Quality, bioactive compounds and antioxidant capacity of raspberries cultivated in northern Mexico

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ABSTRACT
This study aimed to characterize the quality and bioactive compounds from five cultivars grown in Mexico’s northern region: Heritage, Summit, Harvest, and red and yellow Autumn. The physicochemical characteristics, DPPH anti-radical capacity, total phenolics, flavonoid and anthocyanins, polyphenolic profile, and ascorbic acid levels of the raspberries were assessed. The Harvest cultivar presented the highest weight and firmness and the lowest yield, total phenolics, and flavonoids. The yellow Autumn Bliss contained higher concentrations of polyphenols and ascorbic acid, and the red Autumn Bliss contained higher concentrations of flavonoids and anthocyanins and possessed a greater antioxidant capacity. The polyphenol profile indicated the presence of seven phenolic acids, namely, ellagic, gallic, caffeic, chlorogenic, p-coumaric, hydroxybenzoic, and protocatechuic acids; and four flavonoids, namely, catechin, quercetin-3-β-D-glucoside, quercetin-3-glucuronide, and rutin; these compounds were present in all the varieties, except for rutin, in yellow Autumn Bliss. The results of this study highlight the most valuable raspberry cultivars in terms of weight and firmness (Harvest), yield (Heritage), polyphenols and ascorbic acid (yellow Autumn Bliss), and anthocyanins and antioxidant capacity (red Autumn Bliss) in raspberries grown in northern Mexico.

Introduction
Raspberry fruits are subject to growing demand because they are a rich source of phytochemicals, with health-promoting properties that protect against different human diseases [1]. Raspberry fruits contain several bioactive compounds, including flavonoids, anthocyanins, ascorbic acid, and phenolic compounds such as ellagic acid [1,2]. The concentrations of the bioactive compounds in the fruits are affected by environmental conditions and the genetic characteristics of the varieties. Anttonen and Karjalainen [3], observed variations in the phytochemical compositions of raspberries cultivated in different regions of Europe due to the characteristics of the cultivated areas. Castillo et al. [4] evaluated two different cultivation areas in Brazil and found that the bioactive compounds in the raspberry fruits were affected by the cultivation zone. Additionally, Chen et al. [5] reported that the variety significantly affects the biosynthesis and accumulation of bioactive compounds in raspberry fruits.

In recent years, interest in raspberry cultivation has increased in northern Mexico, due to the need to diversify fruit production and expand export markets [6]. Therefore, the purpose of the present study was to evaluate the raspberry varieties Heritage, Summit, Harvest, red Autumn Bliss and yellow...
Autumn Bliss cultivated in northern Mexico. The phenolic profiles, ascorbic acid levels, anti-free radical capacity, total anthocyanins and total flavonoids together with physicochemical characteristics were studied to provide a better knowledge of the attributes in raspberries grown in the Chihuahua region.

**Materials and methods**

Planting was established in the experimental field at Cuauhtémoc, Chihuahua, México (28°24'45.1" N, 106°52'54.9" W and 2060 meters above sea level). The experimental area was planted with five varieties, Heritage, Summit, Harvest, red Autumn Bliss and yellow Autumn Bliss (four repetitions), with experimental units measuring five lineal meters for each variety and repetition. The study was performed on the crop produced in 2017, a year in which precipitation of 539.5 mm and mean minimum and maximum temperatures of 6.8°C and 24.0°C, respectively, were recorded. The data are presented in Table 1 (the monthly records were retrieved from the UNIFRUT meteorological station in Cuauhtémoc, Chihuahua, Mexico).

**Crop management**

The crop was managed using a conventional fertilization system. Commercial synthetic fertilizers composed of nitrogen (ammonium nitrate), phosphorus (triple 17) and potassium (potassium sulfate) were applied. In each of the experimental units, the equivalent of 150 kg ha⁻¹ of nitrogen, 40 kg ha⁻¹ of phosphorous and 190 kg ha⁻¹ of potassium were applied (Table 2) and uniformly distributed, with two applications per month from May to harvest.

**Physicochemical characterization**

The fruits were harvested when they reached a deep red color and analyzed for their physicochemical characteristics of weight, color, firmness, Brix degree, titratable acidity and pH. The average weight of the fruits was obtained by dividing the yield (g) by the number of harvested fruits per experimental unit. The color was determined with a Konica Minolta colorimeter (Spectrum photometer CM-600d),

**Table 1.** Precipitation and minimum and maximum temperatures recorded during the 2017 study year.

| Phenological stage of raspberry cultivation | Minimum temperature (°C) | Maximum temperature (°C) | Precipitation (mm) | Daylight average (hours) | Solar radiation (kw/m²) |
|--------------------------------------------|---------------------------|---------------------------|-------------------|-------------------------|------------------------|
| Sprouting                                  | March                      | 4.02                      | 23.05              | 0.60                    | 11.7                   | 180.24                 |
| Vegetative growth                          | April                      | 6.30                      | 25.61              | 1.90                    | 12.5                   | 236.62                 |
| Vegetative growth                          | May                        | 7.67                      | 27.36              | 4.50                    | 12.8                   | 265.19                 |
| Flowering period                           | June                       | 12.49                     | 31.04              | 11.10                   | 14.1                   | 275.03                 |
| Flowering and production                   | Julio                      | 13.58                     | 25.63              | 288.0                   | 13.8                   | 191.76                 |
| Flowering and production                   | August                     | 13.24                     | 24.51              | 184.80                  | 13.2                   | 181.76                 |

Note: The production during the month of August was considered in this study.

**Table 2.** Chemical fertilizers applied (kg ha⁻¹) during each production season.

| Fertilizers (commercial name) | Active ingredient | Fertilizer dose applied (total) | Mineral dose applied |
|-------------------------------|-------------------|---------------------------------|----------------------|
| Ammonium nitrate              | 35% nitrogen      | 315 kg ha⁻¹                    | 110 kg ha⁻¹ N        |
| Triple 17                     | 17% nitrogen, phosphorus and potassium | 240 kg ha⁻¹ | 40 kg ha⁻¹ N 40 kg ha⁻¹ P |
| Potassium sulfate             | 53% potassium     | 284 kg ha⁻¹                    | 150 kg ha⁻¹ K        |
in which the L, a and b values were obtained using the CIELAB scale. The values are presented as the hue°.

A Brookfield C3T Texturemeter equipped with a 2 mm flat probe was used to measure the fruit firmness. Each fruit was compressed by 2 mm at a speed of 0.5 mm s⁻¹, and the maximum force that developed during the test was recorded [⁷]. The Brix degree, titratable acidity and pH were determined by macerating 10 fruits from each variety to obtain the juice. The Brix degree was determined using an Abbe refractometer (ATAGO DR-A1). The titratable acidity was determined by diluting 5 mL of raspberry juice in 100 mL of distilled water and then titrating it to pH 8.2 using 0.1 N NaOH; the result was reported in mg of citric acid/100 mL of juice. The pH was measured with an OHAUS (Starter 3100) potentiometer. For the physicochemical parameters mentioned above, 10 fruits were used for each measurement, with a total of four replications for each variety studied. After their physicochemical parameters were analyzed, the fruits were lyophilized and stored at −20°C for subsequent analyses of their bioactive compounds.

**Extraction and measurement of total phenol and flavonoid contents**

Methanolic extracts of each variety were prepared by mixing 1 g of each lyophilized sample with 20 mL of 80% methanol and 2% formic acid using the methodology described by Palafox-Carlos et al. [⁸]. The total phenol content was determined using the methodology described by Slinkard and Singleton [⁹] with gallic acid as the standard. Six replications were studied.

The results are reported in mg of gallic acid equivalents (GAE)/100 grams of fresh weight. The total flavonoid contents of six replicates were determined using the colorimetric method described by Zhishen et al. [¹⁰], with quercetin as the standard. The results are reported in mg of quercetin equivalents (EQ)/100 g of fresh weight.

**Total anthocyanin content**

The anthocyanin content was determined using the methanolic extracts obtained for total phenols and flavonoids. The mixtures were centrifuged at 14,000 rpm (18,407 g) (Eppendord centrifuge 5804 R, Germany) for 30 min. The total anthocyanin content was determined using the differential pH method described by Lee et al. [¹¹], using six replications.

The pH was adjusted with pH 1 and pH 4.5 buffer solutions until the same dilution was obtained; finally, measurements from six replications were recorded at 520 and 700 nm. The anthocyanin concentration was calculated from the equation described below; the results are reported in mg of cyanidin-3-glucoside (C3G)/100 g of fresh weight.

\[
\text{Anthocyanin} = \frac{A \times \text{MW} \times \text{DF} \times 10^3}{\varepsilon \times 1}
\]

where \(A = (A_{520 \text{ nm}} - A_{700 \text{ nm}}) \) pH 1.0 - \( (A_{520 \text{ nm}} - A_{700 \text{ nm}}) \) pH 4.5. \( A_{520 \text{ nm}} \) is the maximum absorbance of anthocyanin and \( A_{700 \text{ nm}} \) is the absorbance correction due to interfering substances. \( \text{MW} \) (molecular weight) = 449.2 g/mol cyanidin-3-glucoside (major anthocyanin), \( \text{DF} \) (dilution factor) = 10, \( l = \) path length in cm, \( \varepsilon = 26,900 \) molar extinction coefficient in \( L \times \text{mol}^{-1} \times \text{cm}^{-1} \) of cyanidin-3-glucoside, \( 10^3 = \) conversion factor of g.mg⁻¹

**Extraction, identification and quantification of polyphenols**

The method described by Velderrain-Rodriguez et al. [¹²] was used to extract the polyphenols. The monomeric fraction of the extracts was quantified using ultra-performance liquid chromatography with a diode array detector (UPLC-DAD) (ACQUITY System, class H; Waters, EUA) at 270 nm that was equipped with a BEH C18 column with the dimensions 3.0 × 100 mm. The mobile phases used in the present study were 0.1% formic acid and 100% methanol. The flow and gradient changes were as described by Velderrain-Rodriguez et al. [¹²]. The total running time was 30 min, the column
temperature was set to 60°C, and a volume of 1 μL was injected. All the samples were filtered with 0.22 μm Acrodiscs prior to injection. The results were interpreted using calibration curves with standards and are reported in mg/100 g of fresh weight. Six replications were analyzed.

Chemical products and standards

Pure standards (≥ 93%) and all the reagents used in the present study were obtained from Sigma-Aldrich-Fluka (St. Louis, MO, USA). The HPLC-grade solvents were obtained from JT-Baker (Mexico City, Mexico).

Ascorbic acid levels

To determine the ascorbic acid levels, 1 g of each lyophilized raspberry sample was weighed and homogenized with 20 mL of a metaphosphoric acid: acetic acid: distilled water solution (3:8:89). The mixture was filtered with Whatman N° 1 filter paper, centrifuged at 18,407 g for 15 min at 4°C and finally filtered with a 0.22 μm Acrodisc. Six replications were injected into the instrument (UPLC-DAD). The results are reported in mg of ascorbic acid/100 g of fresh weight.

DPPH anti-radical capacity

The radical removal activity was evaluated using DPPH (2,2-diphenyl-1-picrylhydrazyl) as described in detail by Palafox-Carlos et al. [8]. The ability of antioxidants to reduce the absorbance of the radicals after the incubation was calculated, and the results are reported in mg of Trolox equivalents (TE)/100 g of fresh weight.

Experimental design and data analysis

A completely randomized experimental design was used, with five varieties (treatments), four replications and experimental units measuring four lineal meters with 1.5 meters between rows. For each analysis of the evaluated variables, a homogeneity of variance test was performed. When the homogeneity was detected, the corresponding analysis of variance was applied, and the comparison was performed using the Tukey procedure with a 95% confidence interval. When a heterogeneity of variances was detected, the non-parametric Kruskal-Wallis procedure was applied, and when a significant effect from the treatments was observed, the Mann-Whitney test was applied to compare the medians and determine the best treatment. The information was analyzed with the SAS statistical package.

Results and discussion

The physicochemical characteristics, bioactive compounds and cumulative yields of raspberries grown in northern Mexico were affected by the cultivar. The highest cumulative yield was observed in the Heritage variety, at 15.2 t ha⁻¹, followed by red and yellow Autumn Bliss varieties, with an average yield of 13.4 t ha⁻¹. The Harvest variety presented half the Heritage value, at 7.6 t ha⁻¹ (Table 3).

Physicochemical characterization

The physicochemical characteristics of raspberries are defined by the qualitative traits of size, firmness, color, taste, texture and general appearance; these criteria are important to the majority of consumers. The quality results presented in this study were significantly affected by the variety (Table 3). The quality values were within the ranges previously reported for red raspberries [13,14]. The Harvest cultivar had the highest fruit weight (4.08 g), while the remaining varieties showed no significant
Table 3. Physicochemical compositions and cumulative yield of five raspberry varieties.

| Cultivars          | Heritage   | Summit     | Harvest   | Red Autumn Bliss | Yellow Autumn Bliss |
|--------------------|------------|------------|-----------|------------------|---------------------|
| Weight (g)         | 3.01 ± 0.19 b | 3.04 ± 0.34 b | 4.08 ± 0.47 a | 3.02 ± 0.20 b     | 2.98 ± 0.07 b       |
| Humidity (%)       | 90.2 ± 1.17 a | 89.9 ± 1.96 a | 90.3 ± 2.01 a | 90.1 ± 2.61 a     | 89.8 ± 1.22 a       |
| Color (hue°)       | 26.4 ± 0.75 b | 26.1 ± 0.91 b | 27.4 ± 0.86 b | 26.6 ± 0.71 b     | 79.1 ± 1.7 a        |
| Firmness (g of force) | 65.9 ± 1.25 b | 68.6 ± 3.81 b | 92.3 ± 1.06 a | 66.1 ± 2.36 b     | 63.6 ± 2.61 b       |
| Soluble solids (°Brix) | 11.0 ± 0.13 a | 10.8 ± 0.11 a | 7.0 ± 0.09 b  | 11.0 ± 0.10 a     | 10.5 ± 0.18 a       |
| Titratable acidity (% citric acid) | 2.0 ± 0.26 a   | 1.9 ± 0.33 a   | 1.8 ± 0.29 a  | 1.98 ± 0.48 a     | 1.94 ± 0.56 a       |
| pH                 | 3.08 ± 0.47 a | 3.01 ± 0.22 a | 3.00 ± 0.41 a | 3.04 ± 0.26 a     | 2.85 ± 0.19 a       |
| Cumulative yield (t ha⁻¹) | 15.2 ± 0.30a    | 10.3 ± 0.60 c   | 7.6 ± 1.10 d  | 13.8 ± 0.40 b     | 13.1 ± 0.80 b       |

Mean values in rows with the same letters are not significantly different according to the Mann-Whitney test (α ≤ 0.05).

Differences in the fruit weights, with an average of 3.01 g/fruit (Table 3). In a study from the region of Valle del Jerte, Spain, De Ancos et al. (1999) reported a weight of 3.08 g/fruit for the Autumn Bliss variety and a weight of 2.08 g/fruit for the Heritage variety [13].

Likewise, Weber [15] obtained a weight of 2.1 g/fruit for the Heritage variety cultivated under controlled conditions using tunnel technology. In the present study, the Heritage variety fruit weighed 43.3% more than the value obtained by Weber [15]. If we compare the temperatures of both productive regions, the temperatures recorded under tunnel conditions are higher than those presented in this study (Table 1). Similarly, Sønsteby et al. [16] reported that sub-optimal temperatures (<15°C) in natural outdoor conditions are a limiting factor for flower induction in strawberry plants, which might be related to the productive potential of fruit set. Namely, a low flowering rate is associated with a larger fruit size. Remberg et al. [17] also argue that the post-flowering temperature can affect the size of the raspberry fruit, resulting in a significant decrease in the weight with the increasing temperature (from 12 to 18 and 24°C) throughout the harvest period. The raspberry fruits from the varieties studied here did not show significant differences in the moisture percentage, with an average of 10% dry matter.

The color of the raspberry fruits was statistically equal for the red varieties (with an average value of 26° hue), because the harvest criterion was based on the selection of ripe red raspberries. The mean values for the L, a, b, chroma and hue° (18, 19, 16, 37 and 20) were within previously reported ranges [13]. The values for the yellow variety were 79.11° hue with L, a and b values of 55.18, 6.37 and 33.14 (Table 3). The Harvest variety was characterized by producing fruits with a high firmness, with values of 92.32 g of force, while the Heritage, Summit and red and yellow Autumn Bliss cultivars showed statistically equal behaviors, with an average value of 66.07 g of force (Table 3).

The soluble solids in the raspberry fruits were significantly affected by the studied cultivars, in that the Summit, Heritage and red and yellow Autumn Bliss varieties accumulated a higher Brix degree with an average value of 10.8 Brix degrees. These data are within the range reported in previous studies for red and yellow varieties [17,21]. The titratable acidity and pH of the raspberry fruits were not affected by the types of cultivars and were statistically equal (Table 3).

The titratable acidity and pH values reported in the present study are similar to the values reported by Remberg et al. [17] and Stavang et al. [22]. In general, the Harvest variety was identified as having a greater size, weight and firmness, but a lower concentration of soluble solids. In addition, in the remaining study varieties, the varieties with both yellow and red coloration were statistically equal in terms of their weight, firmness, soluble solids, titratable acidity and pH.

**Total phenols**

The total phenol concentrations in the raspberry varieties were significantly different. Regarding the variability between varieties, the genetic information for the plant is the primary determinant of the phenolic compound contents in plant tissues [23]. The yellow Autumn Bliss variety was characterized by the highest total phenols, at 391.15 mg of gallic acid equivalents (GAE)/100 g fresh weight. The
Summit and red Autumn Bliss varieties followed, with values of 254.22 and 219.93 mg GAE/100 g fresh weight, respectively. The lowest values were obtained for the Heritage and Harvest varieties, which showed statistically equal levels, averaging 187.98 mg of GAE/100 g fresh weight (Table 4).

The levels of total phenolic compounds detected here are within the previously reported ranges of 192–359 mg of GAE/100 g of fresh weight noted by Anttonen and Karjalainen (2005) [3]. Similarly, Ali et al. [18] reported 322 mg of GAE/100 g of fresh weight. These data also resemble previously reported levels ranging from 275 to 320 mg of GAE/100 g fresh weight [24].

However, the results reported specifically for the Heritage variety cultivated in Geneva, New York, USA, presented a higher total phenolic content than the f value of 512.7 mg of GAE/100 g fresh weight reported in the present study [25]. This discrepancy might be related to the temperature; if we compare the temperatures from the two study sites (Geneva and Cuauhtémoc), lower temperatures are recorded in Geneva. The accumulation of phenolic compounds in plants is mediated by phenylalanine ammonium lyase (PAL); this enzyme catalyses the transformation of phenylalanine to trans-cinnamic acid, increasing its activity at a temperature of 6°C [26].

**Total flavonoids**

In the five cultivars studied here, a significant difference in the accumulation of total flavonoids was observed. The red Autumn Bliss and Heritage varieties presented the highest concentrations with statistically equal behavior; the average value was 17.45 mg of quercetin equivalent (QE)/100 g of fresh weight.

The yellow Autumn Bliss and Summit varieties presented values of 15.31 and 13.39 mg of QE/100 g of fresh weight, respectively. The lowest value was observed for the Harvest variety at 9.12 mg of QE/100 g of fresh weight (Table 4). Liu et al. (2002) reported a total flavonoid content of 103.41 mg of QE/100 g of fresh weight for Heritage and 63.53 mg of QE/100 g of fresh weight for a variety with a yellow coloration (Anne) [25]. Carvalho et al. (2013) did not observe a clear trend between red and yellow varieties with respect to the flavonoid contents [27]. While some yellow varieties contain lower flavonoid concentrations, others have similar or even higher values than those of the red cultivars.

In another study by Sariburun et al. (2010) on fruits from the Heritage variety, the flavonoid content was 25.3 mg of QE/100 g fresh weight [20]. Chen et al. (2013) reported a flavonoid content of 118.84 mg of QE/100 g of fresh weight for the red Autumn Bliss variety of raspberry fruits cultivated in Beijing, China, a value higher than the 18.30 mg of QE/100 g of fresh weight detected in the present study [5].

This discrepancy might be related to the daylight hours to which the crops were exposed, because sunlight contributes to the synthesis and accumulation of flavonoids in fruits [28]. One must consider the changes in the solar radiation that reaches the surface of the earth during the day and during the year. In areas with high latitudes, the sun continuously remains above the horizon in the summer, while at lower latitudes, the sun shines for more hours during the longest days of the year (August). In addition to these differences, the characteristic attributes of a climate with long days and cold night temperatures exert positive effects on the biosynthesis of flavonoids in plants [29].

### Table 4. Total phenolics, flavonoid and anthocyanin concentrations in five raspberry varieties.

| Cultivars       | Total bioactive compounds (mg of GAE/100 g of fresh weight) | Total flavonoids (mg of QE/100 g of fresh weight) | Total anthocyanins (mg of C3G/100 g of fresh weight) |
|-----------------|-------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------|
| Heritage        | 196.55 ± 14.9 d                                            | 16.60 ± 1.2 a                                   | 15.07 ± 1.9 c                                      |
| Summit          | 254.22 ± 22.1 b                                            | 13.39 ± 1.1 c                                   | 11.34 ± 0.9 d                                     |
| Harvest         | 179.41 ± 27.3 d                                            | 9.12 ± 1.3 d                                    | 21.46 ± 0.3 b                                     |
| Red Autumn Bliss| 219.93 ± 9.6 c                                             | 18.30 ± 1.2 a                                   | 23.53 ± 0.7 a                                     |
| Yellow Autumn Bliss | 391.15 ± 33.4 a                                        | 15.31 ± 1.7 b                                   | 4.07 ± 1.0 e                                      |

Mean values in rows with equal letters are not significantly different according to the Mann-Whitney test (α ≤ 0.05). GAE = gallic acid equivalents; QE = quercetin equivalents; and C3G = cyanidin-3-glucoside.
Total anthocyanins

The results of the present study indicate significant differences in the total anthocyanins detected in the different varieties. The red Autumn Bliss cultivar presented the highest total anthocyanins at 23.53 mg equivalents of cyanidin-3-glucoside (C3G)/100 g of fresh weight, followed by the Harvest and Heritage varieties at 21.46 and 15.07 mg of C3G/100 g of fresh weight (Table 4). Sariburun et al. (2010) evaluated the Heritage variety and obtained 22.4 mg of C3G/100 g fresh weight, a value similar to the value reported here [20].

De Ancos et al. (1999) collected fruits from Cáceres, Spain, and reported values of 9.05 mg of anthocyanins/100 g of fresh weight for Autumn Bliss and 14.00 mg/100 g of fresh weight for Heritage [13]. However, the anthocyanin contents reported by Pantelidis et al. (2007) in the Autumn Bliss and Heritage varieties were 39.1 and 48.2 mg/100 g of fresh weight, respectively [21]. Those values are higher than the levels reported in this study and in that of De Ancos et al. (1999) [13].

The results may differ due to temperature fluctuations, and scientific evidence shows a significant increase in the anthocyanin content in plants grown under high-temperature conditions (25/30°C) [30]. In the present study, the temperatures fluctuated between 6 and 24°C, which potentially explains why the total anthocyanin levels were lower than the values reported by Pantelidis et al. in 2007 [21], who maintained higher temperatures ranging from 27 and 30°C (the information was obtained from calculations based on the area and the study period).

Continuing with the description of the results of this study, the Summit and yellow Autumn Bliss varieties were identified as having the lowest accumulation of total anthocyanins, with 11.34 and 4.07 mg of C3G/100 g of fresh weight (Table 4). Similarly, Pantelidis et al. (2007) reported values of 3.4 mg of C3G/100 g fresh weight for the Fallgold yellow variety [21]. Additionally, Bobinaite et al. (2012) reported similar values, with 2.1 mg of C3G/100 g of fresh weight for a yellow variety identified as Beglianka [2].

Polyphenol profiles

In the present study, the compounds present from the highest to lowest concentrations were ellagic, gallic, chlorogenic, caffeic and p-coumaric acids, followed by catechin, rutin, quercetin-3-β-D-glucoside, protocatechuic acid, quercetin-3-glucuronide and hydroxybenzoic acid. The yellow Autumn Bliss variety exhibited the greatest accumulation (by summation) of polyphenolic compounds, with 724.02 mg/100 g fresh weight, followed by the red Autumn Bliss and Summit varieties, which were statistically equal, with an average concentration of total polyphenolic compounds reaching 613.73 mg/100 g fresh weight. The lowest values were obtained for the Harvest and Heritage varieties, with a total polyphenolic compound average of 559.85 mg/100 g fresh weight (Table 5).

The results of this study (Table 5) are consistent with previous studies showing that ellagic acid is the primary phenolic compound detected in raspberry fruits [3]. The yellow Autumn Bliss cultivar contained the highest concentration of ellagic acid at 311.85 mg/100 g fresh weight, followed by red Autumn Bliss, with a value of 251.98 mg/100 g fresh weight (Table 5). Carvalho et al. (2013) reported similar concentrations of gallic, caffeic and p-coumaric acids and catechin relative to the levels reported in the present study [27]. Additionally, higher levels of ellagitannins, quercetin-3-O-glucoside and quercetin-3-O-glucuronide are described in yellow raspberry varieties [31], consistent with the results from the present study.

However, the yellow Autumn Bliss variety did not contain rutin, and similar data have previously been reported in the Alpen Gold variety with a yellow coloration, in which no rutin was identified [27]. This information is also supported by previous findings in which the fruits of yellow varieties lack rutin, a type of flavonoid reportedly present in other cultivars [13,32]. According to Bobinaite et al. (2012), even when yellow raspberry cultivars contain few anthocyanins, the concentrations of total phenolic compounds and of ellagitannins (hydrolysable tannins, particularly ellagic acid) as well as the
capacity to capture free radicals are as high as those of many cultivars with a red coloration. This result is attributed to the genetic characteristics of these cultivars [2].

Ascorbic acid

The results of the present study revealed significant differences in the ascorbic acid concentrations between the studied varieties. The yellow Autumn Bliss variety was characterized by having the highest concentration of ascorbic acid at 162.00 mg/100 g fresh weight. The Summit, Harvest and red Autumn Bliss varieties had the next highest and statistically equal concentrations, with an average value of 132.80 mg/100 g fresh weight. The lowest concentrations were observed in the Heritage cultivar at 122.10 mg of ascorbic acid/100 fresh weight (Figure 1). According to Bobinaite et al. (2012), in a farm located in Lithuania that produces red raspberry varieties, 15.6 to 24.4 mg of ascorbic acid/100 g of fresh weight was reported [5]. In northern Greece, Pantelidis et al. (2007) obtained results for Heritage and Autumn Bliss of 32.4 and 37.7 mg of ascorbic acid/100 g fresh weight [21]. Similar data were reported by De Ancos et al. (1999) for those same varieties grown in Cáceres, Spain, with values of 21.26 mg/100 g fresh weight for Heritage and 29.36 mg/100 g fresh weight for Autumn Bliss [13].

In the state of Sao Paulo, Brazil, the varieties Heritage and Autumn Bliss displayed somewhat different behaviors, with values of 54.22 and 47.22 mg/100 g of fresh weight, respectively [4]. The results of the present study are superior to the previously reported values, and a potential explanation is the difference in light intensity (radiation), because several studies have indicated that this factor regulates the phytonutrient content. Strawberries grown with higher intensity light display increased levels of ascorbic acid [30].

If we compare the solar radiation at the site where this study was conducted (Cuauhtémoc, Chihuahua Mexico) with that of Lithuania, Greece, Spain and Brazil, the annual light intensity units produced according to the NASA system (2018) are 2005.92, 1011.57, 1946.42, 1766.62 and 1688.97 Kw-hr/m²/year, respectively. However, the Mexican value is very similar to that of Greece, which reported much lower values of ascorbic acid than those in the present study. Thus, changes in this parameter are affected by several factors simultaneously, one of which is the photoperiod, in addition to the total hours to which plants are exposed to solar radiation. The value is higher in

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Table 5. Polyphenolic profiles of five raspberry varieties.

| Polyphenolic compounds | Heritage mg/100 g of fresh weight | Summit mg/100 g of fresh weight | Harvest mg/100 g of fresh weight | Red Autumn Bliss mg/100 g of fresh weight | Yellow Autumn Bliss mg/100 g of fresh weight |
|------------------------|----------------------------------|---------------------------------|----------------------------------|------------------------------------------|---------------------------------------------|
| Catechin               | 17.2                             | 15.8                            | 16.9                             | 18.6                                     | 17.7                                       |
| Gallic acid            | 149.5                            | 159.8                           | 171.1                            | 119.6                                    | 147.2                                      |
| Protocatechuic acid    | 8.4                              | 12.6                            | 8.5                              | 10.5                                     | 4.0                                        |
| Quercetin-3-glucuronide| 7.7                              | 11.8                            | 8.3                              | 12.8                                     | 13.3                                       |
| Hydroxybenzoic acid    | 7.2                              | 9.0                             | 6.9                              | 10.5                                     | 9.9                                        |
| Chlorogenic acid       | 66.1                             | 83.1                            | 60.5                             | 93.6                                     | 79.3                                       |
| P-coumaric acid        | 24.5                             | 23.3                            | 17.1                             | 22.4                                     | 58.4                                       |
| Caffeic acid           | 36.6                             | 48.5                            | 48.5                             | 42.4                                     | 58.8                                       |
| Ellagic acid           | 209.5                            | 214.9                           | 202.8                            | 251.9                                    | 311.8                                      |
| Rutin                  | 12.7                             | 14.1                            | 12.6                             | 14.4                                     | -- --                                     |
| Quercetin-3-β-D-glucoside| 11.0                            | 19.8                            | 15.3                             | 17.6                                     | 23.4                                       |
| Summation              | 550.7 d                          | 612.9 b                         | 568.9 c                          | 614.4 b                                  | 724.0 a                                   |

Values presented in each column with the same letter indicate statistical equality between varieties in the polyphenolic compound contents with a confidence level of 95% according to the X² test for sample homogeneity.
Cuauhtémoc than that in Greece. The long-day conditions during the growth and maturation of raspberry fruits significantly increased the ascorbic acid concentrations [33].

**Antioxidant capacity**

Based on the results from the present study, the DPPH anti-free radical capacity was significantly different between some varieties. The highest anti-free radical capacity was observed in the red Autumn Bliss cultivar, with values of 476.20 mg Trolox equivalents (ET)/100 g fresh weight. The next highest activity was observed in Harvest at 394.63 mg ET/100 g fresh weight. The Heritage, Summit and yellow Autumn Bliss cultivars performed statistically the same, with the lowest values of DPPH activity at an average of 351.27 mg ET/100 g fresh weight. According to information reported by Chen et al. (2013) for the varieties Autumn Bliss and Heritage, the free radical capture capacities are 691.15 and 725.89 mg ET/100 g of fresh weight, respectively, which are superior to the values reported in this study, potentially due to the geographic location of the cultivation site [5]. Faniadis et al. (2010) reported a substantial effect from the geographical elevation on the antioxidant content of cherries, and climatic conditions, such as high temperatures (25/30°C), significantly increased the total antioxidant activity [19,30]. The temperatures in the study by Chen et al. (2013) ranged from 24°C to 27°C, while in the present study, the temperature ranged from 13 to 24°C [5]. Regarding the similarity in DPPH activity in the red and yellow cultivars, previous reports showed that both the red and yellow varieties were statistically equal in the Heritage cultivar (red) compared to a variety with yellow coloration called Fallgold [18]. The same trend was observed in the present study, in which the yellow Autumn Bliss, Heritage and Summit varieties were statistically equal, and the anthocyanin concentration did not influence the antioxidant capacity of the fruits Figure 2.
Conclusion

The data obtained in this study show variations in the contents of bioactive compounds in different varieties of raspberries grown in the northern region of Mexico. The red Harvest cultivar was characterized by producing fruits with higher weights and firmness levels, but with lower Brix degrees. The yellow Autumn Bliss variety contained higher levels of total phenols, ellagic acid, ascorbic acid and total polyphenols. Heritage, one of the most popular varieties to be cultivated commercially, presented the highest yield but was not the best in terms of the overall contents of bioactive compounds. Significantly lower levels of polyphenols and ascorbic acid and a significantly lower antioxidant capacity were observed. This study highlights the most valuable raspberry cultivars in terms of dietary sources of bioactive compounds that can be cultivated in the northern Mexico because the climatic characteristics of the study area significantly influenced the accumulation of the compounds studied here.

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