



Evaluation of perspective drought-tolerant genotypes of hops (*Humulus lupulus* L.)

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Abstract

Six hop genotypes with high drought tolerance were developed and submitted to the registration trials of the Ministry of Agriculture of the Czech Republic. These genotypes were planted in semi-operational plots at a dry, non-irrigated site in Nesuchyně and at an irrigated control site near the Ohře River in Rybřany. Two genotypes, 5165 and 5304, represent bitter hops with alpha-acid levels above 10% w/w. Three genotypes, 5432, 5461 and 5465, are aroma hops with alpha-acid contents ranging from 6.05% (5465) to 6.95% (5461). Genotype 5559 is a fine aroma type with subtle flavour-hop notes combining attributes typical of Saaz and Kazbek. For all genotypes, the content and composition of hop resins and essential oils, as well as the intensity and character of cone aroma, were evaluated at both sites from 2023 to 2025. In 2025, two genotypes were registered as new Czech hop varieties. Genotype 5165 was registered as Uran, with an alpha-acid content of 11.56–12.61% w/w, beta-acid content of 4.78–5.08% w/w, and essential-oil levels of 1.77–2.19% w/w. Uran exhibits a high aroma intensity dominated by spicy (black pepper, lovage, garlic, onion) and woody (conifer) notes. Genotype 5559 was registered as Art, with an alpha-acid content of 5.42–6.46% w/w, beta-acid content of 5.22–5.82% w/w, and essential-oil levels of 1.02–1.43% w/w. Art combines a hop character reminiscent of Saaz with citrus notes (lemon, orange peel, zesty lime) and fruity tones (sweet tropical fruit such as mango and papaya) inherited from its maternal variety Kazbek.

Keywords: hops, *Humulus lupulus* L., varieties, drought tolerance, hop resins, hop essential oils, aroma

1 Introduction

The total world hop acreage in 2025 is 52,873 ha (Kovářík, 2025). The Czech Republic, with its 4,816 ha, ranks third after Germany (18,962 ha) and the USA (17,091 ha). In the Czech Republic, hops are grown in the three hop-growing regions of Žatec, Ústěk and Tršice. The largest hop-growing area (3,691 ha) is the Žatec region (Vaculík, 2025). Historically, the Žatec region has been divided into the Žatec and Rakovník sub-regions. The Rakovník part is characterised by cambisols and, above all, by a persistent water deficit. Water sources for irrigation are very limited, which is why this area is classified as a dry locality. In recent years, substantial fluctuations in high

temperatures combined with insufficient precipitation have caused high variability in hop performance in dry regions. For this reason, many new hop varieties are tested specifically in this locality (Nesvadba et al., 2020a).

From a historical perspective, hop breeding initially focused on clonal selection within the original populations of the Saaz-type hop. Through clonal selection, eight Saaz clones were gradually registered (Fric, 1994), but only Oswald's clones 31, 72 and 114 found practical use (Nesvadba et al., 2020b). Hybridization methods began to be applied in Czech hop breeding only in the 1950s, leading to the registration of the Bor and Sládek varieties (Linhart and Nes-

vadba, 1994). Subsequent breeding efforts targeted higher alpha acid content, and the first Czech bitter variety, Agnus, was registered in 2001 (Nesvadba and Krofta, 2002). Later, breeding priorities shifted towards the development of varieties with specific aroma (flavour), resulting in the 2008 registration of the Kazbek variety, characterised by a strong citrus aroma (Krofta et al., 2019a).

Breeding for low-trellis systems (Nesvadba, 2016) also deserves attention. This led to the registration of the first Czech low-trellis hop varieties — Country, Jazz and Blues — in 2018 and 2019 (Nesvadba, 2020e). Naturally, hop breeding is a continuous process; therefore, new fine-aroma varieties have been developed using Saaz-derived hybridization, namely Saaz Late, Saaz Brilliant, Saaz Comfort and Saaz Shine (Nesvadba and Charvátová, 2020d). The same applies to new flavour varieties. In 2022 and 2023, a new generation of flavour hops—Juno, Ceres, Saturn, Jupiter, Eris and Pluto—was registered, featuring pronounced fruity, citrus, spicy or woody notes (Nesvadba et al., 2022).

Breeding targets have always included resistance to fungal diseases, high yield, and the required content and composition of hop resins and essential oils (Trefilová et al., 2022). Throughout the breeding process, both qualitative and quantitative traits have been monitored with respect to brewing and cultivation requirements. Given the substantial rise in temperatures combined with frequently very low precipitation, hop breeding is now viewed from a new perspective. In recent years, priority has been given to breeding varieties tolerant to high temperatures and drought (Krofta et al., 2019b). Lack of precipitation significantly reduces hop performance, such as yield and hop resin content (Krofta et al., 2024). Numerous new crossings have been carried out with the aim of obtaining hop genotypes capable of withstanding drought stress. For this reason, since 2021 the research project QK21010136 “*Application of new varieties and genotypes of drought-resistant hops to cultivation and brewing practice*” has been underway.

Within the project, a methodology was developed that was used to test the existing Czech hop varieties (Olšovská et al., 2024a; Nesvadba et al., 2023a; Olšovská et al., 2023). Using this approach, it was demonstrated that, for example, the new fine-aroma varieties Saaz Comfort and Saaz Shine show very good drought tolerance compared with their parent cultivar Saaz (Olšovská et al., 2024a) and possess excellent technological and sensory properties that preserve the traditional taste of Czech lager (Olšovská et al., 2024b). The next step was to extend the testing to new genetic material in order to select varieties that exhibit very low year-to-year variability in hop yield and in the content of key brewing constituents.

This paper aims to evaluate the content and composition of hop resins, hop oils, and the aroma profile of hop cones in promising genotypes exhibiting high drought tolerance. The study integrates three years of field and greenhouse assessments, comparing chemical, physiological and sensory characteristics across contrasting locations. By analysing both bitter and aroma cultivars alongside established Czech varieties, the paper identifies genotypes that combine drought resilience with stable agronomic performance and brewing potential. These findings provide a basis for selecting hops suitable for dry, non-irrigated regions and for supporting further breeding aimed at strengthening drought resistance in Czech hop production.

2 Materials and methods

2.1 Plant Material, Breeding Scheme and Resistance Screening

The development of new hop varieties is carried out using controlled hybridization. Seeds produced from carefully selected parental combinations are sown in greenhouse conditions, where the resulting seedlings undergo initial screening for resistance to downy mildew (*Pseudoperonospora humuli*) and powdery mildew (*Podosphaera macularis*) according to a previously published method (Trefilová et al., 2022). Plants showing resistance or tolerance are transplanted to the breeding hop garden. In the second year, the most promising genotypes are selected and advanced to the next breeding stage.

After approximately five years of field evaluation, the best genotypes are propagated vegetatively and established in a control plot arranged in three replications. This is followed by field and regional trials, during which comprehensive assessments of agronomic performance as well as brewing characteristics are conducted.

2.2 Evaluation of Drought Tolerance

In parallel with field selection, promising genotypes were tested for drought tolerance in greenhouse conditions following previously published methodology (Olšovská et al., 2024a; Olšovská et al., 2023). Genotypes were propagated and assessed using a gasometrical approach. Photosynthetic (A) and transpiration (T) rates were measured with an LCpro SD device (ADC Bioscientific Ltd., UK) prior to the cessation of irrigation and again after ten days of water stress (Nesvadba et al., 2023b). Visual assessment (V) complemented the physiological measurements (Nesvadba et al., 2025). Greenhouse tests were conducted in 2021 and 2022.

Based on drought-tolerance tests, genotypes showing low year-to-year variability in yield and resin content were selected. The best-performing genotypes were subsequently submitted to the registration trials supervised by the Central Institute for Supervising and Testing in Agriculture (ÚKZÚZ).

2.3 Genotypes Selected for Registration Trials

In 2022, six genotypes showing strong drought tolerance were submitted to the ÚKZÚZ registration trials.

5165 (Uran) — a 2006 cross. This genotype originates from progenies of American and European bitter varieties combined with open pollination. The plant exhibits an inverted-cone growth type, purple bine colour, long laterals and very large cones. It is a semi-late variety. Under experimental conditions, hop yields of 2.1–2.8 t/ha were achieved. The genotype was registered in 2025 under the name Uran.

5304 — a 2007 cross. Its pedigree includes the varieties Agnus and Taurus, together with additional breeding material. The plant has a robust, irregular cylindrical growth type, green-red bine colour, long laterals and large cones. It is a semi-late variety with yields of 2.0–2.4 t/ha.

5432 — a 2010 cross. Developed from progenies of Czech, European and American high-alpha varieties combined with the aromatic Saaz and Fuggle types. The plant has a strong cylindrical growth type, red-green bine colour, long laterals and medium-sized cones. Experimental yields reached 2.0–2.4 t/ha.

5461 — a 2011 cross. Developed from progenies of American high-alpha varieties (female) and the Czech aroma varieties Premiant and Harmonie (male). The plant exhibits a spindle-shaped to cylindrical growth type, red-green bine colour, long laterals and medium-sized cones. Experimental yields reached 1.9–2.5 t/ha.

5465 — a 2011 cross. Developed through a back-cross with the Sládek variety; Saaz, Fuggle, Magnum and Northern Brewer also appear in its pedigree. The plant has a medium cylindrical growth type, red-green bine colour, long laterals and medium-sized cones. Experimental yields reached 2.2–2.7 t/ha.

5559 (Art) — a 2013 cross. This genotype originates from the variety Kazbek and the male 03/3, a multiple-cross derivative of American and European bitter varieties with Saaz. The plant has a robust cylindrical growth type, red-green bine colour, medium-long laterals and firm medium-sized cones. It is a semi-late variety with yields of 2.0–2.5 t/ha. The genotype was registered in 2025 under the name Art.

2.4 Field Trials and Locations

Field evaluations were carried out at two contrasting locations:

- Ohře River Basin – Rybňany
Alluvial soils; hop gardens equipped with irrigation (GPS 50.3299241, 13.5957385).
- Rakovník Region – Nesuchyně
Cambisol soils; a dry, non-irrigated locality (GPS 50.1838557, 13.6883724).

Trial plots were established in autumn 2022 at a spacing of 300 × 114 cm, coinciding with the establishment of the surrounding commercial hop garden. For each genotype, a minimum of 14 plants was planted. Harvests were carried out on the full set of plants using a Volf hop-picking machine at the Hop Research Institute Co., Ltd., Žatec.

2.5 Chemical and Sensory Analyses

Composite samples (dry cones) were taken from each harvested batch for chemical analyses. The content and composition of hop resins were determined by HPLC according to the EBC 7.7 method ([Analytica EBC \[online\]](#)). The essential oil content and composition were analysed following the methodology ([Krofta, 2003](#)). Chemical analyses were performed from 2023 to 2025.

2.6 Sensory Analysis of Hops

Each year after harvest, dried hop cones were evaluated for aroma. The assessment focused on the intensity of selected aroma attributes—hoppy/herbal, spicy, fruity, woody, citrusy, grassy, and floral—rated on a 0–10 point scale. In addition, specific aroma characteristics were described. Sensory evaluation was conducted annually with the participation of at least 50 panellists who have experience in sensory evaluation of hops. The evaluation of the aroma character is in accordance with the Czech Atlas of Hop Varieties ([Nesvadba et al., 2022](#)). The intensity of the scent is rated: very low, low, medium, high and very high.

2.7 Statistical Methods

Basic statistical parameters were calculated, including the mean ($\bar{x}$) and standard deviation (s). The coefficient of variation (C_v), which expresses the degree of variability in percentage multiplied by a factor of one hundred, was used for data processing ([Meloun and Militký, 1994](#)).

3 Results and discussion

3.1 Bitter genotypes 5165 (Uran) and 5304

Table 1 shows that **Uran** exhibits similar alpha-acid content at the dry locality Nesuchyně (12.61% w/w) compared with

the irrigated control site Rybňany (11.56% w/w), while also showing lower variability (8.79%). In contrast, at Rybňany the genotype displays also similar beta-acid content (5.08% w/w), resulting in a lower alpha/beta ratio (2.29). The results further indicate that location does not affect the proportion of cohumulone, which amounted to 22.33% rel. in Rybňany and 23.37% rel. in Nesuchyně.

Uran is characteristic of Czech bitter hop varieties and falls within the range reported for Agnus, Rubín, Vital, Gaia and Boomerang. According to Nesvadba et al. (2023b), the alpha-acid content of Uran is comparable with Rubín, Boomerang and Vital (11.33–12.26% w/w). Its beta-acid level is similar to Agnus (4.92% w/w) and exceeds only that of Rubín. Uran also exhibits a relatively low cohumulone proportion, a characteristic shared primarily with Gaia and Vital (Nesvadba et al., 2022).

A higher essential-oil content was recorded for Uran at Rybňany (2.19% w/w) compared with Nesuchyně (1.77% w/w), while the composition of hop essential oils remained unaffected by location. Uran is distinguished by a high proportion of myrcene, reaching approximately 50% rel., which is comparable to the Czech bitter varieties Agnus, Boomerang and Vital (Nesvadba et al., 2022). The variety is also notable for its farnesene content. Among registered Czech hops, farnesene occurs only in Saaz, Saaz Late, Saaz Brilliant, Saaz Comfort and Saaz Shine (Olšovská et al., 2024a). Uran is therefore the first Czech bitter hop variety characterized by the presence of farnesene in its essential-oil profile.

ican hop germplasm. In contrast, hop-like, grassy, herbal and fruity notes (sweet fruit, green apple, blackcurrant) occur only in low proportions.

The overall aroma profile differs markedly from that of Agnus, Rubín, Vital and Gaia, all of which are defined by strong hop-like characteristics. Although Boomerang displays a somewhat similar profile, Uran shows a higher intensity of woody, fruity, herbal and grassy notes (Nesvadba et al., 2022).

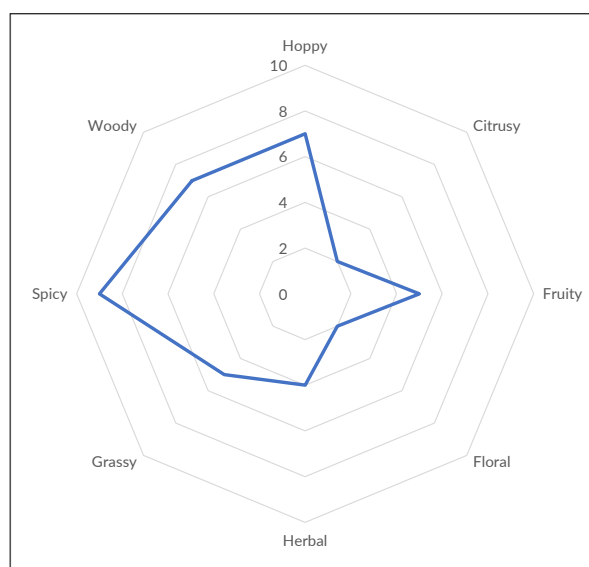


Figure 1 Aroma profile of the hop variety Uran

Table 1 Content and composition of hop resins in the variety Uran in 2023–2025

	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně
x	11.56	12.61	5.08	4.78	2.29	2.64	22.33	23.37
s	2.61	1.11	0.56	0.11	0.60	0.27	0.85	1.60
Cv (%)	22.58	8.79	11.09	2.36	25.97	10.12	3.81	6.83

Table 2 Content and composition of essential oils in the variety Uran in 2023–2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybňany	2.19	53.85	4.80	9.59	6.59	1.95
Nesuchyně	1.77	49.20	4.35	10.28	6.22	1.72

Uran is characterized by a high aroma intensity. As shown in Figure 1, the variety exhibits pronounced spicy notes (black pepper, lovage, garlic) together with distinct woody tones (conifer), traits likely inherited from Amer-

Genotype 5304 shows a markedly higher alpha-acid content at the dry locality Nesuchyně (13.42% w/w) compared with the irrigated site Rybňany (10.67% w/w). Variability, however, is lower in Rybňany, reaching only

3.84%. The elevated level and variability observed in Nesuchyně were influenced by the exceptionally high alpha-acid value recorded in 2025 (15.13% w/w). Genotype 5304 exhibits a high alpha/beta-acid ratio (3.02 and 3.46, respectively), a characteristic otherwise found only in the variety Rubín (Nesvadba et al., 2013). Lower variability in beta-acid content and in the alpha/beta ratio was observed in the dry locality. The cohumulone proportion remains below 30% rel., similar to Uran.

Essential-oil content is slightly higher in Nesuchyně (1.64% w/w) than in Rybnány (1.54% w/w), although overall levels are lower than those of Uran. The composition of hop essential oils does not appear to be influenced by location. Genotype 5304 is characterized by low proportions of myrcene, caryophyllene and farnesene, and by relatively high levels of humulene and the selinenes. In terms of essential-oil profile, 5304 closely resembles the Czech bitter variety Rubín (Nesvadba et al., 2022).

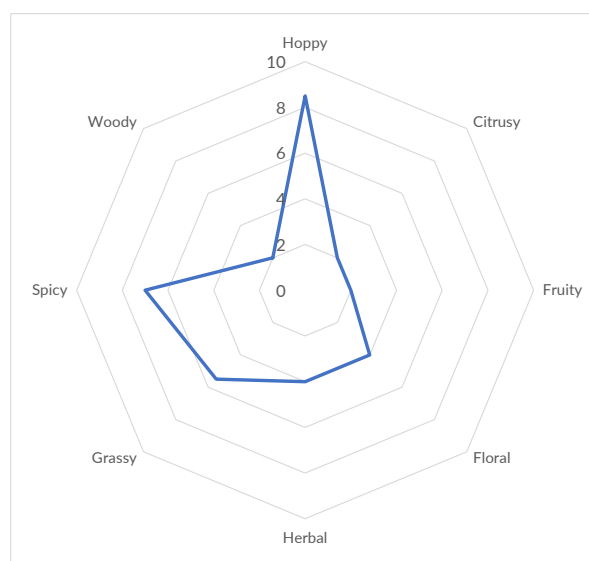


Figure 2 Aroma profile of hop genotype 5304

Table 3 Content and composition of hop resins in genotype 5304 in 2023–2025

Locality	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
	Rybnány	Nesuchyně	Rybnány	Nesuchyně	Rybnány	Nesuchyně	Rybnány	Nesuchyně
x	10.67	13.42	3.59	3.87	3.02	3.46	24.23	27.53
s	0.41	1.55	0.63	0.36	0.44	0.10	0.80	1.16
Cv (%)	3.84	11.55	17.42	9.39	14.62	2.98	3.31	4.21

Table 4 Content and composition of hop essential oils in genotype 5304 in 2023–2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybnány	1.54	23.60	9.26	0.42	19.00	18.15
Nesuchyně	1.64	27.20	9.43	0.65	20.50	16.75

Genotype 5304 is characterized by very high aroma intensity. As illustrated in Figure 2, it displays a pronounced hoppy and spicy aroma (resinous, garlic), while grassy, herbal (ginger) and floral notes occur only in lower proportions. Based on its sensory profile, 5304 aligns with Czech bitter varieties that exhibit a strong hop-like character, particularly Agnus and Vital (Nesvadba et al., 2022).

3.2 Aromatic genotypes 5432, 5461, and 5465

Genotype 5432 shows higher alpha- and beta-acid levels at the dry locality Nesuchyně (6.87% w/w and 4.05% w/w, respectively) compared with the irrigated site Rybnány (6.29% w/w and 3.32% w/w, respectively). At both locations, the alpha/beta ratio remains below 2.

With respect to alpha-acid content and the alpha/beta ratio, 5432 corresponds to Czech aroma varieties such as Bor, Premiant and Sládek. The genotype also displays a low cohumulone proportion, which is typical for Czech aroma hops. The highest variability recorded for this genotype concerns the beta-acid content in Nesuchyně (17.15%).

Essential-oil content is low in both locations, reaching 0.75% w/w in Rybnány and 0.79% w/w in Nesuchyně – the lowest values among the examined genotypes. Comparable levels occur only in the Czech varieties Mimosa and Saaz Shine (Nesvadba et al., 2021). An essential-oil content around 0.7% w/w is also characteristic of the English variety Pilgrim (Trefilová et al., 2022). The composition of essential oils is largely unaffected by location,

except for a moderately higher proportion of humulene (+4.70% rel.) in Rybňany. In terms of oil profile, genotype 5432 resembles Czech aroma varieties such as Bor, Kazbek and Premiant (Nesvadba et al., 2022). It is characterized by low proportions of myrcene, caryophyllene, farnesene and selinenes, and by a correspondingly high proportion of humulene.

Genotype 5461 shows a substantially higher alpha-acid content at the dry locality Nesuchyně (9.65% w/w) compared with the irrigated site Rybňany (8.61% w/w), while the beta-acid content remains essentially identical at both locations. Likewise, the alpha/beta ratio and the cohumulone proportion are stable across sites, indicating that these traits are not influenced by locality. This geno-

Table 5 Content and composition of hop resins in genotype 5432 in the years 2023 to 2025

	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
Locality	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně
x	6.29	6.87	3.32	4.05	1.90	1.72	21.70	25.47
s	0.75	0.57	0.31	0.70	0.28	0.22	1.20	1.66
Cv (%)	11.93	8.26	9.35	17.15	14.77	12.53	5.53	6.53

Table 6 Content and composition of hop essential oils of genotype 5432 in the years 2023 to 2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybňany	0.75	29.90	10.79	1.88	27.95	2.32
Nesuchyně	0.79	26.30	11.24	0.90	30.15	2.66

Genotype 5432 is characterized by low overall aroma intensity. As illustrated in Figure 3, it displays a dominant hoppy and spicy character, while grassy, herbal (mint, marzipan), floral and fruity (tropical fruit) notes occur only in lower proportions. Based on its aroma profile, 5432 resembles varieties with hoppy, spicy and herbal characteristics, such as Blues and Jazz (Nesvadba et al., 2022).

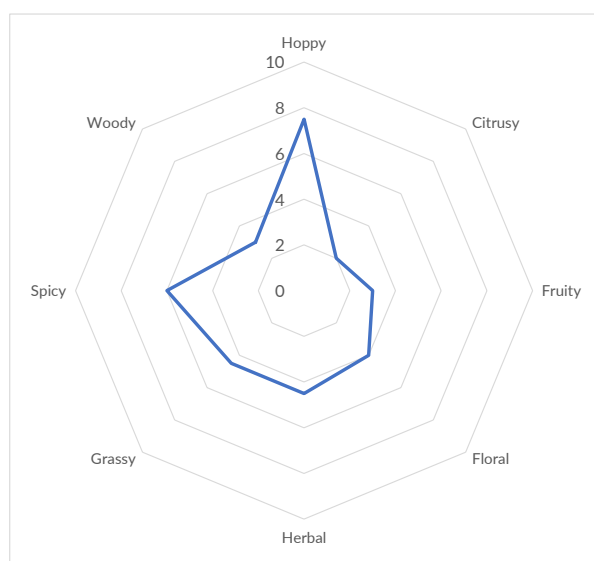


Figure 3 Aroma profile of hop genotype 5432

type is further characterized by very low variability in both the content and composition of hop resins. Compared with Czech aroma varieties, 5461 differs markedly. In terms of alpha-acid content it resembles Bor, Harmonie and Premiant, yet none of the Czech aromatic varieties exhibits such a high alpha/beta ratio (Nesvadba et al., 2022).

Essential-oil content is considerably higher in Rybňany (2.26% w/w) than in Nesuchyně (1.88% w/w). No Czech aromatic variety reaches an essential-oil level above 2.0% w/w; such values are otherwise found only in the bitter varieties Agnus, Boomerang, Gaia, Vital and in the flavour variety Saturn. As with hop-resin traits, the composition of essential oils appears unaffected by location. In terms of oil-profile characteristics, genotype 5461 shows similarity only to the low-trellis variety Jazz (Nesvadba et al., 2022). The genotype is characterized by low proportions of myrcene, caryophyllene, farnesene and humulene, and by a comparatively high proportion of selinenes.

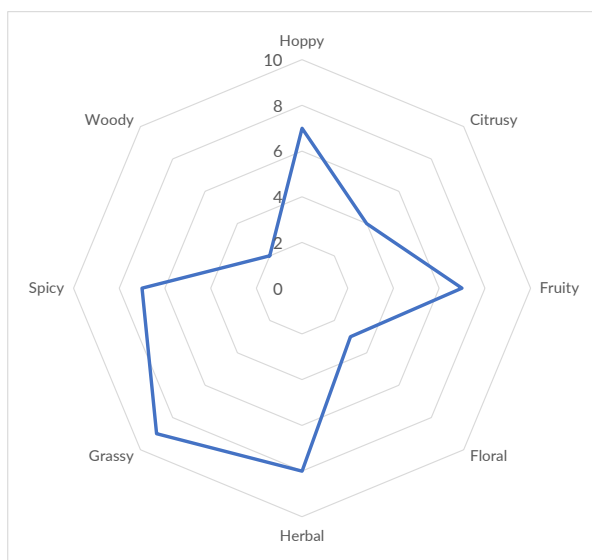
Genotype 5461 is characterized by high aroma intensity and a notably broad aromatic spectrum. As illustrated in Figure 4, it displays pronounced grassy and herbal notes (mint, jasmine), complemented by fruity tones (tangerine peel, orange, blackcurrant) and distinct spicy accents (paprika, garlic). With this combination of attributes, 5461 represents a sensory type that is currently not found among registered Czech hop varieties.

Table 7 Content and composition of hop resins in genotype 5461 in the years 2023 to 2025

	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
Locality	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně
x	8.61	9.65	3.59	3.74	2.40	2.58	27.30	27.23
s	0.76	0.64	0.21	0.04	0.09	0.18	1.11	2.25
Cv (%)	8.77	6.58	5.76	1.08	3.83	6.84	4.08	8.25

Table 8 Content and composition of hop essential oils in genotype 5461 in the years 2023 to 2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybňany	2.26	30.85	7.18	0.46	7.10	14.65
Nesuchyně	1.88	24.85	8.10	0.30	7.49	18.75

**Figure 4** Aroma profile of hop genotype 5461

Genotype 5465 exhibits nearly identical alpha-acid levels at both locations, reaching 6.14% w/w in Rybňany and 6.05% w/w in Nesuchyně. Variability, however, differs considerably: it is markedly higher in Rybňany (16.35%) than in Nesuchyně (5.52%). The beta-acid content shows the opposite pattern — higher in Rybňany (3.76% w/w), but with lower variability (8.08%). The alpha/beta ratio and the cohumulone proportion are nearly identical in

both sites. Taken together, these results indicate that genotype 5465 shows relatively high overall variability. In the coming years, it will be essential to determine whether this instability is genetically conditioned or primarily influenced by environmental factors such as weather patterns or agronomic practices. With respect to alpha-acid levels, 5465 corresponds to the Czech varieties Blues, Bohemia and Sládek (Nesvadba et al., 2022).

Essential-oil content is very high in both locations, reaching 2.30% w/w in Nesuchyně and 2.03% w/w in Rybňany — the highest among all newly evaluated genotypes. The oil profile of 5465 is characterized by elevated proportions of myrcene and humulene, and lower proportions of caryophyllene, farnesene and the selinenes. This places 5465 among the new aromatic hop genotypes with exceptionally high essential-oil levels. As with the previously assessed traits, locality does not appear to influence oil composition. In terms of essential-oil profile, genotype 5465 is similar only to genotype 5461 and to the variety Jazz (Nesvadba et al., 2022).

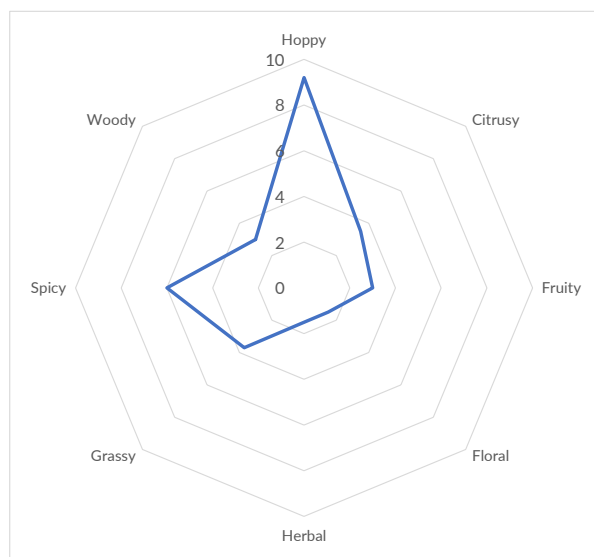
Genotype 5465 is characterized by medium aroma intensity. As illustrated in Figure 5, it displays a dominant delicate hop aroma, accompanied by secondary spicy, grassy and mildly fruity notes (dried fruit, red currant). Based on its aroma profile, the genotype falls between the varieties Sládek and Premiant. From this perspective, 5465 is likely well suited for use in lager-type beers.

Table 9 Content and composition of hop resins in genotype 5465 in the years 2023 to 2025

	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
Locality	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně
x	6.14	6.05	3.76	3.30	1.66	1.88	22.97	26.13
s	1.00	0.33	0.30	0.60	0.41	0.36	1.50	1.08
Cv (%)	16.35	5.52	8.08	18.06	24.79	18.93	6.52	4.13

Table 10 Content and composition of hop essential oils of genotype 5465 in the years 2023 to 2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybňany	2.03	31.00	10.50	0.30	21.95	11.15
Nesuchyně	2.30	33.80	9.67	0.30	22.70	12.50

**Figure 5** Aroma profile of hop genotype 5465

3.3 Fine aroma variety 5559 (Art) with subtle flavour-hop notes

The **Art** variety shows higher alpha- (6.46% w/w) and beta-acid content (5.82% w/w) at the dry locality Nesuchyně compared with the irrigated site Rybňany. These results indicate that Art is likely the variety with the highest drought tolerance among those evaluated. In both locations, it exhibits low variability in alpha-acid content. Among all evaluated genotypes, Art has the highest beta-acid level; comparable values in Czech varieties are found only in Agnus, Harmonie and Sládek

(Nesvadba et al., 2020e). In Rybňany, relatively high variability was recorded in the alpha/beta ratio (20.91%), whereas cohumulone proportion remained extremely stable (0.99%). For fine aroma hop varieties, the alpha/beta ratio typically approximates 1. In terms of alpha-acid content, Art corresponds to the variety Saaz Comfort (Nesvadba et al., 2022).

The essential-oil content of Art is medium-high, ranging from 1.02% w/w in Rybňany to 1.43% w/w in Nesuchyně, with the latter showing an increase of 0.41% w/w. In this respect, Art is closest to the fine aroma varieties Saaz Comfort and Saaz Shine (Nesvadba et al., 2022). A notable difference appears in oil composition: Art does not contain farnesene, a typical component of Saaz-derived varieties (Olšovská et al., 2024b). Conversely, its selinene proportion reaches levels otherwise found only in the Bohemia variety (Nesvadba et al., 2021).

As illustrated in Figure 6, the Art variety expresses a hoppy character inherited from Saaz, while its citrus notes (lemon, orange peel, zesty lime) and fruity tones (tropical sweet fruits such as mango and papaya) originate from the Kazbek parent. Kazbek is well known for its distinct citrus aroma (Nesvadba et al., 2022), a trait typical of the flavour-hop group (Olšovská et al., 2020). Art also displays a mild intensity of spicy notes (white and black pepper). Through this combination, the variety successfully integrates fine-aroma characteristics with flavour-type attributes, forming a unique sensory profile within Czech hop breeding.

Table 11 Content and composition of hop resins of the Art variety in the years 2023 to 2025

	Alpha acids (% w/w)		Beta acids (% w/w)		Ratio (alpha/beta)		Cohumulone (% rel.)	
Locality	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně	Rybňany	Nesuchyně
x	5.42	6.46	5.22	5.82	1.07	1.12	21.13	20.63
s	0.39	0.30	1.12	0.85	0.22	0.12	0.21	1.99
Cv (%)	7.25	4.69	21.37	14.60	20.91	10.58	0.99	9.62

Table 12 Content and composition of hop essential oils of the Art variety in the years 2023 to 2025

Locality	Content (% w/w)	Myrcene (% rel.)	Caryophyllene (% rel.)	Farnesene (% rel.)	Humulene (% rel.)	Selinenes (% rel.)
Rybňany	1.02	31.00	10.50	0.30	21.95	11.15
Nesuchyně	1.43	35.90	15.40	0.30	23.00	13.40

3.4 Evaluation of Tolerance to Water Stress

Table 13 summarises the evaluation of hop plants exposed to water stress. The assessment focused on the rate of photosynthesis (A), the rate of transpiration (T) and visual scoring (V). For comparison, the results of the new genotypes 5165 (Uran), 5304, 5432, 5461, 5465 and 5559 (Art) were evaluated alongside the fine aroma variety Saaz and the bitter variety Rubín.

Based on the photosynthesis rate ($A = 0.00 \mu\text{mol CO}_2/\text{m}^2/\text{s}$) and the visual score ($V = 4$), it is clear that the traditional varieties Saaz and Rubín do not survive a 10-day drought period. Genotype 5304 also ceases growth under these conditions but is able to regenerate once irrigation is restored. This behaviour is reflected in its high variability of alpha-acid content in the dry locality of Nesuchyně (11.55%). Although that table covers only a three-year dataset, this trend is likely to continue.

Very positive results were obtained for genotypes 5165 (Uran), 5432 and 5465, with the best performance observed in 5461 and 5559 (Art). The Art variety, even after ten days of drought, achieved a visual score of 1, corresponding to negligible growth reduction, slightly yellowing lower leaves and minimal drought symptoms. It also maintained very high physiological activity, with A reaching $9.05 \mu\text{mol CO}_2/\text{m}^2/\text{s}$ and T reaching $1.69 \text{ mmol H}_2\text{O}/\text{m}^2/\text{s}$ — values almost identical to those measured before stress ($A 9.62 \mu\text{mol CO}_2/\text{m}^2/\text{s}$; $T 2.45 \text{ mmol H}_2\text{O}/\text{m}^2/\text{s}$).

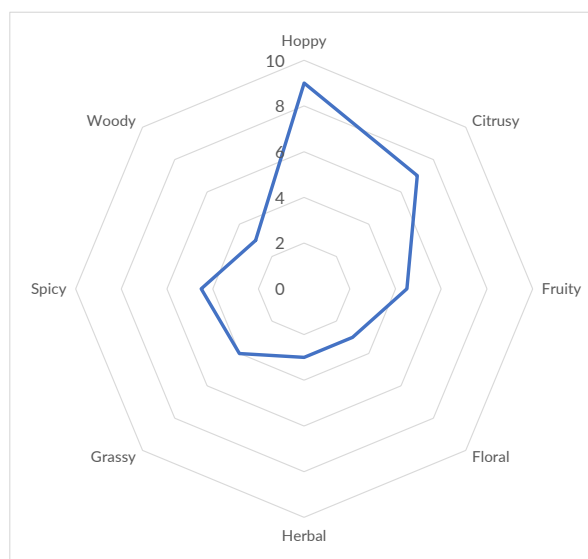


Figure 6 Aroma profile of the Art hop variety

composition and aroma profile, with several showing markedly higher drought tolerance than traditional varieties. Uran and 5304 stand out among bitter hops, although only Uran combines stability with practical brewing relevance. Within the aroma group, genotypes 5432, 5461 and 5465 each exhibit unique sensory and chemical traits, while Art and 5461 achieved the highest physiological resilience under water stress. Overall, the results confirm substantial progress in selecting

Table 13 Assessment of plants for water stress

Genotype	End of irrigation			After 10 days of water stress		
	A ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$)	T ($\text{mmol H}_2\text{O}/\text{m}^2/\text{s}$)	V	A ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$)	T ($\text{mmol H}_2\text{O}/\text{m}^2/\text{s}$)	V
Saaz	8.23	2.13	2	0.00	0.25	4
Rubín	6.69	1.51	1	0.00	0.45	4
5165 ® Uran	8.25	2.03	2	4.88	1.32	2
5304 ®	9.65	2.36	2	3.27	0.86	3
5432 ®	10.50	2.29	2	8.77	1.61	2
5461 ®	11.79	2.92	1	5.15	1.11	1
5465 ®	6.36	1.38	2	6.02	1.26	2
5559 ® Art	9.62	2.45	1	9.05	1.69	1

(A) rate of photosynthesis, (T) rate of transpiration

(V) visual evaluation:

(1) – negligible growth retardation; slightly yellowish lower leaves; minimal drought symptoms,

(2) – slowed growth; plants with yellowish lower leaves; fast regeneration after watering,

(3) – wilted leaves; dried lower leaves; growth stopped; regeneration and continued growth after watering,

(4) – completely dried-up plants; no regeneration after watering

Across the three-year evaluation, all newly assessed genotypes demonstrated distinct and stable characteristics in hop-resin content, essential-oil

hop genotypes capable of maintaining both agronomic performance and brewing quality under drought conditions.

4 Conclusion

From a three-year perspective, the results provide a solid and informative basis for evaluating drought tolerance in Czech hop varieties and breeding lines. Despite the relatively short assessment period, new drought-tolerant genetic material has been obtained, each genotype showing specific and stable patterns in hop-resin content, essential-oil composition and aroma. The bitter-hop varieties Uran and genotype 5304 differ markedly: Uran is already cultivated at several sites and is used by breweries for its distinctive character, whereas 5304 is unlikely to be registered unless it proves useful in brewing practice. Among aroma hops, genotype 5461 is highly promising, although its susceptibility to downy mildew observed in 2025 is a limiting factor. All aroma genotypes are currently undergoing brewery-scale testing. Genotype 5465 appears particularly suitable for dry, non-irrigated areas where existing varieties such as Sládek and Premiant no longer perform reliably.

All evaluated genotypes have a clear future in Czech hop cultivation due to their strong drought tolerance. The new varieties Art and Uran are already being introduced into both cultivation and brewing practice, with further expansion expected in 2026. Additional genotypes may also be registered in the coming years for use in dry locations, and will undoubtedly serve as valuable breeding material for enhancing drought resistance. Since the genotypes differ substantially in hop-resin content, essential-oil composition and aroma profiles, they offer brewers new possibilities for tailoring beer styles. Drought tolerance has become a key prerequisite for maintaining stable hop production in the Czech Republic.

5 Acknowledgement

This article was prepared within the project QK21010136 entitled “*Application of New Hop Varieties and Genotypes Resistant to Drought in Hop-Growing and Brewing Practice*”, funded by the Czech Ministry of Agriculture.

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