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The impact of weather conditions on alpha-acid content in hop (*Humulus lupulus* L.) cv. Aurora

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Abstract: The influence of four main weather attributes on the content of alpha-acids of the hop cv. Aurora for the period 1994–2019 was studied. By analysing correlation coefficients, specific times of the year when the weather conditions affect the alpha-acid content with the goal of creating a forecasting model in Slovenia were identified. The most significant periods of weather that impacted the alpha-acid contents throughout the growing time of year are recognised as attributes of temperatures (T), rainfall (R) and sunshine (S) calculated from the 25th to 30th week (T_{2530}, r = –0.78, P < 0.01; R_{2529}, r = 0.72, P < 0.01 and S_{2529}, r = –0.81, P < 0.01) and attributes of relative humidity (RH) from the 27th to 32nd week (RH_{2732}, r = 0.82, P < 0.01). T_{2530} stands for the amount of active temperatures from June 18 to July 29. Likewise, R_{2530} matches to the precipitation (in mm or L/m^2) during the same time period.

Keywords: hop quality; α-acids; brewing process; biosynthesis; vegetative period

Resins and essential oils, the main brewing components of hops, are synthesized and accumulate in lupulin glands found on the cones produced by female hop plants (*Humulus lupulus* L.). Resins are chemical constituents produced as secondary metabolites. Part of the soft resins are hop-acids, composed of two chemically similar groups of compounds, alpha-acids, or humulones, and beta-acids, or lupulones. They are primarily used in the brewing process for their preservative and bittering properties. Alpha-acids also contribute to microbial stability and enhance foam stability (Moir 2000, Steenackers et al. 2015). The development of alpha-acids in the hop cone takes place from the beginning of cone formation. Development during the two-week period before harvest, however, is crucial as 90% of alpha-acids are formed during this time (Hecht et al. 2004). Alpha-acid content is a genotype-dependent trait of hops and varies from 2–21% of dry cone weight. The impact of weather conditions during the growing season is also important (Donner et al. 2020). Srečec et al. (2013) discovered that weather conditions during the hop vegetative period have a stronger influence on the accumulation of alpha-acids in technological maturity than soil conditions.

Throughout Europe, only a small percentage of hop fields are irrigated. The rest rely on rainfall. Drought and irregular rainfall cause reduced biosynthesis and plant vigour in hops resulting in decreased alpha-acid production (De Keukeleire et al. 2007). Srečec et al. (2008) studied the impact of weather conditions on alpha-acid levels over the growing season of cv. Aurora in Slovenia. They discovered an inverse correlation between average daily temperatures and alpha-acid production (r = –0.39, P < 0.05) and a strong positive correlation between total rainfall and production of alpha-acids (r = 0.46, P < 0.05). Research by Kučera and Krofta (2009) and Možný et al. (2009) demonstrated similar results. July air temperatures affected the development of alpha-

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acids most significantly (Kučera and Krofta 2009). Rainfall during May, June, and July was found to be critical to the development of alpha-acids. During August, the last month before harvest, the impact was inconsequential. These findings may not apply equally to all hop growing regions, as evidenced in similar research conducted by Donner et al. (2020) on several cultivars in the Czech Republic.

Alpha-acid content is an important component in determining the brewing value of hops. With the proliferation of public and private cultivar development programs worldwide since the 1990s, there has been an industry-wide focus on maximising alpha-acid levels. The challenge inherent in hop breeding is to develop cultivars that will both satisfy the changing needs of the brewing industry while being commercially viable on the production side. Since 2000, breeding programs have focused on cultivars that maximise alpha-acid yield while being resistant to the most common diseases (Pavlovič et al. 2011). With the growth of the craft brewing industry, the flavours and aromas imparted by new cultivars have also become a driving force in new cultivar development.

The goal of this research was to determine the impact of weather conditions throughout the growing season on the alpha-acid content in hop cones of cv. Aurora, the most common cultivar in Slovenia. The results will assist in drafting a forecasting model based on weather attributes to predict alpha-acid values of the cv. Aurora as early as four weeks prior to harvest.

MATERIAL AND METHODS

Data set of alpha-acid content of hops. Laboratory data regarding alpha-acid content from the Slovenian Institute of Hop Research and Brewing from 1994 through 2019 were analysed, based on the research plan proposed by Košir and Livk (2019). Annually, 150 samples of dried cones from the Aurora hop cultivar were collected from farms located in the northeastern Slovenia. A standardised conductometric method of a toluene hop extraction was then used to analyse alpha-acid content (Analytica EBC 2000). The Levene's test for equal variance among average alpha-acid values from the three regions in northeastern Slovenia was conducted (Celje (latitude 46°15', longitude 15°5', altitude 244 m a.s.l.), Šmartno pri Slovenj Gradcu (latitude 46°29', longitude 15°7', altitude 455 m a.s.l.) and Maribor (latitude 46°33', longitude 15°38', altitude 269 m a.s.l.). The results demonstrate the estimated average contents of alpha-acids for each region in which hops were produced across Slovenia.

Cv. Aurora. Cv. Aurora is a medium early hop cultivar, a diploid hybrid between Northern Brewer and a TG 77 seedling of unknown origin. It was crossbred at the Slovenian Institute of Hop Research and Brewing and imparts an intense and pleasant hoppy aroma. It contains between 7.2–12.6% alpha-acids. In 2020, 558 hectares were produced, 38% of the total Slovenian hop production.

Meteorological data. Data were collected from January 1, 1994 to December 31, 2019 from the three regions mentioned above, which offered over 300 000 data points for analysis. Available weather data consisted of daily precipitation (mm; i.e., L/m^2), average daily temperatures (°C), total hours of sunshine (h), and the average daily relative humidity (%). Variations in these weather data were not significantly different among these three stations, and no station had consistently higher data values than any other. This average embodies a reasonable approximation and includes all sites within the area where hops are planted in northeastern Slovenia.

Weather attributes. The impact of the correlation between the sum of temperatures, the number of hours of sunshine, total rainfall, and average relative humidity on the alpha-acid content was studied. The results were separated based on each of these parameters, and averages were calculated for each of the three reporting stations near which hops were produced. The "total sum of the average daily temperatures over a growing period" represented the need for heat units. The "total rainfall" denoted the need for water. The "total hours of sunshine" or solar radiation demonstrated the need for sunlight. The following variables were used to denote those terms: temperature (T), rainfall (R), sunshine (S), and relative humidity (RH). The influence of these variables was calculated upon alpha-acid production during two-time intervals.

(1) Beginning with April and ending with August, the various data were calculated for each of the variables on a monthly basis. Each month was designated by a number as follows: 4 – April; 5 – May; 6 – June; 7 – July; 8 – August; and 4, 5 – April + May; 4, 5, 6 – April + May + June; etc.
(2) In addition, average values were calculated for the variables on a weekly basis. Then, they were measured each week beginning with the date of hop harvest (i.e., week 34) through when plant growth

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first began. The values for each meteorological attribute (A) were calculated using the formula:

$$A_{ab} = \sum_{w=a}^{b} p_w$$

$$a = 26 + z - k;\ b = 29 + z;\ k = 1, 2, ... 12;\ z = 0, 1, ...5$$

where: A – variables mentioned earlier (i.e., T, R, S, and RH); p_w – weekly data of a parameter. p_w was calculated based on daily meteorological data obtained from the EARS archives. In our formula above, a stands for the lower limit of the time interval, and b represents the upper limit of the interval at which the values were calculated. The Pearson correlation coefficient was used to measure the correlation between two variables.

Factor analysis. To reduce the number of variables and to support data interpretation, a factor analysis was used. This exploratory technique was applied to a set of the observed variables to find underlying factors (subsets of variables) from which the observed variables were generated.

RESULTS AND DISCUSSION

The study results are demonstrated as two sets – depending on the structure and the analysis of the weather attributes. Interpretation of the impact of weather on the alpha-acids is first presented for fixed monthly intervals and then for variable weekly

Table 1. Average alpha-acid contents of the air-dried hops cv. Aurora with 11% humidity and the values of variables studied during 1994 to 2019

Year	Alpha-acids (%)	Period April–August				Period June–July			
		T	S	R	RH	T	S	R	RH
1994	8.2	2 573.2	1 128.0	639.0	73.5	1 201.7	519.0	251.0	73.7
1995	7.8	2 447.1	1 057.6	505.3	74.0	1 149.7	454.7	199.9	76.7
1996	10.1	2 447.0	1 132.5	661.8	73.3	1 112.9	542.7	267.6	71.3
1997	10.0	2 407.0	1 171.6	548.9	70.8	1 135.2	452.5	280.7	73.0
1998	8.8	2 559.6	1 181.0	581.3	73.5	1 189.8	477.5	357.4	75.0
1999	9.5	2 538.9	1 056.5	723.5	74.8	1 159.3	485.0	315.1	73.7
2000	8.6	2 705.6	1 346.6	387.8	70.0	1 177.4	574.0	204.6	68.6
2001	7.8	2 568.6	1 273.2	473.0	70.5	1 159.1	528.2	251.8	69.6
2002	7.3	2 634.3	1 138.4	559.4	72.6	1 248.8	559.5	204.5	69.4
2003	5.9	2 838.1	1 295.2	316.9	66.1	1 333.3	562.8	147.1	66.7
2004	8.8	2 434.8	1 009.5	593.3	76.0	1 130.3	422.5	312.7	76.3
2005	8.8	2 489.7	1 063.6	710.4	68.9	1 174.8	463.1	293.0	67.5
2006	6.3	2 528.7	1 074.8	577.6	66.7	1 249.3	539.2	133.7	61.3
2007	7.4	2 729.3	1 254.2	491.7	66.2	1 260.5	555.0	217.7	63.0
2008	8.8	2 594.7	1 135.8	629.4	71.1	1 206.3	451.8	356.4	71.6
2009	8.4	2 645.6	1 188.1	577.5	72.0	1 151.4	489.3	268.2	72.3
2010	8.3	2 595.8	1 079.4	479.1	71.3	1 247.4	507.8	175.2	67.3
2011	9.1	2 617.9	1 256.1	478.4	69.9	1 161.2	452.0	275.1	71.8
2012	8.2	2 678.6	1 263.2	504.2	67.7	1 258.8	536.0	205.3	67.8
2013	5.7	2 649.8	1 190.7	360.7	66.6	1 227.5	573.5	112.7	63.6
2014	10.2	2 551.4	1 026.2	637.9	73.9	1 176.2	457.6	302.2	74.1
2015	8.5	2 700.5	1 227.8	472.0	71.6	1 259.4	530.8	236.5	72.5
2016	8.6	2 604.9	1 164.5	553.2	74.2	1 228.0	487.3	205.3	75.5
2017	7.4	2 714.5	1 278.7	439.4	68.2	1 275.9	547.4	208.7	66.3
2018	8.9	2 797.3	1 173.1	541.5	72.6	1 208.4	462.7	212.6	72.5
2019	7.8	2 648.3	1 119.6	603.4	69.3	1 309.1	590.9	277.0	66.9
Average	8.3	2 602.6	1 166.7	527.8	71.1	1 203.6	507.0	237.6	70.4

T – temperature; S – sunshine; R – rainfall; RH – relative humidity

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Table 2. Correlation between the weather variables (A) calculated at monthly intervals and alpha-acid contents for the Aurora hop cultivar

Month interval	T	S	R	RH
4	0.05	–0.04	0.05	0.14
5	0.10	0.36	–0.04	–0.04
6	–0.38	–0.29	0.47*	0.46*
7	–0.71**	–0.74**	0.54**	0.75**
8	–0.32	0.21	0.11	0.48*
45	0.00	0.12	0.08	0.17
56	–0.28	–0.04	0.37	0.39
67	–0.67**	–0.61**	0.74**	0.67**
78	–0.62**	–0.46*	0.45*	0.80**
456	–0.20	–0.06	0.42*	0.38
567	–0.58**	–0.41*	0.73**	0.61**
678	–0.60**	–0.50**	0.64**	0.75**
4567	–0.50*	–0.35	0.67**	0.56**
5678	–0.55**	–0.34	0.67**	0.70**
45678	–0.48*	–0.29	0.61**	0.68**

T – temperature; S – sunshine; R – rainfall; RH – relative humidity; 4 – attribute in April; 45 – attribute in April + May; etc.); $N = 26$; $^{*}P < 0.05$; $^{**}P < 0.01$

periods. The most critical phases of growth and development of hops for each method are revealed, where the T, R, S, and RH illustrate their significant influences on alpha-acid contents or indirectly on the quality and commercial value of the hops.

1st set of results (fixed monthly intervals). Table 1 shows the data collected between 1994 and 2019 from the three meteorological stations that represent the Slovenian hop growing regions. The variables T, R, S, and RH, are shown. Depicted therein are total average values for the variables for the season as well as a separate column highlighting the values from June and July together. The most statistically relevant impact of temperature and rainfall on the ultimate alpha-acid content occurred during June and July. The second column from the left lists the average cv. Aurora alpha-acid contents.

Table 2 demonstrates the Pearson correlation coefficients for each variable in each fixed monthly period relative to alpha-acid production between 1994 and 2019. Analysis of the Pearson coefficients demonstrated that temperature in July had a significantly greater inverse correlation to alpha-acid production ($r = –0.71$, $P < 0.01$), meaning that there is a strong correlation between high temperatures and low alpha-acid values. In August ($r = –0.32$), the correlation weakened to a level similar to that of June ($r = –0.38$). The June/July combined data ($r = –0.67$, $P < 0.01$) were also statistically significant as were the July/August combined data ($r = –0.62$, $P < 0.01$) and the combined June/July/August data ($r = –0.60$, $P < 0.01$).

Rainfall during the June/July period was strongly correlated to the production of alpha-acid throughout the growing season, with the strongest correlation recorded ($r = 0.74$, $P < 0.01$) followed by the May/June/July time frame ($r = 0.73$, $P < 0.01$). Rainfall in August did not significantly affect alpha-acid production.

Sunshine during July demonstrated a strong inverse correlation to alpha-acid production ($r = –0.74$, $P < 0.01$) and a slightly weaker correlation for the June/July period ($r = –0.61$, $P < 0.01$).

Relative humidity in July demonstrated the highest correlation to alpha-acid production in the study ($r = 0.75$, $P < 0.01$) and even higher for the July/August period ($r = 0.80$, $P < 0.01$).

2nd set of results (alpha-acids contents in hops in floating week intervals). Table 3 demonstrates the Pearson correlation coefficients for our variables relative to alpha-acid production presented in an aggregate weekly interval format for the years between 1994 and 2019.

Analysis of the data revealed the highest inverse correlation between temperature and alpha-acid production (T_{2530}, $r = –0.78$, $P < 0.01$) during the interval between weeks 25 and 30. The variable T_{2530}

Table 3. Correlation of weather variables and alpha-acids production for the Aurora hop cultivar in floating weeks for 1994–2019

Week interval	T	S	R	RH
2532	–0.76**	–0.67**	0.64**	0.78**
2732	–0.64**	–0.50**	0.49*	0.82**
2132	–0.59**	–0.46*	0.65**	0.71**
2530	–0.78**	–0.81**	0.72**	0.70**
2130	–0.57**	–0.52**	0.67**	0.62**
2529	–0.57**	–0.52**	0.67**	0.62**
2329	–0.59**	–0.59**	0.69**	0.60**
2129	–0.44*	–0.43*	0.65**	0.57**
2528	–0.59**	–0.54**	0.61**	0.54**
2428	–0.64**	–0.59**	0.67**	0.55**
2128	–0.37	–0.27	0.59**	0.48*

T – temperature; S – sunshine; R – rainfall; RH – relative humidity; $N = 26$; $^{*}P < 0.05$; $^{**}P < 0.01$

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represents the sum of active temperatures from June 18 to July 29. A slightly lower, yet still statistically significant correlation emerged during the intervals of variables T_{2532}, T_{2732}, and T_{2428}. Temperature appears to be highly correlated to alpha-acid production for periods, including the beginning of intensive plant growth until the end of flowering. The impact of temperature in August on alpha-acid production just prior to harvest, however, is weak.

There was still a higher inverse correlation between sunshine and alpha-acid production during this period (S_{2529}, $r = -0.81$, $P < 0.01$). This relationship yielded the highest negative correlation in this study and also occurred during the period between June 18 and July 29, a period that ends approximately four weeks prior to the harvest. The correlation between sunshine and alpha-acid production in August was weak and statistically insignificant.

The highest positive correlation for rainfall in mm or L/m^2 that occurred during the period between June 18 and July 29 yielded the following results (R_{2529}, $r = 0.72$, $P < 0.01$). Rainfall exhibited the highest positive correlation with alpha-acid contents. The strength of the correlation between rainfall and alpha-acid began to decline following July 29. By this late stage, hop plants had fully flowered and were developing cones.

Relative humidity resulted in a higher correlative value to alpha-acid production than sunshine, temperatures, and rainfall, and was the highest in this study RH_{2732} ($r = 0.82$, $P < 0.01$). This tendency occurred between weeks 27 and 32, a period that corresponded to July 2 to August 12. This was significant as it represented an interval, including both cone fertilisation and development.

All the tables denote the direction of the correlative coefficient (i.e., inverse or positive). For an inverse correlation, a negative sign was used as is the standard practice, while no sign was used to indicate a positive correlation. The variables temperature and sunshine had more negative results, while rainfall and relative humidity showed more positive correlations. These pairs of parameters mirrored one another, and basic logic can be applied to the results. More sunshine generally means a higher temperature in the summer months. When it is cloudy, that is a sign that there is less sunshine and also that relative humidity may be higher. Subsequently, there is a greater chance of rainfall when there is less sunshine.

Factor analysis. To avoid extreme multicollinearity, very highly correlated values were first eliminated from the battery of attributes. The principal component method with an orthogonal (varimax) rotation was used for extracting factors on the eight items (Table 4). Several well-recognised criteria for the factorability of correlation were used. Firstly, all items correlated at least 0.4 with all other items, suggesting reasonable factorability. Secondly, an examination of the Kaiser-Meyer-Olkin measure of sampling adequacy was 0.75, above the recommended value of 0.5 generally thought necessary for factor analysis. The diagonals of the anti-image correlation matrix were all over 0.69, supporting the inclusion of each item in the factor analysis. The communalities were above 0.75, further confirming that each item shared some common variance with other items. Principle component analysis was used because the primary purpose was to identify and compute composite coping scores for the factors underlying. An initial analysis was run to obtain eigenvalues for each component in the data. A varimax rotation was used due to the tendency for the principal factor to disappear. This also simplifies the interpretation because, after a varimax rotation, each original variable tends to be

Table 4. Correlation matrix of weather variables used in factor analysis

	S_{2329}	S_{2528}	S_{2530}	T_{2530}	T_{2329}	R_{2129}	R_{2132}	R_{2530}
S_{2329}	1.00							
S_{2528}	0.71**	1						
S_{2530}	0.72**	0.75**	1					
T_{2530}	0.51**	0.66**	0.74**	1				
T_{2329}	0.75**	0.66**	0.61**	0.78**	1			
R_{2129}	–0.56**	–0.47*	–0.50**	–0.53**	–0.61**	1		
R_{2132}	–0.42*	–0.46*	–0.46*	–0.48*	–0.43**	0.85**	1	
R_{2530}	–0.49*	–0.61**	–0.61**	–0.61**	–0.47**	0.82**	0.83**	1

$N = 26$; $^*P < 0.05$; $^{**}P < 0.01$; S – sunshine; T – temperature; R – rainfall

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Table 5. Summary of exploratory factor analysis for weather variables at weekly intervals

Rotated component matrix with the Varimax method and Kaiser normalisation

Variable	component			
	1	2	3	χ^2
S_{2329}	0.936			0.858
S_{2528}	0.862		–0.414	0.820
S_{2530}	0.816	–0.511		0.865
T_{2530}	–0.273	0.834	0.309	0.760
T_{2329}		0.781	0.428	0.883
R_{2129}	–0.308	0.739	0.346	0.942
R_{2132}	–0.247	0.415	0.806	0.931
R_{2530}	–0.228	0.398	0.805	0.936
Eigenvalues	5.27	1.20	0.53	
% of variance*	32.4	31.3	23.7	

N = 26; Loadings over 0.6 are significant and appear in bold; *Percent variance is post-rotation; S – sunshine; T – temperature; R – rainfall

associated with one (or a small number) of factors, and each factor represents only a small number of variables (Abdi 2003). After the varimax rotation factor 1 explains 32.4%, factor 2 explains 31.3% and factor 3 explains 23.7% of the variance (Table 5).

Our results (Table 2) matched with those of Srečec et al. (2008) in Croatia. They discovered a negative correlation in cv. Aurora between the increasing sum of effective temperatures and the production of alpha-acids (r = –0.39), while rainfall and alpha-acid production illustrated a positive correlation (r = 0.46). Evapotranspiration during cone formation negatively impacted alpha-acid production. Srečec et al. (2013) formulated a simple mathematical model incorporating the sum of effective temperatures and rainfalls from the second germination after spring pruning until hop cone maturity to estimate alpha-acids content in hop cv. Aurora. In Central Europe (CZ), Kučera and Krofta (2009) learned that alpha-acid content in the cv. Saaz was influenced by weather conditions in a relatively short time period during June–August, i.e., stages of flowering, cone formation, and ripening. The negative correlation between July temperatures and alpha-acid content had the greatest influence upon their model, which is the same as demonstrated by our research (r = –0.71). Compared to Pavlovič et al. (2012), our research (with our results compared in brackets) more precisely identified the most significant periods for weather impacting cv. Aurora alpha-acid production. The temperature was the most significant during weeks 24 to 31 (25 to 30), total rainfall and sunshine during weeks 25 to 29 (25 to 30), and air humidity during weeks 28 to 33 (27 to 32). Similarly, Donner et al. (2020), using CZ cultivars, determined that high air temperatures during summer had the greatest negative impact on the production of alpha-acid. Other factors negatively correlating alpha-acid production were high temperatures in July and August, the number of days with maximum temperature over 30 °C, and the sum of seasonal temperatures. The Czech hop cv. Agnus showed a stable weather-independent alpha-acid content, while cvs. Saaz and Premiant were more sensitive at this parameter.

The impact of weather fluctuations on the production of hop alpha-acids is significant and linked with the stages of development of the plants, the dates of which vary each year slightly due to naturally occurring changes in climate. Generative bodies in the hop cv. Aurora typically begins to develop in the second half of June (week 26), and the plant is in full bloom by mid-July (week 28). Models to forecast alpha-acid value in advance, based on input data from specific times of the year when weather conditions the most significantly affect alpha-acid content of the cv. Aurora will use two groups of variables. Results demonstrate that three factors explain 87.4% of the variance (Table 5). The first factor (32.4%) captures sunshine data (S); this parameter has the greatest impact from early June to early August. The second factor (31.3%) covers both temperature variables and variables covering rainfall. The third factor (23.7%) embraces the variables of rainfall and ranges from the second half of May to the middle of August, which is 10 days prior to the harvest of cv. Aurora in Slovenia. Results validate the application of the forecasting inputs for further research.

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