synthesis. Such strategies may generate novel approaches for higher rubber yields in *Tk* but await demonstration by either GM or GE.

The noteworthy exception to the limited results of GM/GE approaches on rubber yield is the modification of the *Tk* inulin pathway. In *Tk*, the inulin is stored as crystals in the vacuoles of root parenchyma cells adjacent to the laticifer cells. This localization may suggest a close sink-source relationship between the metabolism of inulin and NR (Stolze et al., 2017). A higher rubber concentration in *Tk* polyploids was accompanied by a lower inulin content (Luo et al., 2018). Inulin and rubber biosynthesis are likely competing pathways for available photosynthate, substrates, and energy (Fig. 2). A comparable competition between sugar (starch) metabolism and rubber production is seen in *Hb* (Silpi et al., 2007). However, field trials with *Tk* did not show a negative correlation between rubber and inulin yield (DRIVE4EU, 2018). In this case, it indicates that neither pathway was limiting in these trials.

A cross-talk between inulin and rubber pathways in *Tk* suggests that it could be feasible to (nearly) completely block the inulin pathway to direct all photosynthate into rubber biosynthesis. This strategy assumes that plant morphology (laticifer formation) and biochemistry (rubber accumulation; carbon storage) follow rubber synthesis. Constitutive overexpression of the inulin-degrading 1-FEH gene was shown to almost double the rubber content in *Tk* (Stolze et al., 2017). Likewise, CRISPR/Cas9-directed knock-out of 1-FFT resulted in a higher rubber content in *A. rhizogenes*-transformed transgenic *Tk* plants (Ariyaratne et al., 2023). However, without the segregation of the genes involved, it cannot be excluded that the hairy root phenotype also played a role (Lankitus et al., 2023). Given inulin's assumed crucial role in overall *Tk* physiology, a partial rather than a total suppression of inulin production seemed likely to be the more fruitful future strategy. However, simultaneous CRISPR/Cas9-directed knock-out of 1-FFT and 1-SST in *A. tumefaciens*-transformed transgenic *Tk* plants completely abolished inulin synthesis. It doubled rubber accumulation without effects on the rubber quality or major impact on the plant phenotype, other than increased laticifer formation (Qin et al., 2025). It demonstrates the feasibility of redirecting sucrose metabolism to rubber synthesis. Further research is required to confirm these findings in the field and assess their impact on extraction protocols.

In theory, other cross-talking pathways beyond inulin may be exploited. For example, downregulating reactions that divert IPP or FPP to other secondary metabolites may increase rubber content. However, the down-regulation of squalene synthase did not result in higher rubber yields (Unland et al., 2018), nor did the down-regulation of oxidosqualene cyclase (Van Deenen et al., 2019). These results demonstrate the complexity of redirecting the flux of terpenoid metabolism towards rubber synthesis. Such strategies could indirectly result in higher useable yields. They may ease the process of extracting rubber or inulin, as was demonstrated for the extraction of inulin from *Ci* (Cankar et al., 2021).

It is currently unclear to what extent the various strategies for yield outlined here are additive. The theoretical maximum for rubber yield upon continued breeding and more efficient channeling of carbon to rubber is unknown. Non-rubber (or non-latex) producing plant species also contain and express SRPP-like genes (Schmidt et al., 2010a), so the proteins involved are likely to have other functions, such as in stress responses (Fricke et al., 2013). Conversely, this could mean that non-rubber-producing plants could be given the capacity to produce rubber. Far-fetched strategies attempt to move NR production away from the plant. RPs from *Tb* are capable of

rubber elongation *in vitro* when supplied with the appropriate precursors (Schmidt et al., 2010b). The same is the case for RPs from *Hb* (Yamashita et al., 2016), suggesting the possibility of industrial *in vitro* production of NR. RPs can be mimicked *in vitro*, which is a first step toward a full *ex planta* production of NR. Progress to date hinges on the long-chain polymerization (Umar et al., 2023).

5.1.3. Regulatory issues for the biotechnological improvement of *Tk*

Many of the above approaches to improve *Tk* imply (advanced) GM or GE. The practical applications possible with GE in plants (Atia et al., 2024; Li et al., 2024) cover most of the breeding targets outlined for *Tk*. It requires that the particular targets have been defined and preferably backed up by a demonstration of the proof-of-concept in the field. Similarly, new strategies based on recombination events may become attractive for genome engineering of *Tk* (Cautereels et al., 2024). In several countries, GE, or new genomic techniques (NGT), are considered part of the new breeding techniques (NBT) that are regulated, or in the process of becoming regulated, as conventional breeding, with New Zealand and Mexico as notable exceptions (situation in August 2025) (Buchholzer and Frommer, 2023; GGRET, 2024). The EU awaits a decision on whether to consider such technology as an example of GM. Currently, the legal verdict on the regulatory status of NGT in Europe is that they must be regulated as GM (Callaway, 2018). The regulatory (Nap et al., 2003) and environmental (Conner et al., 2003) safety considerations for GM crops in Europe imply prohibitively costly assessments of the possibilities for and consequences of potential off-target events (Lee et al., 2018), as well as putative long-term effects of the modification(s) (Globus and Qimron, 2018). In February 2024, a (modest) majority of the European Parliament (EP) supported the EU's new NGT regulations proposed in July 2023 (EP, 2024). Although these regulations seem to be moving towards acceptance, the associated demands of product labeling and a ban on patent use may hamper actual (commercial) application in the EU. It is unknown if and when these regulations will take effect and what the final version will be; therefore, considerable discussion (hence, time) is likely and possible (Winter, 2024). The precise form and adoption of these regulations will impact the future of biotech-improved *Tk* in Europe. Irrespective of such regulatory issues, GM or NGT in *Tk* will continue to facilitate gene function analyses in *Tk* and help to advance breeding.

5.2. Target: inulin yield

As for rubber, the inulin yield reported for *Tk* is highly variable (Arias et al., 2016c; Gorham, 1946). It may reach 1650 kg/ha (Arias et al., 2016c; Kreuzberger et al., 2016). A yield of 128–209 kg/ha was reported in successive field trials (Kreuzberger et al., 2016), which is very modest compared to the yield of 7000 kg/ha of *Ci* (Table 1). Inulin is best considered as an added value relative to rubber. The moment inulin contributes positively to the business case of *Tk*, it will promote its cultivation. As a result, its rubber will become more widely available and cheaper. Consistent yield is also key for inulin, as long as it does not reduce the yield or quality of the primary product, rubber. *Tk* cultivars with relatively high inulin yields could be attractive in response to world markets for specialty uses of inulin, depending on the market prices and increasing demands for such inulin.

Early attempts to increase inulin yield in *Ci* by targeting enzyme activities were unsuccessful (van Arkel et al., 2013), suggesting that *Tk* inulin may also present a challenge. Overexpression of the biosynthetic 1-SST gene from common dandelion (*To*) in *Ci* increased inulin content and DP_n in transgenic *Ci* (Maroufi et al., 2018). Cold nights are known to induce the degradation of inulin in *Ci*. Knocking down all three inulin-degrading 1-FEH genes with gene editing technology (CRISPR/Cas9) in *Ci* prevented such cold-induced degradation (in the greenhouse). It resulted in (slightly) higher inulin content with similar DP_n per plant and higher yields overall (Hingsamer et al., 2022). Similar strategies are feasible for increasing the inulin yield from *Tk*. All genes and cDNAs of *Tk* responsible for inulin metabolism have been cloned and characterized (Stolze et al., 2017), and can steer attempts to increase the yield or quality of inulin in *Tk*. To the best of our knowledge, no deliberate attempts to modify the DP_n of *Tk* inulin, or serendipitous modifications of that DP_n, have been presented in the literature to date. In *Ci*, yield losses in processing were reduced by eliminating sesquiterpene lactone synthesis, which lowered the accumulation of terpenes (Cankar et al., 2021), without higher yields per individual plant. Similar strategies may be worthwhile for *Tk*.

The cross-talk between the inulin and rubber pathways in *Tk* suggests that, in theory, it could be feasible to (nearly) completely block the rubber pathway and direct more photosynthate into inulin biosynthesis. As shown earlier for *Tb* (Post et al., 2012), RNA interference of an RT component indeed resulted in higher levels of inulin in *Tk*. Not surprisingly, this was accompanied by a considerably reduced rubber yield (Niephaus et al., 2019).

5.3. Target: extraction technology

After harvest, the roots must be processed extensively to extract the desired products. Much research attention has been devoted to proper processing. *Tk* root biomass is a heterogeneous mixture compared to the reasonably pure rubber material tapped from *Hb* or the inulin from *Ci*. Its processing should result in rubber and inulin batches with a high yield that meet the industry purity criteria. The basics of parallel processing for rubber and inulin have been outlined earlier (Whaley and Bowen, 1947). In short, the harvested roots are cleaned and dried; however, fresh storage, either whole, sliced, or shredded, is also an option (van Beilen and Poirier, 2007b). The extent to which the roots are cleaned from sand and weeds is of special interest (DRIVE4EU, 2018). Cold post-harvest storage of roots can increase rubber yield at the expense of inulin (Cornish et al., 2013). As root storage and handling may impact rubber and inulin yields, storage time should be kept as short as possible. Further research into the optimal storage conditions is warranted.

In the first processing step, inulin is flushed out with hot water, and the rubber coagulates. From this step on, the inulin and rubber processing pathways diverge. For rubber, the remainder is milled, and the rubber is centrifuged or floated from the slurry (Arias et al., 2016c). The rubber can also be extracted as a dilute suspension of latex in water by shredding the root tissue and stabilizing the

suspension with anticoagulants (van Beilen and Poirier, 2007b). The extraction process is key to an efficient, cost-effective harvest. Detailed technical information on extraction technology is succinctly summarized elsewhere (Arias et al., 2016c; Salehi et al., 2022). Improvements and variations have been suggested for virtually every step in the extraction process (Alrawajfeh et al., 2017; Buranov and Elmuradov, 2010; Fichtner et al., 2024; Liu et al., 2024a; Ramirez Cadavid et al., 2019, 2022; Sikandar et al., 2017; van Dijk and Mank, 2016; Zheng et al., 2025). Currently, no 'industry standard' has yet been established.

As the methodology of extraction influences the properties of the resulting NR (Zheng et al., 2025), extraction technology should be combined with extensive quality control.

Elaborate protocols for the extraction of inulin (Hahn et al., 2016) or the simultaneous extraction of inulin and rubber from *Tk* are available. They differ in details and have particular focal points. Details are documented elsewhere (Chen et al., 2022; Hruschka et al., 2017). For example, the extraction temperature is essential for inulin yield and quality. Such protocols will be key for using both rubber and inulin separately. If *Tk* inulin is mainly used as the source of fructose for HMF and FDCA synthesis, the quality of inulin may be less critical. Therefore, the intended use should be considered when selecting the extraction protocol. Also, the value and use of the processing waste should be considered when evaluating extraction protocols.

5.4. Target: agronomy

Breeding for better *Tk* plant material is accompanied by research and development into improved agronomy. It involves optimal germination conditions, growing and harvest practices, and strategies to minimize harvest losses. Improved agronomy will contribute to overall yield and yield consistency.

Different multi-year field trials demonstrated that field emergence from seed can be poor, and seed germination is a concern (Kreuzberger et al., 2016; Kupzow, 1980; Moussavi et al., 2016). Germination frequency was approximately 75 %, whereas commercial applications require over 99 %. Such germination issues also affect plant density in the field (Kreuzberger et al., 2016; Munt et al., 2012). Improved seed set, harvest, storage, seeding, and seed technologies, such as pelleting, are likely to generate materials or treatments that enhance the germination rate. Good seed quality will improve stand development and yield. Pelleting of seeds, for example, resulted in more uniform germination and better stand development (DRIVE4EU, 2018; Keener et al., 2018). So far, little consideration has been given to using the *Tk* root tips as explants. Hobby growers and professionals are aware of the difficulty in eliminating common dandelion from lawns or other areas where these plants are unwanted (Sterk et al., 1987). *Tk* root tips might be harvested separately before root processing and used for plant propagation. Alternative practices such as sowing pre-germinated seeds or transplanting pre-grown seedlings could also become part of *Tk* crop cultivation. Such applications depend on their agronomic feasibility, costs, and contribution to yield (Eggert et al., 2018).

In addition to seed technology, several aspects require attention and possibly standardization to ensure sustainable yield and facilitate future market introduction. These include the details of optimal planting depth (Kreuzberger et al., 2016), best cultivation practices, such as in rows or beds, and planting density (Eggert et al., 2018). Also, the fertilization scheme (Munt et al., 2012), application of herbicides following germination (Kölzsch et al., 2014), overall water management (Arias et al., 2016b), weed control (Pannwitt et al., 2025) and pest control (DRIVE4EU, 2018) are part of the agronomic challenges.

Such agronomic parameters are being reassessed in field trials in several parts of the world using the newly available *Tk* plant material (Arias et al., 2016c; Kreuzberger et al., 2016). Plant density has been shown to affect rubber yield (Bates et al., 2019; King-Smith et al., 2025). Differences in plant density are likely to have contributed to the considerable variation in yields reported for earlier field trials. Often, the plant density used in trials is not reported. Such missing data hampers the interpretation of yield results. Interpretation is also complicated by the potential mix-up of *Tk* with *Tb* (as addressed above), or the possible contamination with more vigorous but non-producing (triploid) dandelions in open-field trials. Repetition and proper documentation of future field trials are needed. Such issues also deserve consideration as selection criteria in *Tk* breeding.

Whether intercropping, chemical or biological crop protection, mixed cultivation, as in organic farming (Lammerts van Bueren et al., 2011), or other agricultural practices meet the demands of yield and costs for *Tk* cultivation, needs closer attention from research agronomists. It was reported that the foliar application of a natural lipid (lysophosphatidylethanolamine) increased rubber production by approximately 40 % (Park et al., 2024). Methanol sprays may also improve yields (Ganesh et al., 2025). The increases suggest new routes to enhance rubber yield from *Tk*. *Tk* is unrelated to common arable crops. It is, therefore, not likely to be vulnerable to the common pests and diseases of those crops. This way, *Tk* may contribute to diversified crop rotation (Shah et al., 2021). Besides, *Tk* cultivation may contribute to soil improvement due to its penetrating taproot, and it may also have a positive impact on the soil microbiome (Guo et al., 2024). As such, *Tk* could become a valuable component of crop rotation, contributing to more sustainable crop cultivation, as was demonstrated for sugarbeets (Guo et al., 2024).

Much research has been conducted to determine the optimal harvesting time of *Tk*. It is a biennial crop, although it is (or can be) flowering already in the first year of planting (Arias et al., 2016c; Sterk et al., 1987). Earlier, it was suggested that the biennial flowering habit would promote yield (Krotkov, 1945). Field trials indicated that the best harvest time is the summer of the second year, for both rubber and inulin yields (Kreuzberger et al., 2016), confirming earlier results that indicated better yields after two years (Bonner and Galston, 1947; Suomela, 1950). However, the costs of land use relative to reseeded and fertilization may make it economically attractive to breed and develop *Tk* as an annual crop. The spread of *Tk* blowballs may also be of concern and prompt early harvest. Mastering flowering time may help generate such genotypes (Roelfs et al., 2024).

The details of harvesting also need scrutiny. *Tk* roots have been harvested with potato harvesting equipment (Kreuzberger et al., 2016). Chicory root harvesting equipment may be suitable, although the chicory taproot is more robust than the root system of *Tk*. Specialized harvesting equipment tailored to the root habit of *Tk* may contribute to an efficient harvest and boost yield. It may also

improve harvest efficiency and the use of coproducts. The value and commercial use of the harvest waste, as well as the aerial parts of *Tk*, should be considered when evaluating *Tk* cultivars and harvesting protocols.

5.5. Target: side-stream use

The waste material and aerial parts of *Tk* present promising applications as a potentially attractive addition to the future business case (Table 2). Nutraceuticals, pharmaceuticals, or cosmetics may generate considerably higher economic value per unit than bulk products such as rubber or inulin (Stegmann et al., 2020). Given the potential value of herbal medicines, the medicinal use of the aerial parts of *Tk* could be of added value. Requirements are less strict for the personal healthcare market, so development in that area may be more feasible. However, many issues must be considered, investigated, and concluded before additional viable production chains of commercial *Tk* materials can be established. Any medical or health-related application needs further development and regulatory oversight. However, approval for and registration of a health claim is demanding and costly in terms of time and expense, as is registration as a medicine. An application as a 'novel food' will need EFSA approval in Europe and FDA approval in the USA. Therefore, the potential presence of substances that may be of concern for human health should be evaluated (EFSA, 2012). Application as feed may be more straightforward (Zhang et al., 2024c).

6. Economic viability of commercial use of *Tk*

6.1. Economic feasibility

Assessing the economic feasibility of *Tk* as a commercial crop requires analysis of the entire supply chain. It involves the chain from seed planting to market adoption of *Tk* NR, *Tk* inulin, and any additional *Tk*-derived products, as well as their potential re-use (Stegmann et al., 2020). To develop robust business models, the assessment should integrate all cost parameters, including land use, field operations, crop protection, harvesting, biorefinery processes, transport logistics, facility investments, and operational costs of such facilities, particularly for energy and maintenance (Hingsamer et al., 2017).

The DRIVE4EU consortium projected root yields of 40 t/ha/yr (with an 80 % water content) and harvestable fractions of 15 % rubber and 40 % inulin (DRIVE4EU, 2018). Such yields seem feasible with the current *Tk* material. These yields translate to 1200 kg/ha/yr of NR and 3200 kg/ha/yr of inulin. Upon either enzymatic (inulinase) or acid hydrolysis, the latter will give approximately 2600 kg of fructose per hectare per year (Pérez Nebreda et al., 2019; Stökle et al., 2023; Trivedi et al., 2015). Further conversion of fructose via HMF and FDCA produces approximately 1800 kg PEF/ha/yr (Al Ghatta et al., 2021). The remaining root, leaf, and pulp material is being marketed as feed. The analyses demonstrated that, under given assumptions for cost parameters, a viable business case for *Tk* is feasible over a 10-year depreciation period (DRIVE4EU, 2018).

The economic feasibility largely depends on the anticipated market prices for rubber and inulin. Commercial development of inulin-derived products will rely on feedstock availability, production costs, processing volumes, and competition from alternative carbohydrate sources (De Jong et al., 2022). An alternative could be the conversion of fructose into ethanol or other biofuels (Bhagia et al., 2017; Lee et al., 2022). Although the assessment remains valid today, the economic forecasts must be updated regularly to reflect market developments and geopolitical challenges. There may be a 'tipping point' (Scheffer, 2020) with respect to the threats for *Hb* NR production in Asia (disease, costs, climate) that may promote the viability and attractiveness of *Tk* as a crop.

Europe's rubber demand (synthetic and natural combined) is an estimated 5.5 Mt/yr, about 16 % of world production. If *Tk* consistently produces 1200 kg/ha/yr of NR, and *Tk* NR can replace all SR, it would require an area of cultivation of 4.5 Mha to make Europe self-sufficient in rubber. About half that area would be sufficient to replace only SR. An area of 4.5 Mha represents less than 3 % of the EU's total agricultural area (~157 Mha) and 5 % of its arable land (~99 Mha) (Eurostat, 2024). A one-in-four crop rotation scheme, as recommended for *Ci* (Baert and Van Bockstaele, 1992), would quadruple the area, although the area can be used for other crops. Cultivating *Tk* in marginal lands could further reduce the pressure on arable land.

Cultivating *Tk* on 4.5 Mha would yield 14.4 Mt of inulin annually. This yield is over 36-fold more than the current *Ci* production of 0.5 Mt from 60,000 ha at 8 t/ha/yr. Niche markets that demand the longer-chain *Tk* inulin may create added value. However, inulin for food applications is more easily met by growing more *Ci*, thereby obviating the need for regulatory approval for inulin as a food ingredient. Therefore, *Tk* inulin is better suited as a fructose feedstock for green chemistry, particularly for the synthesis of HMF, FDCA, and PEF. *Tk* inulin would yield 7.9 Mt/yr of PET, meeting 80 % of the annual EU PET demand (9.9 Mt/yr), provided there is cooperation throughout the entire value chain. Similar calculations for other parts of the world will likely show that replacing SR and NR with NR from *Tk* is doable and viable if inulin is a profitable side-stream use.

6.2. Commercial use

Although *Tk* NR could replace *Hb* NR in most, if not all, applications, its commercialization is hampered by availability and costs. The prototype use of *Tk* rubber in car tires by Apollo Vredenstein, dubbed the Fortezza Flower Power in 2017, dates back to 2012 (DRIVE4EU, 2018; Sørensen, 2017; van der Hoeven, 2017; Continental's 2014 Taraxagum (www.taraxagum.com) truck tire (Continental, 2016) is also still in the prototype phase. As long as availability and costs are issues, *Tk* rubber may target niche markets with a 'green' connotation to appeal to sustainability (Zwart et al., 2015), such as bicycle tires. Continental's Urban Taraxagum bicycle tire won the prestigious Red Dot Design Award in 2020 (Red_Dot, 2020). This tire is currently mass-produced in Germany and available worldwide at a premium price. To the best of our knowledge, this is the first and, to date, the only product on the market that contains

Tk rubber.

7. Circular economy and indirect agronomy

7.1. Circular economy and recycling of *Tk*-based material

An issue that is gaining importance in the economy of any product is its circularity: what to do with the material after it has served its purpose (Gursel et al., 2022; Stegmann et al., 2020). It should preferably be considered before actual application as part of the supply chain in any business model (Papamichael et al., 2024). The strategies for sustainability are known as the R strategies: refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose, recycle, and recover (Morseletto, 2020). Re-use and recycle require particular prior consideration for any rubber, including *Tk* NR. The same applies to PEF from *Tk* inulin.

Rubber re-use and recycling, notably of vulcanized rubber from, e.g., used tires, is both technically and legally complex and challenging (Leong et al., 2023; Wiśniewska et al., 2023; Zhao et al., 2024). For example, (re-)using waste crumb rubber as pellets in sports fields has met with heavily debated health concerns (Bleyer, 2017; Moreno et al., 2023). Devulcanisation technologies result in so-called reclaimed rubber as an alternative to virgin rubber (Wiśniewska et al., 2022). Currently, about 5–10 % of all rubber is reclaimed. NR may biodegrade better than SR with the help of enzymes or selected (consortia of) microbes or fungi (Guajardo and Andler, 2024; Joseph et al., 2022; Leong et al., 2023). Such biodegradation is likely compromised by vulcanization (Lubura et al., 2023), so future analyses in the context of vulcanization-free (Huang et al., 2024) or devulcanization technologies (Wiśniewska et al., 2022) are warranted (Chittella et al., 2021). A better understanding of the degradation of NR in the field or waste dumps (Bosco and Mollea, 2021) could outline novel strategies for NR biodegradation in cases where recycling is not an option. Focusing on rubber reclaiming issues could benefit the future business case of *Tk* rubber.

Although inulin-based PEF offers clear environmental and application-oriented advantages over the PET it aims to replace, its re-use and recycling are challenging (De Jong et al., 2022). PEF re-use and recycling may be a bigger challenge than rubber, especially given the widespread adverse effects of micro(nano)plastic pollution (Bos et al., 2024; Li et al., 2022; Walker and Fequet, 2023). Attention to the issues concerning *Tk* inulin-derived PEF would benefit the attractiveness of *Tk* as a crop.

7.2. Indirect agronomic considerations

Large-scale cultivation of *Tk* may have additional indirect consequences for agriculture and ecosystems that should be taken into consideration. *Tk* is cultivated in temperate regions, which reduces the need for long-distance transport from the tropics. Its cultivation may help prevent deforestation in areas where *Hb* is cultivated. Moreover, *Tk* grows relatively well on marginal soils. Therefore, *Tk* cultivation may enlarge the area available for agriculture. *Tk* cultivation does not need to compete with other uses of otherwise uncultivated land. It will not result in undesired land-use changes, such as the replacement of food production areas by rubber cultivation (Harvey and Pilgrim, 2011). The long-term ecological effects on biodiversity and health of marginal soils may be a matter of concern.

Tk may be a host of plant diseases (Aono et al., 2022). In that case, large-scale cultivation may result in the establishment of an undesired reservoir for such pathogens. The common dandelion (*To*) is considered a pan-global weed. *Tk* is not considered very competitive (van Beilen and Poirier, 2007b) and shows relatively poor establishment in the field (Moussavi et al., 2016). Still, the potential for gene flow between *To* and *Tk* may be a matter of concern because of undesired ecological consequences (Iaffaldano et al., 2018). A rare natural hybrid was described (Malecka, 1971), so the apomixis in *To* may not always be sufficient to prevent gene flow. However, no such gene flow was observed in areas of intensive *Tk* cultivation (DRIVE4EU, 2018). Novel *Tk* cultivars, such as future *Tk*/*To* hybrids, may have markedly improved seed germination, increased vigor, or (GM) herbicide tolerance. These properties may contribute to their invasive potential, competition with weeds, or ability to spread new properties. Such issues and their potential consequences need consideration (Uhlemann and Thiele, 2024).

8. Future prospects

Tk is close to becoming a valuable addition to the crop portfolio of the temperate regions as a commercial producer of NR, inulin, and possibly other components. It assumes that the need for geopolitical independence in NR production, the phasing out of fossil-based SR, and the use of renewable feedstocks for green chemistry continue to be recognized and supported. Also, these needs should be priced into the market accordingly.

Targeted research and development across agronomy, biotechnology, breeding, and bioprocessing will develop higher-yielding and resilient cultivars for changing climate conditions. These will sustain and improve market opportunities for a crop that aligns well with current societal and environmental needs. Strategies of all-inclusive breeding and biotechnology are recommended that consider yield robustness, agronomic performance, and potential effects on an agroecosystem. New cultivars could exhibit more efficient photosynthesis, increased root biomass, higher seed vigor, a more robust root system with enhanced rubber yields, and allow for planting schemes that facilitate easier harvesting and improved extraction efficiency. As rubber biosynthesis involves IPP that feeds multiple different biosynthetic pathways, a promising strategy should be to promote rubber synthesis by reducing competing pathways without detrimental effects on plant growth and survival. Focus should be on plant material that channels energy and photosynthate into rubber. Particular attention to pests and disease management in future large-scale *Tk* cultivation is warranted, and **the added value of *Tk* in crop rotation systems merits closer examination**. The development of cultivars that enable an annual harvest would further enhance the attractiveness of *Tk*. Cultivation and processing practices should be harmonized and fine-tuned internationally.

Cooperation between stakeholders across different value chains and regions (DRIVE4EU, 2018; Salehi et al., 2021; TARDISS, 2025) will contribute to sustainable and sustained yields of *Tk*.

With the advances and approaches of synthetic and systems biology, as well as artificial intelligence (Yang and Reyna-Llorens, 2023; Zhang et al., 2025), it is conceivable that the biosynthetic routes for rubber and inulin, along with the accompanying required morphology, will be fully designed. Such a design could aim to increase the number or size of laticifers in the root. It could result in *Tk* with fist-thick tap roots similar to those of *Ci* or sugar beet, or with Jerusalem artichoke-like tuber formation. More far-fetched alternatives would be transplanting current rubber pathways to plants with superior and well-established agronomic characteristics, or an industrial *ex planta* synthesis of NR (Umar et al., 2023). Without legal reconsiderations of the regulatory status of agricultural biotechnology-improved material, there would seem to be little future for developing and using open-air GM or NGT-derived *Tk* cultivar material in Europe (Purnhagen et al., 2018), in contrast to other parts of the world. Areas outside of Europe may expand and utilize GM/GE-amended *Tk* to produce NR. This situation should be reconciled with the EU policy of NR as a 'critical raw material'. The complex issues associated with the development and large-scale cultivation of a novel crop for bulk products, such as NR and inulin, require a careful balance between societal needs and the valuable applications of these products.

Declaration of generative AI and AI-assisted technologies in writing

In the preparation of this work, the authors have utilized Grammarly to correct potential grammatical or spelling errors, conform to scientific English, and enhance the readability of the text, as well as Perplexity to suggest relevant (grey) literature sources. After using these tools, the authors have carefully reviewed and edited the text as needed, and take full responsibility for the content of this publication.

CRedit authorship contribution statement

Jan-Peter Nap: Writing – review & editing, Writing – original draft, Software, Resources, Conceptualization. **Hetty C. van den Broeck:** Writing – original draft. **Jeroen van Arkel:** Writing – review & editing. **Ruud A. de Maagd:** Writing – review & editing. **Ingrid M. van der Meer:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

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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.

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Data availability

Data will be available on request.

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