



Effect of Competition from Two Contrasting Weed Species On the Yield of Rubber Dandelion (*Taraxacum kok-saghyz*)

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Abstract

Effective cultivation of the potential rubber crop *Taraxacum kok-saghyz* (TKS) is hindered by weed competition, which can lead to substantial yield losses. A major challenge is the absence of effective weed control tools, specifically designed for TKS, in contrast to the situation that is available for major crops. Consequently, residual weed populations often remain, thereby exacerbating competition. A promising solution is the development of more targeted weed management strategies that focus on the competition ability of specific weed species or density thresholds. This study is the first to investigate the effect of two contrasting weed species, *Viola arvensis* (low competitive) and *Chenopodium album* (high competitive), on rubber yield using pot experiments on two sites. Results indicate that rubber yield is significantly affected by the weed species. In the presence of *V. arvensis*, higher yields (0.02 g/plant in Brunswick and 0.01 g/plant in Quedlinburg) were observed than in the presence of *C. album* or a mixture of both species (0.001–0.01 g/plant), with a strong site effect. This study reveals that rubber yield was independent of increasing weed densities. However, it was dependent on decreasing dry matter and increasing rubber content. The results suggest that managing weeds in TKS depends on the weed species, thus necessitating the development of species-specific weed management strategies in future research agendas.

Keywords Minor crops · Weed management · Weed species · Reduced herbicide use · *Taraxacum kok-saghyz*

Introduction

Taraxacum kok-saghyz RODIN (TKS) is a potential crop for industrial used natural rubber (van Beilen and Poirier 2007) and interesting active pharmaceutical ingredients. Multidimensional incentives address the pathway to develop TKS from a wild plant to a large-scale crop, including molecular efforts to understand the mechanism of the natural rubber biosynthesis (Lin et al. 2018), breeding and the development of cropping systems tailored to temperate regions. A key challenge in establishing TKS as a reliable crop is the competition with weeds. While it is common practice in conventional agriculture to control weeds in primary crops

using a variety of very effective herbicides, it has proven more challenging to develop similarly tailored solutions for new or minor crops. For TKS, most herbicides can only be tolerated at lower doses than registered (Eggert and Thiele 2020; Pannwitt and Thiele 2024), resulting in the survival of residual weed plants after herbicide applications (personal observations).

To utilize weed management measures effectively in TKS cultivation, a comprehensive weed management strategy is essential. In case of herbicide usage, this strategy must aim to minimize phytotoxic effects on the crop. In order to limit the damage to the crop, precise weed management techniques are required. One strategy designed to address this challenge is site-specific weed management, which involves the precise application of herbicides according to the spatial variability of weed populations within a field (Gerhards et al. 2022), thereby minimizing the potential for phytotoxic effects. In order to be able to decide whether a specific area in the field should be treated with herbicides, a better understanding of crop-weed interaction is necessary. This is particularly important for understanding how specific weed species affect TKS yield and quality. To date, no economic thresholds have been

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identified for weed densities, either for single species or for groups of weed species. Furthermore, there is a lack of research regarding the complex effects of weeds on rubber yield.

TKS is a perennial dicotyledonous species, but is typically cultivated as an annual spring crop, growing within a 6–9 month period. It forms a rosette of leaves with a typical diameter of 25 cm, reaching a height of approximately 15 cm during flowering. After flowering, TKS has the tendency to undergo a summer dormancy under abiotic stress (Ulmann 1951; Kreuzberger et al. 2016). The species TKS accumulates high-quality natural rubber within the cytosol of the laticifers of its roots (Schmidt et al. 2010). The quality of the rubber is comparable to that of the rubber tree (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.), the primary source of natural rubber globally. However, *Hevea*, being native to Southeast Asia, is facing significant challenges, including limited suitable arable land (van Beilen and Poirier 2007; Uteulin et al. 2023) and low genetic diversity, which makes it highly susceptible to fungal diseases (van Beilen and Poirier 2007). In contrast, TKS, native to the Tian Shan region of Kazakhstan (Hellier 2011), demonstrates potential for natural rubber production in temperate regions.

In its native habitat in the Tian Shan intermountain valley, TKS grows in meadows characterized by a mesogalophytic vegetation, which is tolerant to salt and changing water regimes (Ivashchenko et al. 2021). However, as these meadows are typically grazed, TKS plants experience minimal aboveground competition for light. In contrast, the cultivation of TKS in temperate regions is often characterized by increased light competition due to ineffective weed management and limited understanding of the crop-weed interaction. While light availability is considered a key limiting factor for TKS yield (Gao et al. 2020), the impact of light competition on yield performance in temperate agricultural settings remains to be elucidated.

To improve weed management in TKS, it is crucial to understand the specific impact of competition from various weed species on rubber yield. Weed species vary widely in their competitive abilities, which are largely determined by their distinct morphological and physiological traits (Marshall et al. 2003). One key trait influencing weed competition is the ability to compete for light, which is often the most limiting resource during crop establishment (Rajcan and Swanton 2001). However, weeds commonly found in agricultural fields exhibit a range of competitive capabilities, suggesting that certain species may pose a greater threat to TKS yield than others may.

In order to investigate the interaction of weeds and TKS, we conducted a pot experiment at two locations with a strongly competitive weed, *Chenopodium album* L., and a less competitive weed *Viola arvensis* Murray. Both

weed species are common in TKS fields in Germany. This study addresses two primary questions: (1) whether the specific weed species influence rubber yield in TKS, and (2) whether increasing weed density further reduces TKS root dry matter and rubber content.

Material and Methods

Experimental Setup

To analyze the effect of weed competition on TKS and its rubber yield we conducted a semi-field pot experiment. Two experimental sites in Germany (JKI Quedlinburg and Brunswick) were selected to use this “space for time” approach to compare the effect of two environments on the crop-weed competition, thus avoiding the necessity of waiting a year to repeat the study. The two sites differed in mean annual temperature (8.9 and 10.9 °C), mean annual precipitation (497 and 640 mm per year), soil type (chernozem and loamy sand), and elevation above sea level (140 and 80 m).

At both experimental sites, three scenarios of crop-weed competition were established, varying in weed species and densities. In the first scenario TKS was combined with *C. album* (TKS_CHEAL) and in the second with *V. arvensis* (TKS_VIOAR). The third scenario combined TKS with both weed species (TKS_both). The planting design for TKS was set at 34 plants in three rows, with a 22.5 cm separation between rows and a 5.5 cm separation between plants within a row. This design was implemented in all three scenarios. The weeds were planted in a density gradient (Fig. 1), with each scenario subjected to a distinct density level, thereby creating a three-level competitive environment. The scenarios involving single weed species (TKS_CHEAL; TKS_VIOAR) included a high density patch (high_CHEAL, 71 plants m⁻²; high_VIOAR, 142 plants m⁻²), a low density patch (low_CHEAL, 19 plants m⁻²; and low_VIOAR, 56 plants m⁻²), and a patch without any weeds (no_CHEAL, no_VIOAR). The scenario involving the co-occurrence of both weed species (TKS_both) exhibited a medium-density patch of both weed species (CHEAL, 23 plants m⁻²; VIOAR, 56 plants m⁻²). The density patches at the top and bottom positions of these pots alternate between high and low density, respectively (high CHEAL, 59 and low VIOAR, 47 plants m⁻² vs. low CHEAL, 12 and high VIOAR, 83 plants m⁻²) (Fig. 1). In the context of this study, pots from all scenarios were planted in a consistent manner to ensure that the positions of the plants remained uniform across each repetition of the given scenarios. Each scenario was replicated three times at each trial site.

For the crop, we used TKS seeds derived from a population originally mixed from USDA accessions (W6-35162,

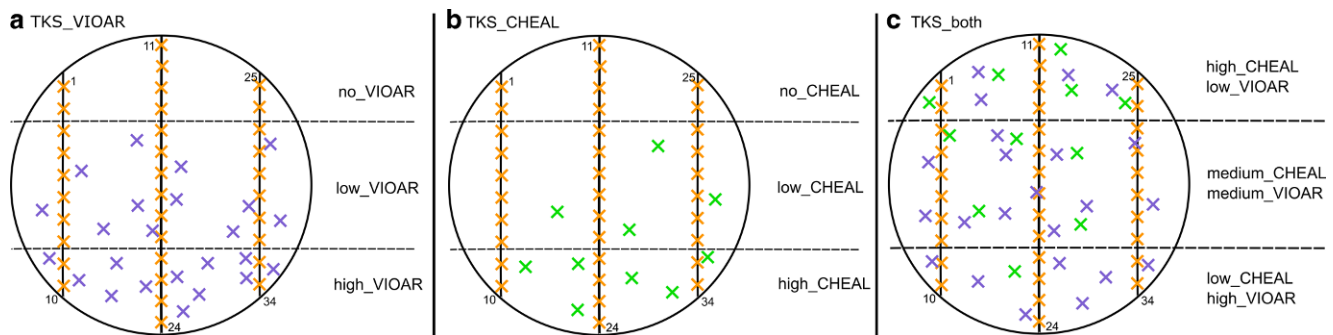


Fig. 1 Planting scheme used for the experimental pots at both trial sites, with each colored cross indicating a single plant of the respective species, with orange indicating *T. kok-saghyz* (TKS); green, *C. album* (CHEAL); purple, *V. arvensis* (VIOAR)

W6-35165, W6-35177, and W6-35179, W6-35180, -35183) collected in Kazakhstan in 2008 by Barbara Hellier (Hellier, 2011). This plant material was subsequently propagated for several years at the JKI field trial site in Quedlinburg, Germany, serving as a model plant. The seeds of the annual weeds *C. album* and *V. arvensis*, were obtained from the JKI weed seed collection in Brunswick, Germany.

To reduce the potential impact of varying plant age as a competitive factor, all plants were cultivated in the greenhouse to BBCH 14–16 under identical conditions and subsequently transplanted to the experimental pots, which had a diameter of 0.7 m and a height of 0.9 m and were filled with approx. 200 l of soil from the designated locations.

Transplantation was conducted in mid-May in Brunswick and at the beginning of June in Quedlinburg, in accordance with the planting scheme (Fig. 1).

During the trial, the pots were kept free of spontaneous weeds, to avoid any extra competition. The entire crop and weed plants were harvested after 120 and 128 days in Quedlinburg and Brunswick, respectively. The plants were then washed in order to remove the soil, separated into shoot and root portions, and subsequently dried to constant weight at 60 °C to determine the dry matter (DM) of roots and shoots separately. This was done in all pots for TKS, and, in addition, for the weeds in one pot for each of the three scenarios at both trial sites. To determine the rubber content, dry TKS roots from two adjacent plants were ground into powder using a mill. An aliquot of 100 mg was analyzed for the rubber content by NMR spectroscopy at lifespin GmbH (Regensburg, Germany) (Stolze et al. 2017). The rubber yield of a plant was calculated as the product of the root dry matter and the rubber content.

Statistical Analysis

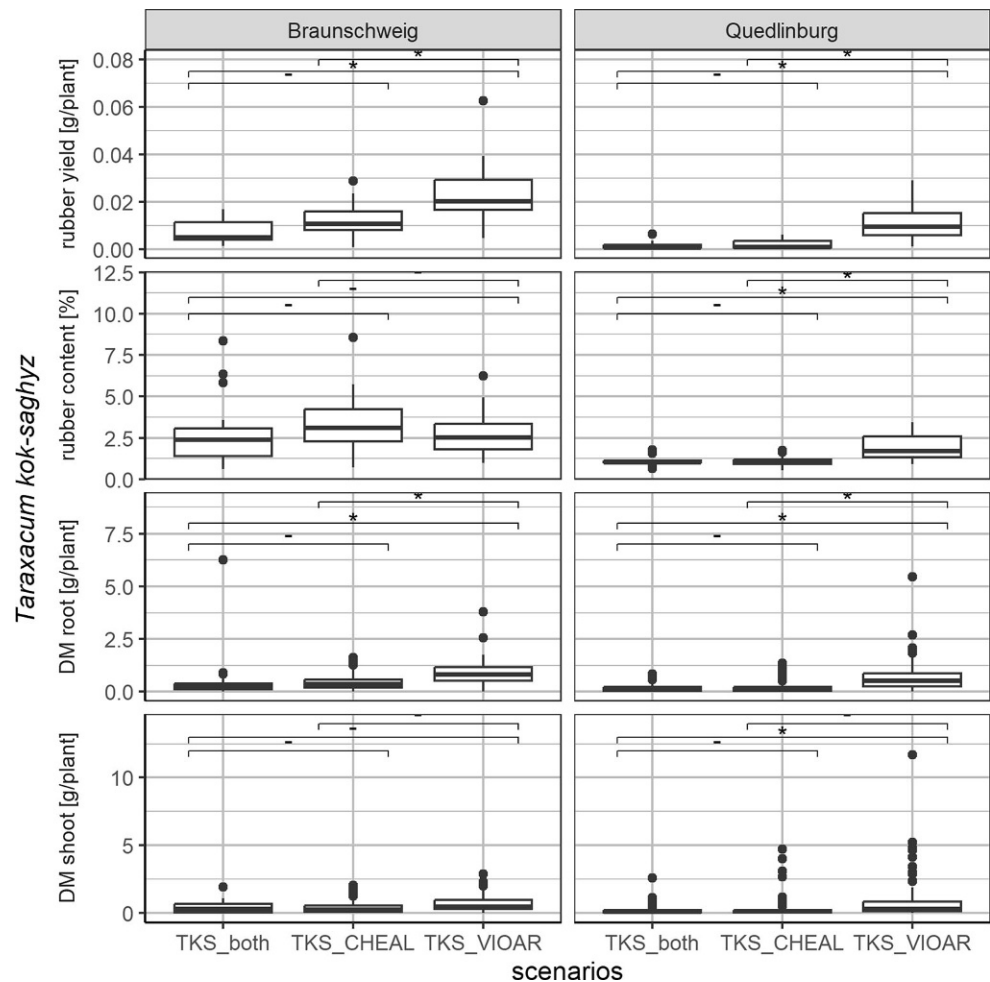
The presented trial design consisted of three scenarios with specific weed density gradients. Because we had only three scenarios and the competition gradients were ordinal scaled, we discarded regression analysis and decided to compare

the competition levels directly. However, as the weed density gradients were specific to the scenarios not all competition levels could be compared to each other and a global effect of the levels could not be estimated. On the other hand, we were able to compare the competition effect by scenario. Rubber yield, rubber content, dry matter of the roots, and dry matter of the shoots served as response variable. The Tukey HSD test was employed to test the group differences in these responses to all three contrasts we had for the three scenarios with the repetition set as a random factor. As the site effect was very strong, we decided to separate the dataset and conducted these tests for both sites separately. We used R (R Core Team 2024) to conduct the analysis. With the package glmmTMB (Mollie E. Brooks et al. 2017) we build the linear models and with emmeans (Russell V. Lenth 2024) we conducted the pairwise comparisons.

Results

In order to ascertain the impact of two weed species on rubber yield in TKS, the global effect of three different scenarios (TKS_CHEAL, TKS_VIOAR, TKS_both) on the performance of TKS was analyzed. The performance of TKS was measured in terms of TKS root dry matter, rubber content and the product of the latest, rubber yield, as well as shoot dry matter (Fig. 2). Shoot dry matter was quantified to gain insight into the overall development of the plant under specific scenarios. The same variables were used to understand the effect of different competition levels within the three scenarios on rubber content and dry matter (Fig. 3). In addition to the parameters of TKS, the shoot and root dry matter of the weeds were collected from pots at each site. This was done in order to facilitate a more comprehensive understanding of the performance of the weeds within the scenarios (Fig. 4 and 5).

Fig. 2 Four harvest parameters: rubber content, dry matter of the roots supplemented by the rubber yield as the product of both. The fourth parameter is the dry matter of the shoots of *T. kok-saghyz*. All parameters are given for the three crop-weed scenarios (TKS_both, TKS_CHEAL, TKS_VIOAR) after a growing period of 128 and 120 days in two trials sites Brunswick and Quedlinburg. The comparison was done for scenarios per site separately using the TukeyHSD test. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$



Rubber Yields Are Higher when Grown with *V. arvensis* than with *C. album* or both Weed Species

Analyzing the rubber yield of TKS under three different scenarios, we found a clear impact of the trial site, with Brunswick showing higher rubber yield than the site in Quedlinburg (Fig. 2). Although the site exerted a considerable influence, the impact of the scenario was less pronounced but consistent across both sites. Specifically, the two scenarios TKS_both and TKS_CHEAL yielded similar results, whereas TKS_VIOAR resulted in significantly higher rubber yield. Higher yields in Brunswick (median rubber yield in Brunswick: TKS_both 0.005 g/plant, TKS_CHEAL 0.011 g/plant, TKS_VIOAR 0.020 g/plant; median rubber yield in Quedlinburg: TKS_both 0.001 g/plant, TKS_CHEAL 0.001 g/plant, TKS_VIOAR 0.010 g/plant) can be primarily attributed to a combination of higher root dry matter and, more importantly, higher rubber content than in Quedlinburg. At both sites, the dry matter of the roots was slightly higher for TKS_VIOAR than for the other two scenarios.

TKS Reduces Root Dry Matter and Increases Rubber Content While Weed Competition Increase

Each pot was planted with TKS and weeds in a specific pattern, which resulted in three levels of competition. The effect of weed competition through different competition levels on rubber yield was comparable at both sites (Fig. 3). The lowest rubber yield occurred at high densities of *C. album* and the highest yield at low densities of *V. arvensis*. In contrast to the effect on rubber yield, the effect of competition levels on rubber content was found to be significant. Interestingly, the direction of this effect was site dependent for *C. album*, while the effect of *V. arvensis* remained consistent across both sites. In Quedlinburg, the highest rubber content was observed at low density of *C. album* (scenarios TKS_both and TKS_CHEAL) and at high densities in Brunswick (scenario TKS_CHEAL). Furthermore, increasing densities of *V. arvensis* in the TKS_VIOAR scenario led to a notable increase in rubber content at both sites.

The effect observed for root dry matter was mirrored for shoot dry matter, with similar patterns of biomass accumulation in response to varying weed densities. Lower weed

Fig. 3 Four harvest parameters: rubber content, dry matter of the roots supplemented by the rubber yield as the product of both. The fourth parameter is the dry matter of the shoots of *T. kok-saghyz*. All parameters are given for the three different competition levels of each scenario (TKS_both, TKS_CHEAL, TKS_VIOAR) at Brunswick and Quedlinburg. The pairwise comparison was conducted for every scenario and site separately using the TukeyHSD test. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

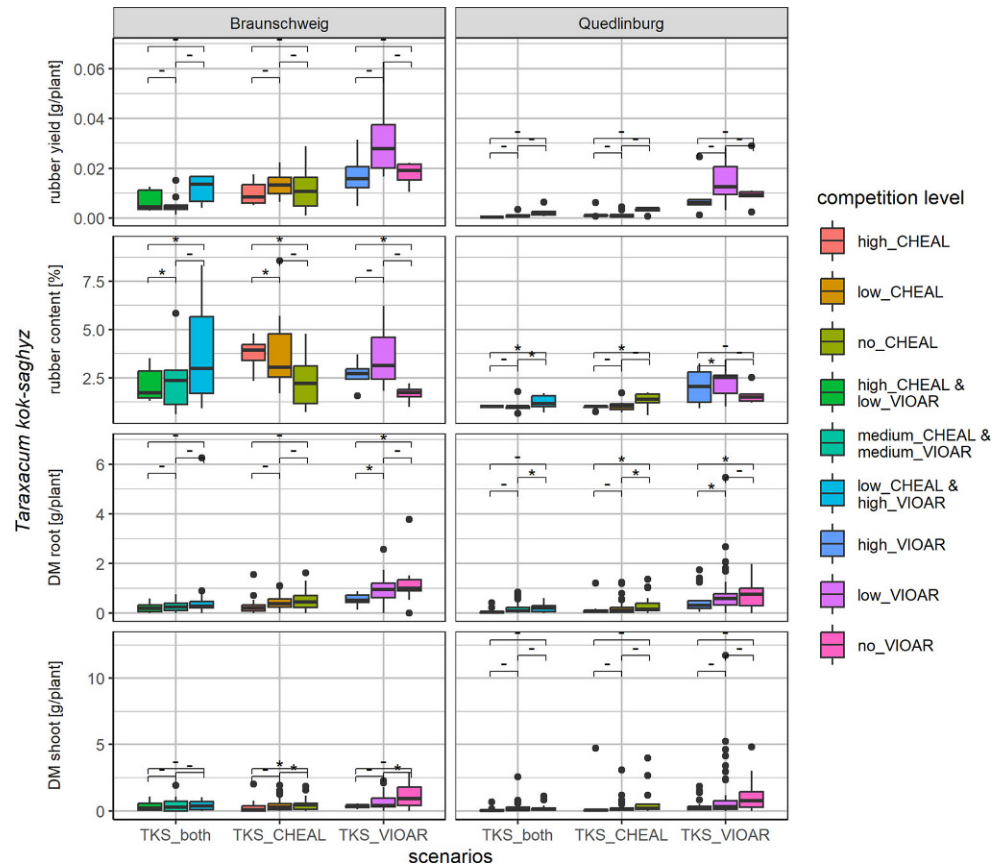
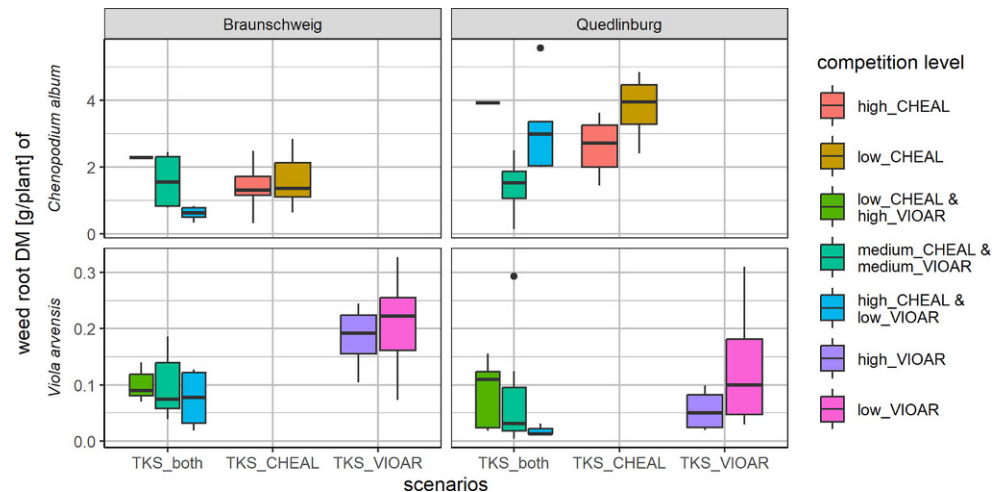


Fig. 4 Dry matter of the roots of the weed species *C. album* and *V. arvensis* for the different competition levels of each crop-weed scenarios (TKS_both, TKS_CHEAL, TKS_VIOAR) at Brunswick and Quedlinburg



densities generally resulted in higher root dry matter, with consistent trends across different scenarios.

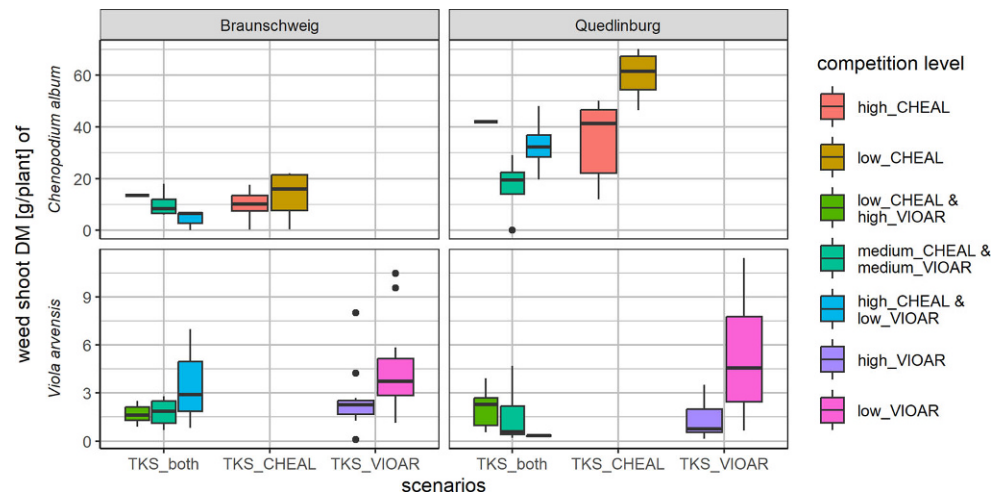
Weed Dry Matter Differs Between the Trial Sites

At harvest, the weeds were at the end of their vegetation after seed maturity. Seed shedding had already begun for many plants. The root and shoot dry matter of all weed plants of one repetition were quantified for each competi-

tion level within the three scenarios and two trial sites (Fig. 4). The weeds were assigned to the same competition levels as TKS, with the exceptions of the “no_CHEAL” and “no_VIOAR” levels, which did not contain weeds (Fig. 1). As with the parameters of TKS, the site of the experiment had a significant effect on the weed biomass.

In Quedlinburg, the pots were dominated by large *C. album* plants, which appeared much more robust compared to those at Brunswick, where *C. album* plants were notable

Fig. 5 Dry matter of the shoot of the weed species *C. album* and *V. arvensis* for the different competition levels of each crop-weed scenarios (TKS_both, TKS_CHEAL, TKS_VIOAR) after a growing period of 128 and 120 days in two trial sites Brunswick and Quedlinburg



lighter and smaller. This visual observation was supported by the weed dry matter of the shoots (Fig. 5). The root dry matter of *C. album* was higher in Quedlinburg than in Brunswick. In contrast, the root dry matter of *V. arvensis* was higher in Brunswick than in Quedlinburg (Fig. 4).

When comparing the two weed species, the root dry matter of *C. album* was approximately ten times higher than the root dry matter of *V. arvensis*. For *C. album*, the shoot dry matter was higher in Quedlinburg than in Brunswick. For *V. arvensis* the shoot dry matter exhibited a relatively consistent level at both sites (Fig. 4 and 5).

Discussion

In this study, we investigated the effect of weed competition on the rubber yield of *Taraxacum kok-saghyz*, focusing on the influence of the common agricultural weed species *Chenopodium album* and *Viola arvensis*. Our results indicate that both the species and the density at which they are distributed, defines the level of rubber yield. Specifically, the competitive effects varied depending on whether the weeds were present as single-species or as mixed-species communities. The trial site also played a crucial role in determining the growth of the weeds as well as the rubber yield, proving that both weeds and environmental factors interact to affect rubber content and root dry mass.

We hypothesized that the rubber yield of TKS is strongly influenced by the weed species growing alongside it, a hypothesis that was supported by our results. In detail, we observed higher rubber yield when TKS was grown with *V. arvensis* compared to *C. album* or a mixture of both species. These findings underscore the significant impact of weed species composition on TKS performance. *V. arvensis* and *C. album* differ considerably in their ecological characteristics, especially in their competitive abilities. Marshall et al. (2003) described that *V. arvensis* is approximately ten times

less competitive than *C. album*. Both are annual weeds capable of germinating in both spring and summer. They vary in traits that form the competitiveness, such as plant height or seed weight (Eslami and Ward 2021; Doohan and Monaco 1992). *C. album* has been shown to be highly competitive (Eslami and Ward 2021), whereas *V. arvensis* exhibits lower competitiveness (Degenhardt et al. 2005). This difference in competitiveness, particularly in terms of plant height and its influence on light availability, is likely to explain the higher rubber yield observed when TKS was grown with *V. arvensis*, as the latter may exert less competitive pressure on light.

In its native habitat, TKS typically grows in a loose stand alongside perennial and salt-tolerant species that are often grazed, thus limiting the natural competition for light (Ivashchenko et al. 2021; Uteulin et al. 2023). However, in European agricultural settings, TKS faces competition from highly adapted, tall weed species that compete for light. Unlike these annual weed species, TKS as a wild plant is not adapted to and does not profit from high nitrogen levels as common annual weeds do in European agriculture. In particular, tall weed species shade the rubber crop's canopy and result in a marked decrease in photosynthetic product accumulation under shaded conditions (Gao et al. 2020). Moreover, the effect of continuous weed growth without management, which intensifies competition for light, further reduces TKS stand density (Uhlemann et al. 2019). Unlike the approaches that consider the cumulative effect of all weed species present in a given field; our study employed a species-specific competition trial. We found that the impact of weeds on the rubber yield depends on the competitive ability of the specific weed species present. This suggests that TKS can tolerate certain weed species without significant yield losses, allowing a more nuanced approach to manage weeds in TKS. In particular, species such as *V. arvensis*, which are less competitive, exert minimal negative effect on TKS yield. Our findings support site-

specific weed management strategies, primarily focusing on controlling the most competitive weed species that have the greatest potential to reduce TKS rubber yield.

Nevertheless, the level of the rubber yield, which is the product of root dry matter and rubber content, varies according to the specific trial site. With this regard, the yield has been observed to be higher in Brunswick than in Quedlinburg under weed competition. Conversely, the weed shoot dry matter exhibits an inverse trend. The weed species *C. album* was larger, as indicated by the weed dry matter of the shoots at the time of harvest (Fig. 5), whereas the weed species in Brunswick was lighter. This result was obtained, even though the weeds were already very mature and has lost a good part of their leaves and seeds before harvest. This discrepancy in weed growth may be attributed to a higher nutrient supply at the Quedlinburg site, which was more efficiently utilized by *C. album* than by the rubber crop TKS. Previous research (Jäck et al. 2021) has shown that *C. album* benefits from increasing nitrogen availability in comparison to crops as pea and barley, which may explain the observed growth differences between the two sites. Furthermore, the resulting larger *C. album* plants might have induced a higher competition. This might be an explanation for the low rubber content and yield in Quedlinburg. Overall, the findings suggest that site-specific soil properties play a crucial role in shaping plant growth and competitive interactions, with *C. album* thriving under nutrient supply, while TKS was less responsive to these changes.

TKS exhibited resilience to another key factor in crop-weed competition, namely, the level of competition due to increasing weed densities, as this did not significantly reduce rubber yield. At the trial site Brunswick, where weed-crop competition was lower compared to Quedlinburg, increasing weed species densities did not significantly reduce rubber yield in TKS. Interestingly, TKS showed an increased rubber content when grown alongside higher plant densities of the individual weed species *V. arvensis* or *C. album* in Brunswick. In contrast, in sugar beet, another root crop, it is known that the biomass yield, and therefore the sugar yield, is negatively affected by weed pressure (Bhadra and Paul 2020). However, in most cases, the sugar content of sugar beets at harvest does not correlate with competition from weeds at all (Heidari et al. 2007; Longden 2008; Gerhards et al. 2017; Hamed et al. 2023). Only in the case of very massive weed pressure can the sugar content also decrease (Kulan and Kaya 2023).

However, the high level of competition led to a reduction in root dry matter. To the best of our knowledge, this is the first study examining the effect of weed species on both rubber content and root dry matter in TKS, and as such, we can only compare our results with those of previous studies on TKS grown in a pure stand. In those studies, increasing planting densities resulted in a reduction in root

dry matter per plant (Eggert et al. 2018; Bates et al. 2019), while rubber content remain stable despite higher planting densities (Bates et al. 2019). Thus, TKS may be able to tolerate or even benefit from a certain threshold of competition with weed species, potentially due to a stress induced enhancement of the rubber synthesis. However, the interaction between naturally occurring weeds and the biosynthesis of rubber content remains underexplored.

To date, research has primarily focused on the effect of rubber on the environment rather than the impact of environmental factor on rubber synthesis. However, there are mechanism mediated by the rubber (cis-1,4 polyisoprene) that positively affect soil health. For example, rubber can alter the soil microbiome in ways that can preserve the plant from pathogen attacks (Böttner et al. 2023; Guo et al. 2024). Additionally, rubber has been shown to reduce feeding damage from certain pests, as plants are less attractive to them compared to those plants with very little rubber (Böttner et al. 2023). While external factors that trigger increased rubber production are rare, some have been identified, such as the application of natural lipid lyso-PE (Lysophosphatidylethanolamine) which has been shown to accelerate rubber synthesis in TKS (Park et al. 2024). To understand the effect of external factors on the rubber content, future studies may focus on investigating the biochemical responses of TKS to interspecific competition under different environmental conditions. In addition, agronomic strategies that could help to increase rubber content while minimizing the negative impact on root dry matter should be investigated.

This study provides a first-view assessment of the complex interaction between weed species and their impact on TKS under controlled, semi-field conditions. A pot experiment was conducted to examine these interactions, with the study design potentially inducing edge effects—variation in the boundaries of the experimental units, as shown in Fig. 3. These effects were particularly evident under low-competition scenarios, where rubber content was high, but were less observed in the absence of competition. The opposite would be expected. However, given the relatively large diameter of the experimental pots, it is reasonable to assume that edge effects were not pronounced enough to significantly influence the overall outcomes. This likely explains why the model selection procedure discarded those models incorporating edge effects in the analysis of all harvest parameters.

In our experimental design we have integrated different density levels within a single plot. This design differs from other studies, which often use fixed densities in a pot. The advantage of our design is that it reflects the reality in the field where weeds can grow at different densities around the crop. This reality and the effects on TKS are shown in Fig. 2. A disadvantage of the condensed method, however,

is that competing weeds will not only act in the zone intended for them, but may also affect plants in the weed-free zone because the distance is not large enough. In our case this might be a reason for the higher yield in TKS_VIOAR compared to TKS_CHEAL even in the weed free competition level (Fig. 2).

Within the study design, we decided to focus on only one weed cohort, although in agricultural fields, weeds do not germinate all at once (Håkansson 1983). They have one or several germination peaks with some variability. We did not include this effect in our study, but limited our design to weed species and the density gradient. In general, individual weed plants that germinate later in season do not compete very well with crops. This is often related to successful canopy closure and therefore a strong competition for light by the crops, as was reviewed by Jha et al. (2017). As TKS is not a tall growing plant, this effect is unlikely to be observed with this specific crop. However, canopy development might be a selection criterion for future breeding efforts.

In conclusion, TKS has the potential to become an alternative source of natural rubber and a lot of effort is being put into it. Weed competition is one of the major causes of yield loss in TKS, suggesting that considerable effort needs to be devoted to weed management in TKS. Our study provides one of the first insights into the interactions between TKS and two common weed species with contrasting competitive abilities. Our results proof that management of certain highly competitive weeds is appropriate to avoid yield losses. Thus, a more specialized species-specific weed management in TKS is even a better approach than a simple site-specific approach for future management strategies in TKS. However, a major issue to be resolved is the definition of the critical period for weed control measures for a precise timing of weed control measures for a sustainable rubber production of TKS. As a next step towards a precise weed management, our data could be incorporated into simulation models, such as those developed to simulate the growth of individual plants within a crop (von Redwitz et al. 2024). All this information can help to anticipate and evaluate the consequences of new technologies, such as the use of robotic individual plant weeding, or the consequences of reduced herbicide use when lower doses are applied with the consequence of a certain level of weed survival, a problem faced by minor crops have to deal with. Our work is therefore relevant not only to TKS, but also to a wider range of other minor or underutilized crops.

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Conflict of interest H. Pannwitt, C. von Redwitz and K. Thiele declare that they have no competing interests.

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