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Physiological traits, fruit morphology and biochemical performance of six old fig genotypes grown in warm climates "Gafsa oasis" in Tunisia

Samira Maatallah [a,b,**], Monia Guizani [a,b], Karima Lahbib [c], Giuseppe Montevecchi [d,e], Giulia Santunione [d,*], Kamel Hessini [f], Samia Dabbou [g,h]

[a] Non-Conventional Water Valuation Research Laboratory (LR VENC), National Research Institute for Rural Engineering, Water, and Forestry (INRGREF), University of Carthage, Hedi EL Karray Street, El Menzah IV, Tunis, 1004, Tunisia
[b] Regional Center for Agricultural Research, Institution of Research and Higher Education Agriculture (IRESA), Sidi Bouzid, 9100, Tunisia
[c] Laboratory of Biodiversity, Biotechnology and Climate Changes, Faculty of Sciences of Tunis, University of Tunis El Manar, El Manar II, Tunis, 2092, Tunisia
[d] Department of Life Sciences (Agri-Food Science Area), University of Modena and Reggio Emilia, Via Amendola 2, 42122, Reggio Emilia, Italy
[e] BIOGEST - SITEIA Interdepartmental Center, University of Modena and Reggio Emilia, Piazzale Europa 1A, 42124, Reggio Emilia, Italy
[f] Department of Biology, College of Sciences, Taif University, Taif, 21944, Saudi Arabia
[g] Unit of Bioactive and Natural Substances and Biotechnology UR17ES49, Faculty of Dental Medicine of Monastir, University of Monastir, Avicenne Street, 5019, Monastir, Tunisia
[h] Faculty of Dental Medicine of Monastir, University of Monastir, Avicenne street 5019, Monastir, Tunisia

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ABSTRACT

The study assessed the physiological parameters in leaves and the morphological/pomological traits in fruits of six fig cultivars (*Ficus carica* L.) – Sawoudi, Bayoudhi, Mlouki, Assal, Zidi, and Mozai – which grow in the arid climate of the Gafsa oasis (in the center of Tunisia). These cultivars are distinguished by different peel colors ranging from greenish, yellowish-brown, up to dark purple.

Experiments measured chlorophyll and gas exchange in the plant leaves and various morphological, pomological, and chemical parameters, including phenolic compounds and antioxidant enzyme activities of the peel and pulp.

The results showed that the Mlouki and Assal cultivars had the highest rates of photosynthesis (Pn) (10.17 and 10.44 μmol CO_2 m^{-2} s^{-1}, respectively). In addition, the fruits of these cultivars showed the highest concentration of sugar in the peel and flesh, as well as the highest values of solid soluble content (22.23 and 20.83 °Bx, respectively). Mlouki had the highest fruit weight (66 g) compared to the other cultivars studied. As for the acidity of the fruit, Bayoudhi showed the highest values (6.56 g MAE 100 mL^{-1}), while the fruits of Assal and Zidi had the lowest acidity values. Biochemical determinations showed that Sawoudi had important enzymatic activity assessed by catalase (10.64 and 12.08 U min^{-1} g^{-1} in flesh and peel, respectively) and peroxidase, while Mlouki and Assal fruits showed the lowest values. The results also confirmed that the fig peel had higher antioxidant enzyme activity than the flesh. It can be concluded that the Mlouki cultivar exhibits superior overall quality with the highest weight and sugar content, while the dark-peeled cultivars (Sawoudi and Zidi) show the highest concentrations of phenolic compounds and antioxidant enzyme activities.

The characteristics of these cultivars are in line with consumer demands, and therefore farmers can be encouraged to devote themselves to multiplying their cultivation.

1. Introduction

Ficus carica L., a species of fruit tree, is considered one of the oldest

* Corresponding author.
** Corresponding author. Non-Conventional Water Valuation Research Laboratory (LR VENC), National Research Institute for Rural Engineering, Water, and Forestry (INRGREF), University of Carthage, Hedi EL Karray Street, El Menzah IV, Tunis, 1004, Tunisia.
E-mail addresses: samira.maatallah@iresa.agrinet.tn (S. Maatallah), guizanimonia@ymail.com (M. Guizani), karima.lahbib@fst.utm.tn (K. Lahbib), giuseppe.montevecchi@unimore.it (G. Montevecchi), giulia.santunione@unimore.it (G. Santunione), kamelhessini@gmail.com (K. Hessini), samia.dabbou@fmdm.u-monastir.tn (S. Dabbou).

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and best-adapted trees in the Mediterranean basin and arid ecosystems [1] and more than 800 varieties of the genus *Ficus carica* can grow in a warm climate. Fig growth and production are strongly dependent on environmental conditions. In general, the dry Mediterranean and warm-temperate climates seem to represent the best conditions to achieve high-quality fruit production [2]. Data from the Food and Agriculture Organization of the United Nations (FAO) stated that world fig production is constant. Over 281,522 ha of fig cultivation are present all over the world, producing about 1,315,588 t in 2019 [3].

Abbreviations

APX	ascorbate peroxidase activity
C3GE	cyanidin-3-*O*-glucoside equivalents
CAE	citric acid equivalents
CAT	catalase activity
CE	catechin equivalents
Ci	intercellular CO_2
CIE	International Commission on Illumination
gs	stomatal conductance
HTE	hydroxytyrosol equivalents
PCA	principal component analysis
POD	peroxidase activity
Pn	photosynthetic assimilation
QE	quercetin equivalents
TA	titratable acidity
Tr	transpiration rate
TPC	total phenolic content
WUEins	water use efficiency

The cultivation of figs is widespread in Tunisia, and it is present in different environmental conditions, occupying 37,774 ha. According to Mars et al. [1] the most fig-producing Tunisian areas are the South-East, South-West, the Middle East, the North-East, and the North-West, with a production of about 34 % of figs. In 2018, Tunisia's average annual fig production was estimated at 27,350 t, while the Gafsa oasis produced about 2600 t [4].

The fig tree constitutes an extremely rich and diversified phylogenetic heritage, which is represented by several cultivars well adapted to the eco-geographical conditions, with particular agronomic and ecological characteristics [5]. In Tunisia, different fig cultivars are historically found in different climate zones; in addition, natural and sub-spontaneous forms are native to the North and the Center of the Country [6]. In fact, fig trees have a crucial ecological role, they help to maintain the balance of the ecosystem in many uncultivated areas, particularly in areas with a semi-arid or arid climate. However, despite their importance, local cultivars in the Mediterranean region are currently facing a serious threat of genetic erosion due to a range of biotic and abiotic stresses, such as intensive urbanization and monovarietal crops [7], especially those cultivated in the oasis.

In different regions of the world, complex agro-ecosystems like those described above are in crisis and decline [8]. Specifically, numerous threats affect species growing in the historic oasis of Gafsa, such as the effects of climate change, in particular the accentuation of drought and its consequences on water availability, inadequacy of demographic pressure, and urbanization in relation to the limited carrying capacity of the ecosystem oasis and pollution. All these factors added together have resulted in the current environmental and socio-economic situation, which weakens and deteriorates the value of ecosystem services and reduces their resilience [9]. In this respect, crop growth and development under climatic changes are subjected to unfavorable conditions, resulting in low productivity and quality [10–13]. Raising temperatures [14], soil salinization [15,16], and drought [17,18] are the major impacts of climate change, especially in arid and semi-arid ecosystems. All of these represent environmental stresses that disturb plant physiology involving photosynthetic efficiency [19], stomatal performance [20], cell water status [21], and nutrient balance and utilization [22,23].

Accordingly, environmental stresses have an impact on fig physiology, although this species has shown remarkable plasticity of adaptation to semi-arid and arid ecosystems. In fact, under drought conditions (rise in temperature and lack of precipitation), physiological (net photosynthetic assimilation, transpiration rate, and stomatal conductance), morphological, and phenological traits of fig tree undergo several forms of adaptation [24]. In addition, recent studies have shown that genotype [24], leaf development stage [25], fruit development [26], age, growing area, edapho-climatic conditions, and period of measurements [27] all have an impact on gas exchange capacity [28]. On the other hand, semi-arid and arid environmental conditions reduce the incidence of fungal diseases and improve the sensory qualities of fruits [29]. Therefore, selecting cultivars that have the ability to adapt and perform well in stressful environments is regarded as an efficient and inexpensive tool to combat stress issues [30–32].

Given their high nutritional value, figs have been a popular food among humans for a very long time. In addition to being consumed fresh or dried, figs are also used to extract flavors, create natural food colorings, prepare and preserve foods (such as candied figs and figs in syrup) [33]. Furthermore, the quality of fresh fruit depends not only on its nutritional and bioactive components but also on other parameters related to its morphology and sensory properties, including firmness, color, flavor, and aroma [34].

Due to their abundance of secondary metabolites such as polyphenols, essential oils, and alkaloids, fig fruits have been long studied as sources of natural substances and molecules. These products are highly recommended for their healthy properties. Figs also contain various antioxidants [35] which are mainly found in the edible peel of the fruit. Dark-colored figs usually contain more antioxidants than lighter-colored cultivars [36].

One of the current scientific interests is to identify and characterize the varieties of figs of superior quality. In addition, the commercial importance of figs and their health benefits have prompted researchers to identify good-quality fig cultivars [37].

Previous studies on figs have focused on their polyphenol content [38]. Fig fruits are characterized by an elevated antioxidant potential due to their higher anthocyanins, flavonol glycosides, and phenolic acids [39]. Additionally, these fruits are an important source of fiber, trace minerals, proteins, sugars, and organic acids. Fresh fig fruits contain eight main phenolic compounds, which are chlorogenic acid, catechin, epicatechin, rutin, cyanidin-3-*O*-rutinoside, luteolin-8-*C*-glucoside, quercetin-3-*O*-glucoside, and kaempferol-3-*O*-glucoside [40]. Besides their physiological roles in plants, these compounds act as reducing agents, hydrogen donors, and free radical scavengers [41].

Anthocyanins mainly accumulate in fig peels, which can take on a violet, blue, or pink color [39]. The production process of secondary metabolites with antioxidant roles varies depending on several factors, such as plant development [42], plant tissues, and growing season [43].

Various findings mentioned that the production of reactive oxygen species (ROS), often leading to oxidative stress, occurs as a result of environmental stresses [44], such as salinity [45], waterlogging [46], and drought [47]. Faced with these conditions and in order to defend themselves against cytotoxic species of activated oxygen, the fig tree has developed many specific protective mechanisms, which include antioxidant molecules and enzymes [48].

In recent years, like other Mediterranean Countries, Tunisia has been exposed to severephenomena that can affect the sustainability and biodiversity of its oases, which are also threatened by the evolution of urban planning (socio-economic factors). Water scarcity and lack of regeneration in several trees also pose a real threat to the biodiversity of fig genotypes.

To the best of our knowledge, little information is available regarding the physiological traits, phenolic characterization, and activity of antioxidant enzymes (catalase, peroxidase, and ascorbate peroxidase) in the fruits of local fig cultivars from the Gafsa oasis. Antioxidant molecules and enzyme production mechanisms have been developed by fig trees to cope with stressed environmental conditions and as a defense against cytotoxic species of activated oxygen [48].

In this context, this study aimed to evaluate some specific physiological and nutritional parameters, as well as to compare the composition and antioxidant potential in the flesh and peel of six local genetic resources of figs (Bayoudhi, Sawoudi, Mlouki, Assal, Zidi, and Mozai) grown in the Gafsa oasis to encourage farmers to consider and cultivate the most promising cultivars.

2. Material and methods

2.1. Description of the studied site

This study was conducted in the historic oasis of Gafsa (South-West Tunisia) (34° 32′ 10″ N, 8° 46′ 22″ E; 381 m a.s.l.), recognized as Ingenious System of World Agricultural Heritage (GIAHS) by the FAO (Fig. 1). Its creation dates back to the earliest times in history.

The study area is classified as a mountain oasis located in the arid bioclimatic phase. It is known for its biological diversity, characterized by multi-layered systems (three levels of planting) at very high density, in some places exceeding 400 feet/hectare. It covers 700 ha, of which 8.36 % is occupied by fig trees.

The soil is sandy, loamy-clayey, characterized by scarce fertile resources. Water in the oasis comes from numerous natural sources, which spring from the deep aquifer known as the "Gafsa-North aquifer". Irrigation is ensured by reservoirs or large beds (drilling from groundwater) that are submerged for irrigation (4 times/month in summertime, and the allocated quota is 2 h 47 min per hectare with an average salinity of 2.8 g/L) [49].

2.2. Soil characteristics and climate data

Most of the soils in the historic Gafsa oasis belong to the brown steppe class of soils. Their origin is generally fluvial, composed mainly of clay. According to a previous study carried out by FAO (2010), the soils of the oasis are characterized by a lumpy structure and a good water retention capacity (15–20 %), with an organic matter content ranging between 1.5 and 2.0 %. The analysis carried out on soil profiles did not show excessive levels of gypsum or active limestone (<1 %) [49].

Climatic data that occurred in Gafsa during the experimental periods were taken from the website Infoclimat.fr and are presented in Fig. 2. The region studied was characterized by an arid climate with the highest temperatures, which peaked in July 2018 and 2019 (41.1 and 38.9 °C, respectively). The cumulative rainfall in 2018 and 2019 was 159 and 129 mm, respectively (Fig. 2).

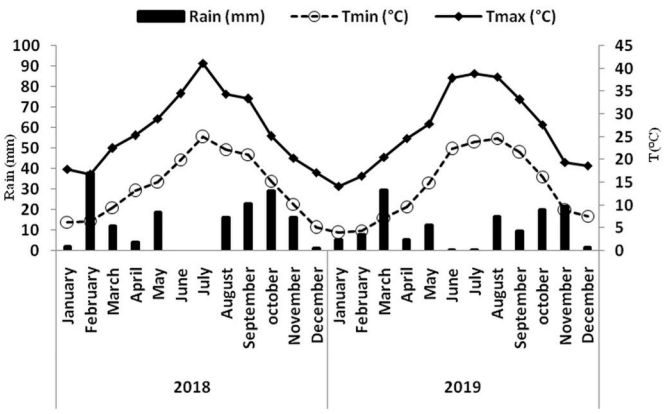

Fig. 2. Weather data for two consecutive seasons (2018–2019) for the Gafsa oasis.

2.3. Plant material

The ripe fruits of six *Ficus carica* L. cultivars (Bayoudhi, Sawoudi, Assal, Mlouki, Zidi, and Mozai) were harvested by hand during the third week of July for two consecutive years (2018 and 2019). The fig cultivars studied are "unifers" having a single crop a year [50] with the exception of the Mozai cultivar, which is considered a "biferous" cultivar (harvested twice a year) [51]. In all cultivars, leaf emergence occurred in April, while fruit development took place on one-year-old shoots.

For each cultivar, 5 to 10 undamaged fruits were sampled from four randomly selected trees, aged 35–40 years, from four sides of the trees. The selected trees were vigorous and uniform in terms of size, shoot length, and diameter. Then, 12 fruits for each cultivar were selected and immediately separated into peel and flesh (including seeds), ground into liquid nitrogen, and then freeze-dried using a freeze dryer and kept at −80 °C until subsequent analysis.

2.4. Chlorophyll content and foliar gas exchange parameters

Leaf chlorophyll content (reported as SPAD value) and gas exchanges were measured simultaneously in the same leaves. Three leaves from each variety tree were examined to determine SPAD values using a Minolta SPAD meter (SPAD-502 Plus, Konica Minolta sensor, Japan). This sampling was performed on three trees per cultivar.

Gas exchange was measured using a portable LC*pro* + photosynthesis device (ADC Ltd. BioScientific., Hoddesdon, UK). The analyses were

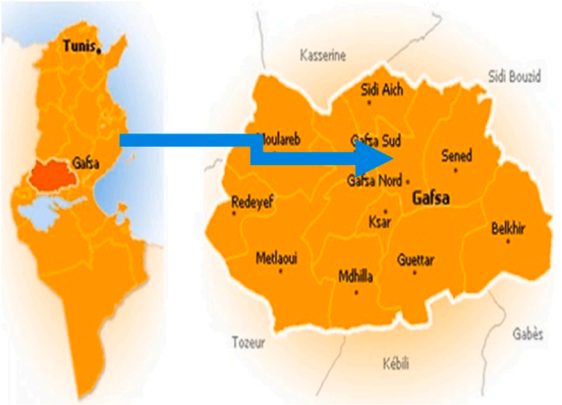

Fig. 1. Historic oasis of Gafsa.

performed on three leaves per tree considered (three plants for each cultivar studied). The following parameters were determined from mature leaves under saturating daylight sunlight (11–13 h): net photosynthetic assimilation (Pn, μmol CO_2 m^{-2} s^{-1}), stomatal conductance (gs, mmol H_2O $m^{-2}s^{-1}$), transpiration rate (Tr, mmol H_2O $m^{-2}s^{-1}$), water use efficiency (WUEins = Pn/Tr), and intercellular CO_2 (Ci, μmol mol^{-1}). The measurements were taken in July, during the fruit harvest.

2.5. Morphological, pomological, and ethylene production of fig fruits

The shape of fruits varied among cultivars and was described according to Ref. [52]. The height of the fruit (mm) was measured from the base of the fruit to the end of the collar or neck (Fig. 3). On average, over the course of 2 years, 25 fruits randomly selected for fruit weight (g) were calculated using a digital weighing scale with a sensitivity of 0.001 g. The length of the peduncle (mm) was measured from the peduncle base to the branch. The shape and diameter of the peduncle (mm) were determined according to Refs. [52,53] (Figs. 3 and 4).

The consistency of the flesh of a partially peeled fruit was assessed immediately after harvesting using a penetrometer (FT 327, QA Supplies LLC, Italy). The soluble solids (SSC) content in the juice, obtained by homogenizing three sampled fig fruits for each replication in a mixer, was determined using a digital refractometer (Atago-Palette PR 101, Atago Co., Tokyo, Japan), and the results were expressed in °Bx.

Concerning the juice pH, it was measured by a pH-meter (MP 220, Mettler Toledo, Switzerland), and electrical conductivity was assessed by a conductivity meter (Hanna HI8733, Italy). To determine titratable acidity (TA), free acids were neutralized in fig juice diluted in water twice using a solution of 0.1 N NaOH that was added drop by drop up to pH 8.2 [54]. Citric acid, the most prevalent organic acid in figs, was used to express the results as g citric acid equivalents (CAE) 100 mL^{-1} [55]. Iodometric titration of ascorbic acid was used to measure vitamin C concentrations [56].

Peel color was assessed immediately after collection with a Minolta colorimeter CR-300 (Konica Minolta Sensing, Inc., Japan), which provided CIE (International Commission on Illumination) coordinates (L*, brightness; a*, redness; b*, yellowness) in ten fruits. Four measurements were taken on the peel of each fruit, two measurements from opposite sides.

At harvest time, ethylene production was measured by a portable ethylene analyzer (F-900, Felix Instruments, Camas, WA, USA). Six to ten samples of fruit were immediately transported to the laboratory and then placed in the container of the F-900. Ethylene emissions were measured in real time and expressed in ppm [57].

2.6. Dosage of total sugars

A modified version of the method described by Kader et al. [58] was used to extract sugars. In short, 15 mL of 80 % ethanol and 0.1 g of freeze-dried fruit were homogenized and boiled in a water bath at 95 °C for 15 min. Before being centrifuged at 3075 *g* for 10 min, the mixture was filtered. The method developed by Dubois et al. [59] was used to determine carbohydrate content. An aliquot of 1.5 mL of concentrated sulfuric acid and 0.3 mL of phenol (5 % w/v) were combined with 0.3 mL of supernatant. Absorbance was measured at 490 nm after a 5-min incubation period at 105 °C.

To determine the overall sugar content, a calibration curve built through a glucose solution was used. The results were expressed in g of glucose equivalents per 100 g of fruits.

2.7. Determination of phenolic compounds and anthocyanins

Organic extracts were prepared by homogenizing 5 mL of a methanol solution with 0.5 g of dry plant material (freeze-dried peel and flesh) with an Ultra-Turrax (T 25 D, IKA, Germany) homogenizer. The suspension was centrifuged for 15 min at 4 °C. The extraction was carried out twice on the same residue. The organic extracts obtained were stored at −20 °C to carry out subsequent analyses.

The total phenolic content (TPC) was determined according to the method of Montedoro et al. [60]. The methanol extract was diluted and mixed with the Folin-Ciocâlteu reagent (1/10; v/v) and sodium bicarbonate (75 g/L). Subsequently, the mixture was incubated for 2 h at room temperature before absorbance measurement at 765 nm. The TPC was expressed as mg of hydroxyltyrosol equivalent (HTE) 100 g^{-1} dry weight (DW).

Total flavonoids were quantified according to the method of Zhishen et al. [61]. A diluted sample of methanol extract was combined with 75 μL of $NaNO_2$ (5 %) and left to rest for 6 min. Subsequently, 150 μL of $AlCl_3$ (10 %) were added. The final volume was adjusted to 2.5 mL by adding, after 5 min, 0.5 mL of NaOH (1 M). After careful mixing of the resulting solution, the absorbance was read at 510 nm. Results are expressed as mg of catechin equivalent (CE) 100 g^{-1} DW.

The *o*-diphenol content was determined by a colorimetric assay [36]. Briefly, 100 μL of the methanol extract was added to an equal volume (1 mL) of HCl (0.5 N), NaOH (1 N), and a solution of $NaNO_2$ (1.45 N) and $Na_2Mo_42H_2O$ (0.4 N). After that, the mixture was incubated for 30 min. Finally, the absorbance was measured at 500 nm and the results are given as mg of hydroxytyrosol equivalent (HTE) 100 g^{-1} DW.

The flavonol content was evaluated according to Romani et al. [62]. Methanol extracts were blended with 10 % ethanol, 0.1 % HCl in 95 %

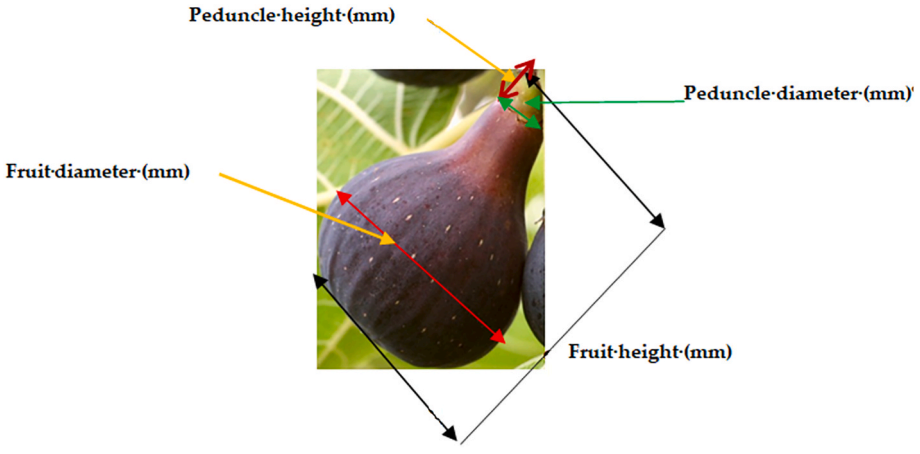

Fig. 3. Schematic presentation of the size of the figs determined in the six cultivars. Fruit diameter: the maximum equatorial diameter of the fruit (mm); height of the fruit: longitudinal height of the fig tree (mm); peduncle height: longitudinal height of the peduncle on its shortest side (mm); peduncle diameter: diameter of the free peduncle (mm).

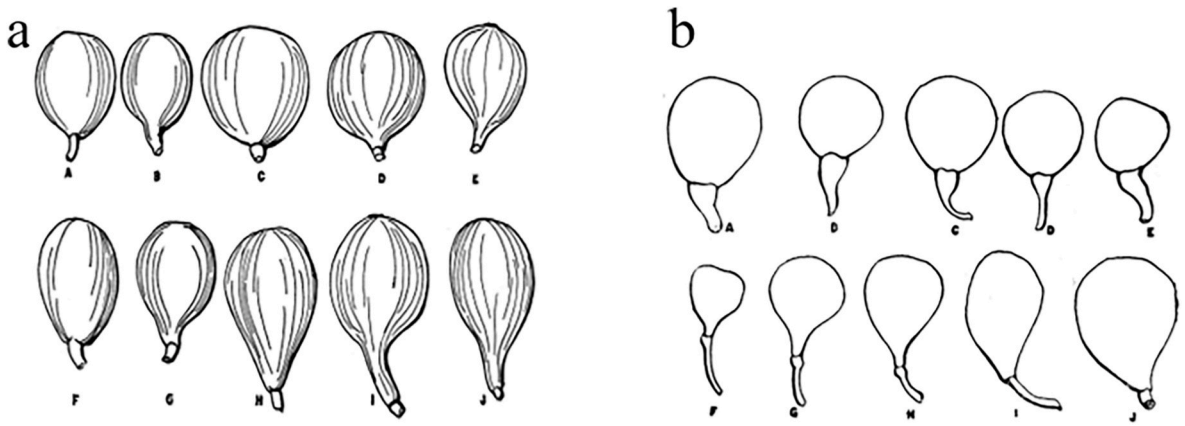

Fig. 4. Fruit forms (a) (A, B; Spherical with and without neck; C, D: oblate with and without neck; E, F: turbinate with and without neck; G, pyriform with thick neck; H: pyriform with neck undifferentiated from body; I: long and curved neck; J: oblique-pyriform) and stalks (b) (A-E, variously enlarged; F–I, long and slender; J, short and thick).

ethanol, and 2 % HCl. Then, the resulting solution was left at room temperature for 15 min before reading the absorbance at 360 nm. The total flavonol content was expressed as mg of quercetin equivalents (QE) 100 g^{-1} DW.

The concentration of anthocyanins was assessed following the procedure described by Chung et al. [63]. Five grams of plant material (fig peel or flesh) were homogenized with 10 mL of methanol solution (HCl 0.5 N/methanol 80 %). The solution obtained was kept at 4 °C for 24 h in the dark. Subsequently, the absorbance was read at 535 and 700 nm after centrifugation and filtration. The concentration of anthocyanins was determined according to Giusti and Worlstad [64] using a molar extinction coefficient (ε = 25965 L mol^{-1} cm^{-1}) and the values are expressed as mg of cyanidin-3-*O*-glucoside equivalents (C3GE) 100 g^{-1} DW.

2.8. Evaluation of enzyme activity and oxidative stress indicators

The enzyme extract was prepared as follows [65]: 1 g of dry plant material was combined with 10 mL of 50 mM phosphate buffer (pH = 6.8) containing 1 mM of EDTA and PVPP (1 %). The mixture was then centrifuged at 15,000 *g* for 30 min at 4 °C. An enzyme extract was created from the resulting supernatant.

2.8.1. Peroxidase (POD) activity assay (EC 1.11.1.7)

Based on the absorbance of tetra-guaiacol production in the presence of guaiacol and hydrogen peroxide (H_2O_2) in 1 min, POD activity was measured. An aliquot of 100 μL of the enzyme, 2600 μL of phosphate buffer (pH = 7.0), and 100 μL of H_2O_2 (12 mM) were combined into a mixture, and 200 μL of guaiacol (7 mM) was added to measure the activity of the enzyme. The enzymatic activity of the POD was monitored for more than 1 min at 470 nm. A unit of enzyme activity (U $min^{-1}g^{-1}$ DW) is the amount of enzyme required to catalyze the formation of 1 μmol of tetra-guaiacol per min [65].

2.8.2. Ascorbate peroxidase (APX) activity assay (EC 1.11.1.11)

To measure the APX activity, the method of Zhang et al. [66] was used. Briefly, potassium phosphate (50 mM, pH = 7.0), ascorbic acid (0.5 mM), and H_2O_2 (1 mM) were added to the enzyme extract (100 μL). The decrease in absorbance at 290 nm was calculated over the course of 1 min. An enzyme unit (U) is the amount of enzyme required to oxidize 1 μmol of ascorbate in 1 min, and the activity of the enzyme APX was expressed as U min^{-1} g^{-1} DW.

2.8.3. Catalase (CAT) activity assay (EC 1.11.1.6)

The catalase activity was measured by adding 3 mL of enzyme extract to a test tube along with a reaction mixture consisting of phosphate buffer (50 mM, pH = 7.0) and H_2O_2 (15 mM). The decrease in absorbance at 240 nm was measured over a period of 1 min [57]. An enzyme unit (U), defined as an absorbance reduction of 0.01 per min, was established for the purpose of measuring CAT activity. Results were expressed as U min^{-1} g^{-1} DW.

2.8.4. Malondialdehyde (MDA) dosage

The malondialdehyde concentration was measured using a colorimetric method [67] To precipitate the proteins for the experiment, dry plant material (0.5 g) was mixed with 10 mL of 1 % trichloroacetic acid (TCA) at 4 °C. The precipitate obtained was pelleted by centrifugation for 15 min at 4 °C 3075 *g*. The supernatant (1 mL) was added to 4 mL of buffer (0.5 % thiobarbituric acid + 20 % TCA + H_2O solution) and heated to 95 °C in a water bath for 30 min. After 2 min of thermal shock and cooling, a second centrifugation lasting 10 min was performed. The absorbance of the colored supernatant was measured at 532 nm and adjusted for non-specific absorbance at 600 nm. The following formula was used to determine the MDA content, expressed as 100 μmol g^{-1} DW.

$$MDA = [(A_{532}\text{-}A_{600}) \times V] \times 1000/\varepsilon \times W$$

where V is the volume of the homogenizing medium; ε is the absorbance coefficient of MDA; and W is the dry weight.

2.8.5. Determination of hydrogen peroxide content

Regarding the determination of H_2O_2, 0.5 g of dried plant material and 5 mL of a TCA solution (0.1 %) were centrifuged at 5,000 *g* for 15 min. The supernatant obtained (0.5 mL) was mixed with 0.5 mL of phosphate buffer ($NaH_2PO_4 + Na_2HPO_4$; pH = 7) and 0.5 mL of KI (1 M). Subsequently, the solution was incubated for 15 min at 25 °C in a water bath, and absorbance was measured at 390 nm [68]. H_2O_2 content was expressed as 100 μmol g^{-1} DW.

2.9. Statistical analysis

The SPSS software (version 17.0 for Windows, SPSS, Chicago, IL, USA) was used to perform the statistical analysis. Mean values (n = 3) and standard deviation were used to show the results. The analysis of variance (one-way ANOVA) was used to compare the mean values after evaluating the application criteria (normal distribution and homoscedasticity). Duncan's test was used to rank the averages of the fig cultivars studied.

The relationships among the cultivars, the various parts of the fruit, and their composition were highlighted using principal component analysis (PCA) using the XLSTAT (2014) software for Windows (Add in Soft, New York, USA).

3. Results

3.1. Chlorophyll content and gas exchange parameters

Table 1 shows the variation in chlorophyll content, expressed as SPAD, in the leaves of the six fig cultivars. The highest chlorophyll content was found in the leaves of Assal cultivar (51.36 SPAD), followed by Bayoudhi and Mlouki, while this content decreased in the leaves of Zidi cultivar.

The gas exchange parameters (Table 1) showed that the highest photosynthetic assimilation rate (Pn) was 10.44 μmol CO_2 m^{-2} s^{-1} in Assal, followed by Mlouki. However, ANOVA showed no significant differences among the studied cultivars, except for Zidi, which had a significantly lower Pn rate compared to the other cultivars. Moreover, our results showed that the transpiration rate (Tr) varied between 1.78 and 2.67 mmol H_2O m^{-2} s^{-1}. Indeed, Bayoudhi, Sawoudi, and Mlouki exhibited the highest values, while Zidi showed the lowest. In addition, we found that Assal, Mlouki, Bayoudhi, and Mozai cultivars had significantly higher stomatal conductance (gs) values, ranging between 369.33 and 397.34 mmol H_2O m^{-2} s^{-1}. Zidi recorded the lowest value (277.64 mmol H_2O m^{-2} s^{-1}). In addition, our results showed that the intercellular CO_2 content varied significantly depending on the cultivar. In fact, Assal, Mlouki, and Bayoudhi had the highest Ci values (Table 1). Finally, the estimated WUEins revealed that Mozai was the most efficient (4.63 μmol CO_2 μmol^{-1} H_2O), followed by Assal, while Sawoudi was the least efficient, as shown in Table 1.

3.2. Morphological characterization

Table 2 shows that the morphological characteristics of fig fruits varied significantly from one cultivar to another. In particular, the Mlouki cultivar displayed the largest diameter (53.63 mm), followed by Mozai (52.74 mm), and Sawoudi, while Bayoudhi, Assal, and Zidi had the smallest diameters. Sawoudi and Mlouki fruits also showed the highest fruit height, reaching up to 55.02 mm.

The shape of the peduncle (Fig. 4) varied significantly among the cultivars. Indeed, an A-shape was observed in Sawoudi and a G-shape in Bayoudhi, whereas Mlouki, Assal, Zidi, and Mozai cultivars were J-shaped. The peduncle diameter varied in a significant way among the cultivars. It reached 9.11 mm in the Mozai fruit, followed by Mlouki and Sawoudi (7.13 and 7.00 mm, respectively). As for the height of the peduncle, the Bayoudhi fruit showed the longest item (12.95 mm) characterized by long stalks, followed by Sawoudi and Assal (Table 2).

Similarly, morphological results showed that the fruit forms varied among cultivars studied, indeed, Bayoudhi fruit had a long and curved neck. Moreover, Mozai and Mlouki distinguished by similar fruit form (oblate without neck). As for Sawoudi cultivar, its fruits had an oblate shape with neck. Assal fruit had a pyriform shape with thick neck as shown in Fig. 3. The last cultivar Zidi was characterized by a turbinate form with neck (Table 2).

Regarding the fruit weights, Mlouki and Mozai displayed the highest values (66.00 g and 59.50 g, respectively), while Bayoudhi, Assal, and Zidi showed much lower weights (around half of Mlouki's fruit weight).

3.3. Color analysis

The peel color of the sample set studied was very diverse, ranging from green to black (Table 2 and Fig. 5). Indeed, Bayoudhi and Assal cultivars showed a green to light orange color, while Zidi and Sawoudi cultivars had purple to black colors. The Mozai fruit was distinguishable due to its specific chromatic range, which ranged from green to yellow, while Mlouki's fruit was green-purple (Fig. 5).

Peel color analysis of the six cultivars showed that Bayoudhi, Assal, and Mozai fruits had higher average brightness (L* = 71.32, 70.16, and 66.8, respectively) and yellowness (b* = 47.82, 43.67, and 46.86, respectively), while negative values of a* (Fig. 6). Sawoudi and Zidi cultivars exhibited similar colors and stood out by a considerable decrease in L* compared to the other cultivars, with an increase in the reddish color (a*) which varied between 12.57 and 14.46 for Sawoudi and Zidi, respectively. These cultivars were also characterized by lower values of b*. Mlouki's fruit is characterized by a multicolored peel (green, yellow, and purple), showed fairly high values of L* and b* (51.05 and 25.05, respectively) and a low value of a* (7.14), indicating a magenta color (Fig. 6).

3.4. Ethylene production and pomological parameters

Table 3 shows the rate of ethylene production in the fruit of the different fig cultivars studied at the time of harvest. Mozai fruit recorded the highest ethylene production (1.78 ppm), followed by Assal. The fruits of Mlouki, Sawoudi, and Bayoudhi showed the lowest ethylene release, with Bayoudhi fruit showing a decrease of about 60 % (Table 3).

The determination of the texture of the fruit revealed a significant difference among the six fig cultivars. The Mlouki fruit showed a significantly higher texture (2.78 kg cm^{-2}), followed by the Zidi fruit (Table 3). In contrast, Assal and Bayoudhi fruit showed weaker firmness, with reductions of 68 % and 78 %, respectively.

Concerning the pH of the fig juices of the studied cultivars, it ranged between 4.80 and 5.61 (Table 3). There was a slight variation in this parameter among the cultivars analyzed. Similar variations were observed for conductivity, where the values ranged between 2.12 and 2.83 mS. Regarding soluble solids content (SSC), the Mlouki fruits showed the highest value (22.23 °Bx), followed by the Assal, Bayoudhi, and Zidi fruits (about 20.50 °Bx), while the Sawoudi fruits had the lowest SSC.

The titratable acidity of the samples (Table 3) showed that Zidi fruits had the lowest acidity values (2.67 g CAE 100 mL^{-1}), while Bayoudhi fruits had a higher TA value (twice as high as Zidi). Vitamin C content ranged between 0.17 mg 100 g^{-1} FW in Mlouki and 0.26 mg 100 g^{-1} FW in Sawoudi's fruit, with no significant differences found between the six fig cultivars.

3.5. Total sugars

The results of the total sugars in the peel and flesh of the different cultivars studied are shown in Fig. 7, with values ranging from 2.55 to 14.58 g 100 g^{-1} DW. The Assal and Mlouki cultivars were the richest in

Table 1
Chlorophyll content and gas exchange parameters in the leaves of the six fig cultivars studied.

Cultivars	Chlorophyll content (SPAD)	Pn (μmol CO_2 m^{-2} s^{-1})	Tr (mmol H_2O m^{-2} s^{-1})	gs (mmol H_2O m^{-2} s^{-1})	Ci (μmol mol^{-1})	WUEins (μmol CO_2 μmol^{-1} H_2O)
Bayoudhi	47.14 ± 1.63 ab	9.94 ± 0.87 a	2.61 ± 0.38 a	370.33 ± 8.38 a	388.32 ± 18.74 a	3.87 ± 0.56 bc
Sawoudi	44.50 ± 1.08 bc	9.67 ± 1.38 a	2.62 ± 0.39 a	318.94 ± 11.80 b	325.36 ± 44.67 c	3.71 ± 0.45 c
Mlouki	47.12 ± 2.06 ab	10.17 ± 0.37 a	2.67 ± 0.44 a	375.63 ± 17.19 a	390.24 ± 13.62 a	3.91 ± 0.72 bc
Assal	51.36 ± 1.08 a	10.44 ± 0.34 a	2.31 ± 0.14 ab	397.34 ± 16.02 a	410.36 ± 33.35 a	4.53 ± 0.33 ab
Mozai	45.45 ± 1.12 bc	9.85 ± 1.24 a	2.13 ± 0.07 bc	369.33 ± 20.53 a	358.43 ± 8.10 b	4.63 ± 0.67 a
Zidi	41.29 ± 1.63 c	7.52 ± 0.83 b	1.78 ± 0.20 c	277.64 ± 28.02 c	293.44 ± 18.35 d	4.24 ± 0.33 abc

The values are the means of three different fig leaf samples ($n = 3$) ± standard deviation. Different letters (a > b > c > d) indicate significant differences ($p \leq 0.05$) among the six cultivars. Pn: photosynthetic assimilation, Tr: transpiration rate, gs: stomatal conductance, Ci: WUEins: Pn/Tr.

Table 2
Morphological characterization of the fruit of the six fig cultivars studied.

Cultivars	Fruit diameter (mm)	Fruit height (mm)	Peduncle diameter (mm)	Peduncle height (mm)	Fruit stalks	Fruit shape (forms)	Weight (g)	Color
Bayoudhi	41.34 ± 4.57 b	44.12 ± 4.91 b	5.07 ± 1.34 c	12.95 ± 3.88 a	G	Neck long and curved (I)	35.37 ± 8.91 c	Green-yellow
Sawoudi	49.83 ± 4.64 a	55.02 ± 5.98 a	7.00 ± 1.26 b	9.52 ± 3.40 b	A	Oblate with neck (D)	50.77 ± 11.74 b	Purple-black
Mlouki	53.63 ± 6.46 a	50.97 ± 9.40 a	7.13 ± 1.01 b	7.65 ± 3.04 bc	J	Oblate without neck (C)	66.00 ± 17.49 a	Green-purple
Assal	39.30 ± 5.49 b	42.79 ± 4.64 b	5.36 ± 1.10 c	8.98 ± 1.45 b	J	Pyriform with thick neck (G)	34.57 ± 4.33 c	Green-light orange
Mozai	52.74 ± 5.03 a	45.18 ± 3.55 b	9.11 ± 1.78 a	6.49 ± 1.32 c	J	Oblate without neck (C)	59.50 ± 12.77 a	Green- yellow
Zidi	41.56 ± 2.73 b	43.44 ± 4.22 b	4.99 ± 1.04 c	7.59 ± 3.26 bc	J	Turbinate with neck (E)	35.19 ± 8.29 c	Purple-black

The values are the means of three different fig samples ($n = 3$) ± standard deviation. Different letters (a > b > c) indicate significant differences ($p \leq 0.05$) among the six cultivars.

Fig. 5. Morphological and chromatic appearance of the six fig cultivars studied.

sugar, regardless of the tissue (flesh or peel). Bayoudhi, Sawoudi, and Zidi displayed the lowest total sugar content. In addition, the flesh of Mozai, Zidi, and Sawoudi contained more sugar than the peel, with the difference in the flesh of Mozai and Zidi being up to twofold. However, no significant difference was found in the other cultivars (Mlouki, Assal, and Bayoudhi) between the two compartments (Fig. 7).

3.6. Phenolic composition and anthocyanin content

Fig. 8A displays that the TPC values in the six cultivars studied ranged from 116.59 to 1350.79 mg HTE 100 g^{-1} DW in the peel of Bayoudhi and Zidi, respectively. In most of the cultivars (Zidi, Sawoudi, Mlouki, and Mozai), phenolics were more abundant in the peels, with the exception of Assal fruit, where the flesh compartment was more concentrated in phenols.

Similarly, flavonoid content was more concentrated in the peels of the different cultivars (Fig. 8B). The results showed that the flavonoid content varied from 17.38 mg CE 100 g^{-1} DW (in the flesh of Bayoudhi) to 228.32 mg CE 100 g^{-1} DW (in the peel of Zidi). As for the flesh, Zidi, Mozai, and Assal were richer in flavonoids compared to the other cultivars. Generally, Zidi and Mozai cultivars exhibited the highest levels of TPC and flavonoids, particularly in the peel tissue (Fig. 8A and B).

Moreover, the analysis of the fig fruits revealed higher concentrations of flavonols and *o*-diphenols in all cultivars studied (Fig. 8C and D). Aside from Mozai, the flavonol content was more concentrated in the peel (Fig. 8C), with the highest value recorded in the peel of Zidi (328.04 mg QE 100 g^{-1} DW). The flavonol content in the flesh tissues ranged from 12.11 to 232.31 mg QE 100 g^{-1} DW. Zidi and Mozai fruits exhibited the highest flavonol concentrations, while Assal fruit had the lowest content in both flesh and peel.

The *o*-diphenol concentrations varied significantly among the cultivars (Fig. 8D). Zidi fruit showed the highest concentration in peel and flesh (492.00 and 127.76 mg HTE 100 g^{-1}DW, respectively). In contrast to the other cultivars, the flesh of Sawoudi and Bayoudhi showed a high content of *o*-diphenols compared to the peel (Fig. 8D).

Finally, Fig. 8E shows the results of the anthocyanin content. The highest concentrations were found in the peel of Zidi (3.62 C3GE 100 g^{-1} DW), followed by Mozai, while Bayoudhi exhibited the highest concentration in the flesh, followed by Sawoudi.

3.7. Enzymatic antioxidant activities and indicators of oxidative stress

Table 4 illustrates the variation in antioxidant enzyme activities (CAT, POD, and APX) among the cultivars. The activity of CAT varied significantly depending on the cultivar and the part of the fruit considered (peel and flesh). In all cultivars studied, the peels were distinguished by their higher antioxidant activities, with the highest CAT activity recorded in Sawoudi (12.08 U min^{-1} g^{-1} DW). On the contrary,

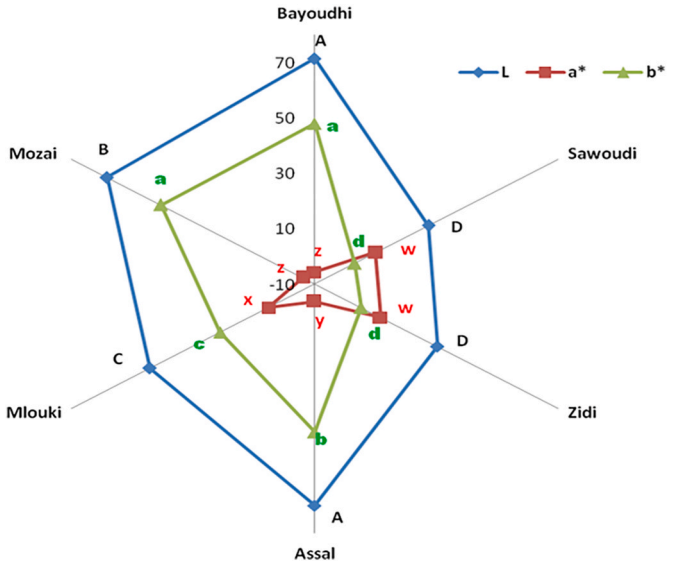

Fig. 6. Variation in the color of the peel of the six fig cultivars studied. The values are the mean of ten different fig fruits from each cultivar ($n = 10$). The letters (A > B > C > D > E), (a > b > c > d) and (w > x > y > z) indicate significant differences ($p \leq 0.05$) between the L, b*, and a*, respectively, measured in the peel of the fruit of each cultivar. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the lowest value was found in the peel of Mlouki.

In the flesh, CAT activity was 10.64 U min^{-1} g^{-1} FW in Sawoudi and dropped to 0.42 U min^{-1} g^{-1} FW in Mlouki.

POD activity ranged between 0.03 U min^{-1} g^{-1} DW in Zidi flesh and peel, and 0.78 U min^{-1} g^{-1} DW in Mozai peel, while Sawoudi showed the highest value in flesh.

Finally, as for APX activity, the flesh parts displayed higher activity than the peels. The flesh of Mlouki showed the highest value (1.33 U min^{-1} g^{-1} DW), while Mozai had the lowest APX activity in the flesh, with a reduction of more than 90 %. The Bayoudhi peel exhibited the highest APX activity, while all the other cultivars had values around 0.10–0.15 U min^{-1} g^{-1} DW.

In addition, the variation in oxidative stress indicators presented in Table 4 revealed that lipid peroxidation, as indicated by the concentration of MDA, occurred in all studied cultivars (Table 4). Indeed, the level of MDA in the flesh was greater than that recorded in the peel. Moreover, the results showed that Bayoudhi flesh had the highest MDA level (2.12 µmol g^{-1} DW). However, the peels of Sawoudi, Mozai, and Zidi exhibited significantly higher levels than those recorded in the other cultivars.

H_2O_2 content was more abundant in the peel part, varying between 0.23 µmol g^{-1} DW in Mozai and 2.85 µmol g^{-1} DW in Sawoudi fruit. However, in the flesh part, the level of this oxidant did not exceed 0.84 µmol g^{-1} DW (Sawoudi). Besides, H_2O_2 contents were more concentrated in Sawoudi, Mlouki, and Assal. However, Mozai fruit exhibited a lower level of H_2O_2.

3.8. Principal component analysis (PCA)

PCA was carried out to obtain a simple and complete visualization of the relationships among all variables. Fig. 9 shows that the two principal components (PC) accounted for 62.41 % of the total variance.

The biplot shows that the mean values of Mozai, Assal, and Bayoudhi cultivar samples were grouped in the positive quadrant of PC1 and were characterized by increased ethylene production, stomatal conductance (gs), net photosynthesis (Pn), acidity (Ac), peroxidase (POD) and ascorbate peroxidase rates (APX) as well as L* and b* values. In contrast, Zidi's samples in the negative quadrant of PC1 were characterized by a higher concentration of total phenolic content (TP), flavonoids (FL), flavonols (FV), *o*-diphenols (O-DP), chlorophyll, MDA, and intracellular CO_2.

The Sawoudi samples were located in the negative quadrants of PC2, which was characterized by higher values for firmness (FFir), pH, °Bx (SSC), a*, anthocyanins (ANT), and vitamin C. Finally, samples of Mlouki cultivar were placed in the negative quadrant of PC2 and the positive quadrant of PC1, and these samples were positively correlated with higher values of fruit weight (FW), fruit diameter (FD), fruit height (FH), total sugars (TS), H_2O_2, and transpiration rate (Tr).

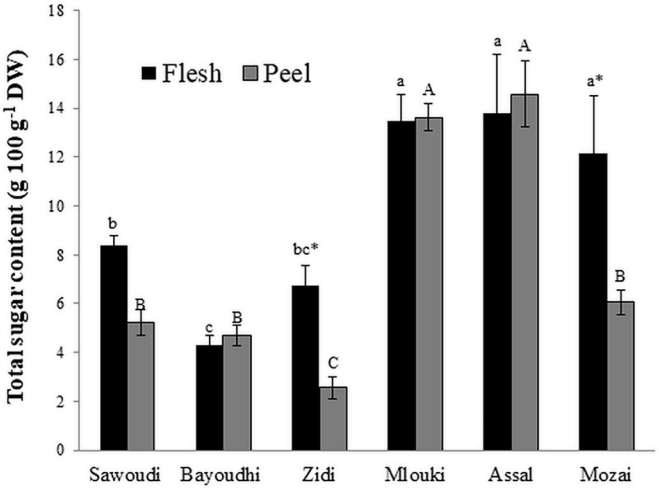

Fig. 7. Change in the total sugar content in the peel and flesh of the fruits of the six fig cultivars studied. The values are the means of three different fig samples ($n = 3$) ± standard deviation. The letters (a > b > c > d > e) and (A > B > C > D > E) indicate significant differences ($p \leq 0.05$) among the flesh of the six cultivars and the peel of the six cultivars studied, respectively. Different subscripts *, **, indicate significant differences between peel and flesh where '*' means significant difference at $p \leq 0.05$ and '**' significant difference at $p \leq 0.01$.

Table 3
Ethylene production and pomological properties of the six fig cultivars studied.

Cultivars	Ethylene (ppm)	Firmness (kg cm^{-2})	Fig juices pH	Conductivity (mS)	SSC (°Bx)	TA (g CAE 100 mL^{-1})	Vitamin C (mg 100 g^{-1} FW)
Bayoudhi	0.72 ± 0.15 c	0.60 ± 0.07 f	4.80 ± 0.54 b	2.82 ± 0.47 a	20.57 ± 0.30 b	4.90 ± 0.60 a	0.22 ± 0.02 a
Sawoudi	0.88 ± 0.09 c	1.83 ± 0.06 c	5.22 ± 0.11 ab	2.97 ± 0.39 a	18.70 ± 0.43 c	3.07 ± 0.90 cd	0.26 ± 0.08 a
Mlouki	0.94 ± 0.13 c	2.78 ± 0.04 a	5.61 ± 0.19 a	2.83 ± 0.31 a	22.23 ± 0.15 a	4.20 ± 0.01 b	0.17 ± 0.06 a
Assal	1.33 ± 0.33 b	0.88 ± 0.05 e	5.51 ± 0.15 a	2.12 ± 0.45 b	20.83 ± 0.15 ab	2.77 ± 0.49 d	0.18 ± 0.03 a
Mozai	1.78 ± 0.12 a	1.36 ± 0.09 d	5.19 ± 0.01 ab	2.72 ± 0.18 ab	19.93 ± 1.87 bc	3.83 ± 0.47 bc	0.18 ± 0.08 a
Zidi	1.06 ± 0.12b c	2.34 ± 0.19 b	5.51 ± 0.15 a	2.57 ± 0.06 ab	20.50 ± 0.36 b	2.67 ± 0.42 d	0.20 ± 0.01 a

The values are the means of three different fig samples ($n = 3$) ± standard deviation. The letters (a > b > c > d > e > f) indicate significant differences ($p \leq 0.05$) among the six cultivars. CAE: citric acid equivalents.

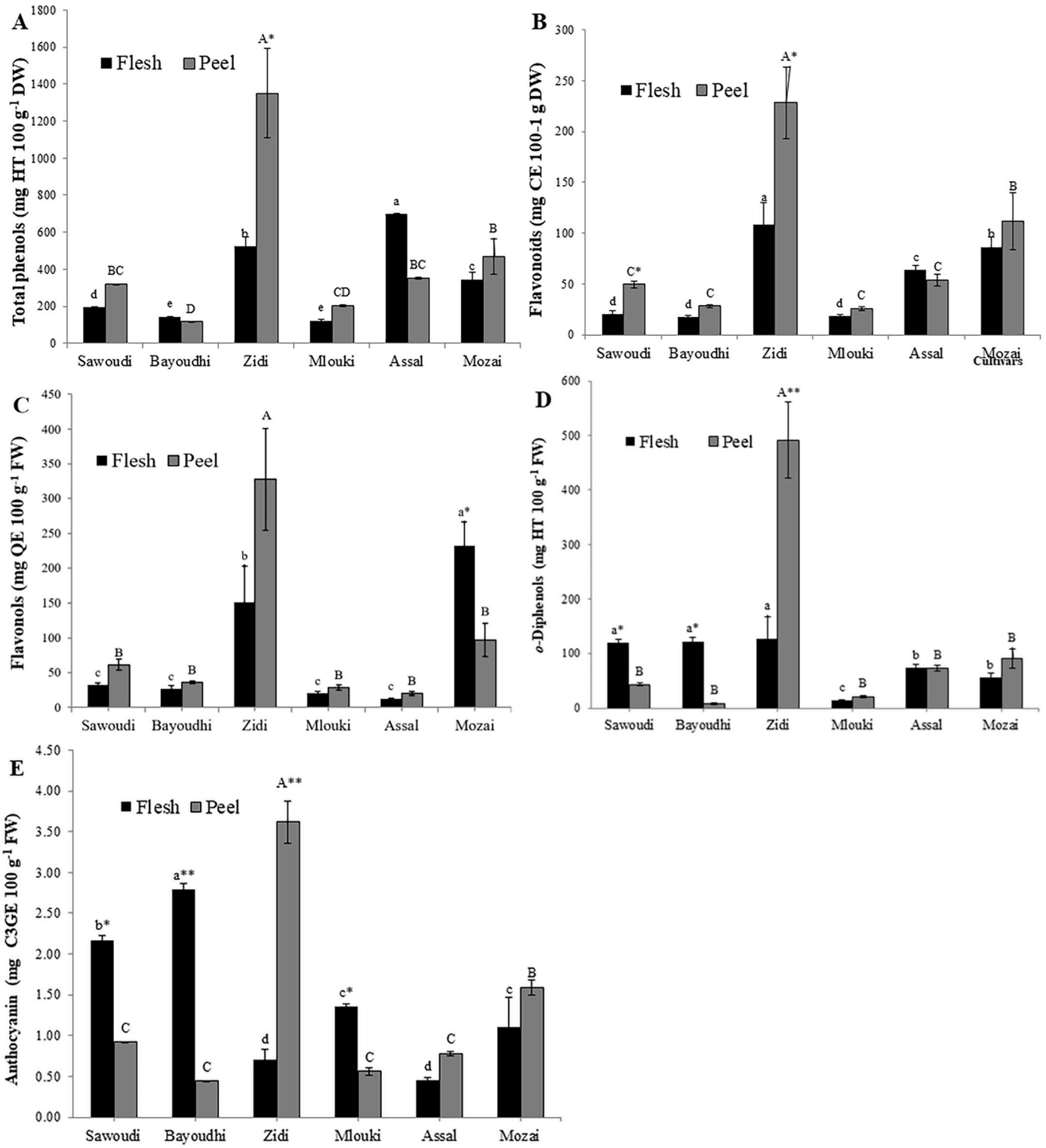

Fig. 8. **A.** Results of total phenolic content (TPC); **B.** flavonoid content; **C.** flavonol content; **D.** *o*-diphenol content; and **E.** anthocyanin content, in the peel and flesh of fruits of the six fig cultivars studied. The values are the means of three different fig samples ($n = 3$) ± standard deviation. The letters (a > b > c > d > e) and (A > B > C > D > E) indicate significant differences ($p \leq 0.05$) between the flesh of the six cultivars and the peel of the six cultivars studied, respectively. Different subscripts *, **, indicate significant differences between peel and flesh where '*' means significant difference at $p \leq 0.05$ and '**' significant difference at $p \leq 0.01$.

4. Discussion

The aim of this research was to contribute to the conservation of Tunisian genetic resources of fig trees, to ensure the sustainability of production, and to improve and preserve local fig cultivars, especially those grown in a desert mountain climate. In the context of global warming, the scarcity of water resources, and the increase in salinity, more attention needs to be paid to the worrying situation of fruit trees grown in Tunisia. However, there are few previous studies that have related the physiological behavior of fig trees to the morphological characterization, pomology and quality of the fruit, especially those grown in the oasis of Gafsa. This work focused on the study of six

Table 4
Results of the enzymatic activities and oxidative stress indicators in fruit flesh and peel of six fig cultivars.

Cultivars	Catalase (CAT) (U min^{-1} g^{-1} DW)		Peroxidase (POD) (U min^{-1} g^{-1} DW)		Ascorbate-peroxidase (APX) (U min^{-1} g^{-1} DW)		MDA (μmol 100 g^{-1} DW)		H_2O_2 (μmol 100 g^{-1} DW)	
	Flesh	Peel	Flesh	Peel	Flesh	Peel	Flesh	Peel	Flesh	Peel
Bayoudhi	1.50 ± 0.10 d	2.53 ± 0.25 D*	0.37 ± 0.10 bc	0.44 ± 0.14 C	0.50 ± 0.01 c*	0.31 ± 0.01 A	2.12 ± 0.01 a**	0.98 ± 0.01 B	0.29 ± 0.11 bc	2.23 ± 0.11 B**
Sawoudi	10.64 ± 0.30 a	12.08 ± 1.13 A	0.70 ± 0.10 a	0.60 ± 0.10 B	0.35 ± 0.01 d*	0.15 ± 0.02 B	1.68 ± 0.01 c*	1.36 ± 0.01 A	0.84 ± 0.08 a	2.85 ± 0.10 A**
Mlouki	0.42 ± 0.07 e	1.32 ± 0.08 E*	0.33 ± 0.03 c	0.56 ± 0.03 BC*	1.33 ± 0.08 a**	0.16 ± 0.01 B	1.90 ± 0.03 b*	0.84 ± 0.02 B	0.43 ± 0.10 b	2.36 ± 0.15 B**
Assal	1.50 ± 0.10 d	2.35 ± 0.05 D*	0.42 ± 0.01 bc	0.43 ± 0.01 C	1.01 ± 0.01 b**	0.14 ± 0.01 B	1.69 ± 0.02 c*	0.95 ± 0.02 B	0.42 ± 0.09 b	2.04 ± 0.08 C**
Mozai	2.70 ± 0.28 c	3.68 ± 0.35 C	0.44 ± 0.05 b	0.78 ± 0.10 A*	0.13 ± 0.04 f	0.10 ± 0.07 B	1.45 ± 0.23 d	1.29 ± 0.19 A	0.18 ± 0.01 c	0.23 ± 0.03 E*
Zidi	3.44 ± 0.32 b	6.83 ± 0.30 B**	0.03 ± 0.05 d	0.03 ± 0.01 D	0.22 ± 0.07 e	0.16 ± 0.07 B	1.86 ± 0.10 bc	1.55 ± 0.31 A	0.25 ± 0.02 c	0.42 ± 0.02 D*

Values are the means of three different fig samples ($n = 3$) ± standard deviation. Letters (a > b > c > d > e > f) and (A > B > C > D > E) indicate significant differences ($p \leq 0.05$) among the flesh of the six cultivars and the peel of the six cultivars studied, respectively. Different subscripts * ($p \leq 0.05$), ** ($p \leq 0.01$), indicate significant differences between peel and flesh.

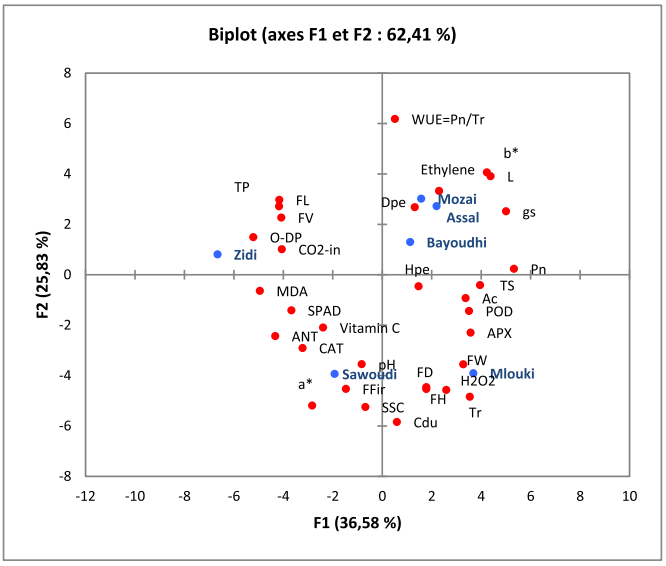

Fig. 9. Principal component analysis (biplot: scores and loadings diagrams) of the first two principal components (PC1 vs PC2) based on phytochemical, morphological, pomological, and physiological compounds analyzed (FH: fruit height, FD: fruit diameter, FW: fruit weight, APX: ascorbate peroxidase, CAT: catalase, Dpe: peduncle diameter, Ac: acidity, Hpe: peduncle height, POD: peroxidase, FW: fruit weight, TP: total phenolic content, FL: flavonoids, FV: flavonols, O-DP: *o*-diphenols, ANT: anthocyanins, MDA: malondialdehyde content, CO_2-in, FFir: fruit firmness, TS: total sugars, SPAD: chlorophyll content, Pn: net photosynthesis, gs: stomatal conductance, Tr: transpiration rate, L*, b*, and a*: CIELab color coordinates, WUE = Pn/Tr, Cdu: conductivity, SSC: °Bx, and H_2O_2: H_2O_2 content).

different fig cultivars with the aim of encouraging farmers in oasis to select and cultivate the latter for their important economic interests and the high nutritional value of the fig fruit.

F. carica species, characterized by a larger leaf surface area and thickness, which allows them to maximize chlorophyll production, have a good potential for gas exchange, leading to a strong adaptation to the arid Mediterranean climate [69]. Gas exchange capacity is an essential factor in assessing the ability of fig cultivars to adapt to their growing conditions [28]. In fact, climatic conditions (high temperatures, low rainfall) alter the leaf chlorophyll content and gas exchange parameters such as net photosynthetic assimilation, stomatal conductance, and transpiration rate in fig trees [70].

The present study revealed that the Assal, Bayoudhi, and Mlouki cultivars showed higher levels of chlorophyll and net photosynthetic assimilation (Pn) content, while Zidi had the lowest values (Table 1). In all cultivars studied, the concentration of chlorophyll in fig leaves affected their net photosynthetic assimilation (Pn) level. According to Mardinata et al. [71], chlorophyll is the key pigment for photosynthesis. Indeed, the role of palisade parenchyma containing chlorophyll pigment is very important for CO_2 conductance from ambient air to carboxylation sites in chloroplasts.

In all cultivars, the results also showed that Pn ranged between 7.52 μmol CO_2 m^{-2} s^{-1} and 10.44 μmol CO_2 m^{-2} s^{-1}. These results are in agreement with those indicated by Ammar et al. [72], which found that Pn measured during August ranged from 3.7 to 9.5 μmol CO_2 m^{-2} s^{-1}, in Zidi and Bither Abiadh cultivars grown in a semi-arid climate, in central Tunisia. However, Can et al. [73] reported that, during the period of the increase in carbohydrates demand (August), Pn values reached 29.45 μmol CO_2 m^{-2} s^{-1} in a rain-fed climate (Turkey). According to these previous studies, Pn can vary significantly depending on climatic conditions and cultivar effects.

In the present study, the concentration of carbon dioxide in the intercellular spaces of a leaf (Ci) varied significantly between cultivars and followed that of Pn values. The variation of Pn is related to stomatal behavior, which determines the penetration of CO_2 into the leaf. Maximum stomatal conductance (gs) was found in Assal, Mlouki, Bayoudhi, and Mozai cultivars (397.34, 375.63, 370.33, and 369.33 mmol H_2O m^{-2} s^{-1}, respectively). According to Can et al. [28], gs reached 270–370 mmol m^{-2} s^{-1} in some fig cultivars growing in Turkey. As a matter of fact, gs controls several parameters, such as photosynthetically active radiation, water status, and air temperature.

In all studied cultivars, the transpiration rate (Tr) did not exceed 2.67 mmol H_2O m^{-2} s^{-1}. However, Can et al. [28] indicated that Tr could reach more than 10 mmol H_2O m^{-2} s^{-1} in humid climates.

In the present study, the Zidi cultivar showed the lowest values of Pn, Tr, and gs. Campostrini et al. [74] and Gonzalez-Rodriguez and Peters [75] have previously reported a positive correlation between gas exchange parameters (Pn, Tr, and gs), relative chlorophyll content, and environmental factors. A similar behavior has also been reported in other deciduous fruit trees, such as apples [76] and peaches [70].

Instantaneous water use efficiency (WUEins) is considered one of the most important parameters used in genotype selection and evaluation for the best water use efficiency [77], especially in arid climates. The results indicated that Mozai and Assal had the highest WUEins (4.63 and 4.53 μmol CO_2 μmol^{-1} H_2O, respectively), which proved a good efficiency in water use. In addition, fig cultivation in the oasis is distinguished by low light availability, multi-layered systems, and high

planting density compared to widely spaced trees in commercial orchards. Therefore, these different factors maximize the yields of good-quality fruits by increasing the photosynthetic capacity. In fact, reducing light penetration into the oasis can avoid excess sunlight (which increases photo-oxidation) and could be a good mechanism to prevent photoinhibition in a warm climate [78]. This microclimate that characterizes the oasis tends to increase humidity and reduce transpiration by lowering leaf temperature.

Aside from the physiological parameters, the ripening period of the fig, the color of the peel, the shape of the fruit, and the sensory quality are considered among the most important characteristics of the fruit and plant for 'fresh fig selection programs' [79]. The fruit weight and diameter of the studied cultivars ranged from about 34 g (Assal) and 41 cm (Bayoudhi and Zidi) to 66 g and 53 cm (Mlouki). According to Gozlekci [80], the differences in the morphological characteristics can be attributed to growing season conditions, agricultural practices, tree age, genotype, and environmental interaction. In particular, Fateh and Ferchichi [81] reported that the Bayoudhi cultivar from southern Tunisia had higher fruit weight (63.8 g) and size (48.7 and 56.2 mm height and diameter, respectively) than the results found in the present study. Similarly, Trad et al. [82] and Fateh et Ferchichi [6] have found that Zidi fruits harvested in Tunisia's sub-humid climate (Djebba and Beja), with rainfall of 600–800 mm, were characterized by a higher fruit weight and diameter, reaching 101.79 g and 57.48 mm, respectively.

Regarding the peduncle, the results showed that its height ranged from 6.49 mm in the Mozai to 12.95 mm in the Bayoudhi fruit (Table 2). These results are similar to those obtained in a previous study [83], which reported that fruits with excessively long stalks are not desirable for the fresh fig industry.

Skin color and flesh firmness are strongly correlated with the quality of the product. According to Condit [52], the epidermal cells are colorless, and the color of figs is found in parenchyma cells lying just beneath the epidermis. Assessment of fruit color showed that Sawoudi and Zidi had similar dark colors, with L* ranging between 32 and 35 and a higher value of a* (Fig. 4) in comparison with the other samples. According to Solomon et al. [84], fig color appearance correlates with total polyphenols, flavonoids, anthocyanins, and antioxidant capacity. Moreover, their results have confirmed that 'dark figs' contained more phytochemicals than 'lighter fruits'. In general, consumers share a common trend, showing a preference for dark-colored figs for fresh consumption [85]. It is possible that this consumer behavior is linked to the ancestral combination of green with the unripeness or bitterness (toxicity) of the fruit.

Flaishman et al. [2] have reported that fig fruits have traditionally been classified as climacteric, albeit with moderate respiratory activity and a moderate ethylene production rate (1–10 μL kg^{-1} at 20 °C). Chessa et al. [86] have stated that the ripening process of the fig fruit is accompanied by an increase in the production of ethylene. In general, ethylene can affect the growth cycle of fruits even at low concentrations of 0.1 μL kg^{-1} or even less [57]. In the present study, the results showed that ethylene production varied significantly among cultivars and reached a value of 1.78 ppm in Mozai fruits.

The vitamin C content in the whole fruit ranged between 0.17 and 0.27 mg 100 g^{-1} FW, and no significant difference was recorded among the different cultivars studied. These values are rather low compared to those recorded by Pereira et al. [87] in the fig cultivar Bananas. The National Nutrient Database, USDA (2016), has stated that the vitamin C content of figs is about 2 mg 100 g^{-1} FW. Vitamin C biosynthesis can vary significantly according to stage of ripeness, environmental conditions, cultivation practices, and genotype [87].

Firmness is considered an important parameter and is generally used to determine fruit harvest as well as the degree of ripeness during postharvest [88]. The results for fruit firmness showed that this parameter depended significantly on the cultivar. The Mlouki and Zidi cultivars had the highest consistency values (2.78 and 2.34 kg cm^{-2}, respectively). Pereira et al. [89] have reported that fig firmness decreased during the ripening process (from 2.57 N mm^{-1} to 0.75 N mm^{-1}).

Caliskan and Polat [90] and Trad et al. [91] have stated that the high content of soluble solids, low acidity, and sufficient firmness of the flesh in the fig fruit are among the most important characteristics of good quality and high consumer acceptance. The present results showed that Sawoudi and Mlouki exhibited a higher soluble solid content (SSC) ranging between 18 and 22 °Bx, respectively. Similar results have been shown by Caliskan and Polat [90] in Turkish fig cultivars.

Mlouki and Assal cultivars showed elevated concentrations of sugars in both tissues (peel and flesh), compared to other studied cultivars. Trad et al. [91] have suggested that the high content of soluble solids and reducing sugars are the main factors that improve the flavor and quality taste in figs. Lama et al. [92] have explained this increase in soluble sugar levels at the time of ripening of the fig fruit by a net import of photosynthesis rather than by a synthesis of this compound from the reservoirs stored in the fruit.

The pH values of the fig cultivars studied ranged between 4.80 and 5.61 (in Bayoudhi and Mlouki, respectively). Likewise, many previous studies have indicated that the pH values of Tunisian and Italian fig fruits could not exceed 6 [81,93]. The ripening of fig fruits is accompanied by an increase in pH values and a decrease in acidity (TA). Bayoudhi and Mlouki fruits were the most acidic (4.90 and 4.20 g CAE 100 mL^{-1}, respectively). According to Pereira et al. [63], the TA of fig fruits grown in Spain ranged between 0.72 and 2.14 g CAE 100 mL^{-1}, whereas Aljane et al. [81] mentioned that total acidity in some Tunisian fig cultivars did not exceed 1.86 g CAE 100 mL^{-1}.

As for phenolic compounds, they are usually more abundant in the peel of the fig than in the flesh part. The cultivars studied in the present work showed higher levels of phenolic compounds in the peel (116.59–1350.79 mg HTE100 g^{-1}DW in Bayoudhi and Zidi, respectively), as well as in the flesh (121.95–697.64 mg HTE100 g^{-1}DW), than those reported in previous studies. In fact, as stated by Kamiloglu and Capanoglu [94], the total phenolic content in the peel of Bursa Siyahi (a Turkish cultivar) was about 930 mg of HTE 100 g^{-1} FW, while its content in the flesh was 351 mg of HTE 100 g^{-1} FW. In addition, the results of Solomon et al. [84] on dark and green fig fruits showed that the concentration of total phenolic compounds reached 463.0 and 100.6 mg of HTE 100 g^{-1} FW in the peel and flesh, respectively.

All the results above are in agreement with other studies, which reported that the polyphenol content in dark-skinned figs was significantly higher than that in light-skinned figs [79,95]. In general, the richness of phenolic compounds in the dark-colored peels is related to the accumulation of anthocyanins during the maturation process [96].

In the present work, flavonoid content significantly varied among cultivars, with the highest concentrations recorded in Zidi peel (228.32 mg CE 100 g^{-1} FW). Kamiloglu and Capanoglu [94] have found similar results in Bursa Siyahi fig (234 mg CE 100 g^{-1}DW). Conversely, Solomon et al. [84] and Aljane et al. [36] have reported lower concentrations in other cultivars (21.50 and 17.59 mg CE 100 g^{-1} FW, respectively).

In general, flavonoids are commonly classified as 'environmental compounds' because they are often produced in direct response to environmental conditions [97]. According to our findings, flavonoid compounds were most abundant in Zidi (dark peel) and Mozai (light peel). Vallejo et al. [97] have reported that figs with dark-colored peels were more concentrated in flavonoids, while Aljane et al. [36] have stated that yellowish-green fig groups were the richest in this compound.

Flavonols represent another class of polyphenols that are abundant in the peel parts of the fig fruits. In the present work, their concentrations reached 328.04 mg QE 100 g^{-1} DW in Zidi peel. Wojdyło et al. [98] have reported that concentrations of flavonol congeners ranged between 408 and 2178 mg QE 100 g^{-1} DW in Spanish fig cultivars.

Significant differences were found among the cultivars studied with regard to *o*-diphenol content. Indeed, Zidi's peel was the richest, with a concentration reaching 492.0 mg HTE 100 g^{-1} DW, while Bayoudhi's peel exhibited a very low concentration (<10 mg HTE 100 g^{-1} DW). This huge disparity in results suggested that the variation of these compounds

essentially depended on the cultivar.

Anthocyanins were present in the peel and flesh tissues of all cultivars studied, and the highest concentration was recorded in the peel of the Zidi fruit (3.62 mg C3GE 100 g^{-1} DW). Previous research studies have suggested that the anthocyanin content ranged between 0.43 and 108.9 mg C3GE 100 g^{-1} DW in the peel [99,100]. In addition, according to Ayuso et al. [101], dark fig peels are interesting sources of anthocyanins, and for this reason, fig peels, and fruit in general, should not be discarded. Indeed, fig peels are currently used in the food industry as a sustainable source of natural food coloring. However, in the case of the fig, the consumption of the peel depends on the local culture, its state of integrity, and the presence of annoying tactile sensations in the mouth.

Multivariate exploratory analysis is an effective technique used to outline a similarity model among fig variables and samples, as mentioned above [51,98,102]. In the present study, phytochemical variables were found to be useful in distinguishing Zidi cultivars that represent excellent sources of antioxidant substances. Khadhraoui et al. [102], and Veberic et al. [103] have shown that phytochemical variables were able to distinguish fig cultivars, as they found a strong correlation among the amounts of total phenols, phenolic acids, flavonoids, and antioxidant capacity. In this study, the results of the PCA allowed to group the cultivars into four clusters with regard to physiological, morphological, and phytochemical parameters.

The concentration of phenolic compounds in fig fruit was positively correlated with its antioxidant potential and its ability to scavenge free radicals in order to prevent the onset of oxidative stress [104]. Protective oxidative systems in fruit also include antioxidant enzymes such as CAT, POD, and APX. The results proved that Sawoudi fruit exhibited the highest antioxidant enzymatic activities assessed by catalase (12.08 and 10.64 U min^{-1} g^{-1} DW in the peel and flesh, respectively), followed by Zidi. Instead, the fruits of other cultivars, especially those with a light-colored peel, showed lower catalase activity.

The higher antioxidant activity of dark-peeled fig cultivars could be explained by their richness in polyphenols, anthocyanins, and flavonoids. According to our findings, the activities of POD and APX were significantly lower than those of CAT. In addition, antioxidant enzymatic activities in the peel part were higher than those measured in the flesh tissue, mainly for CAT. Similar results have also been found in peach fruits [105]. CAT and POD are among the most important fruit protection systems against the harmful effects of reactive oxygen species (ROS) [57].

These enzymes also play an important role in the elimination of markers of oxidative stress (MDA and H_2O_2). According to PCA's analysis, MDA was loaded on PC1 with a relevant weight, while H_2O_2 was loaded on PC2, and for this reason both can be considered effective parameters to separate the samples set in subclusters. The present study indicated that Sawoudi had the highest level of H_2O_2 in both tissues, while the Bayoudhi fruit showed the highest level of lipid peroxidation (MDA content) (2.12 μmol 100 g^{-1} DW) in the flesh. The MDA content is an indicator of rapid senescence, loss of membrane integrity, fruit damage, and membrane lipid peroxidation [106,107]. Indeed, the degree of lateral cracking of the peel can be the main cause of damage to the fruits and oxidative stress, as observed in Sawoudi, Bayoudhi, and Zidi. Besides, the work of Kong et al. [108] has revealed that the presence of lateral cracking in the peel of fig fruit was mostly associated with the loss of sensory and nutritional properties. In addition, Condit [52] has suggested that the prominent ribs (longitudinal ridges running from the base to the apex) that characterize fig fruit make the peel more susceptible to injury during handling.

5. Conclusion

The findings of the study revealed that Mlouki's fruit, with its green and purple coloration, exhibited the highest weight and sugar contents, rendering it highly desirable for both retailers and consumers. Besides, dark-peeled fruits, such as Sawoudi and Zidi, demonstrated a remarkable richness in phytochemicals, including total phenolic content, flavonoids, and anthocyanins, as well as notable enzymatic activity, particularly in catalases and peroxidases. This enzymatic activity contributes to their resistance against oxidative and degradative phenomena.

Considering the results of the present study, the valorization of fig peel as a by-product in the food supplements, flavors, and colorants sectors due to its richness in sugars and phenolic compounds and its higher antioxidant enzyme activities could represent a valuable avenue to be explored.

Finally, the results gathered from this study highlight Sawoudi, Zidi, and Mlouki cultivars as having the best quality of fruit and could therefore be excellent choices for future fig cultivation efforts. The morphological and chemical characterization of these Tunisian fig cultivars can serve as a foundation for prioritizing funding programs aimed at optimizing the use of fresh and dried figs.

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Institutional Review Board statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board.

Informed consent statement

Not applicable.

CRediT authorship contribution statement

Maatallah S: Writing – original draft, Methodology, Data curation, Conceptualization. **Guizani M:** Writing – original draft, Visualization, Investigation, Software. **Lahbib K:** Formal analysis, Validation, Software. **Montevecchi G:** Writing – review & editing, funding acquisition, Software. **Santunione G:** Writing – review. **Hessini K:** Conceptualization, review & editing& editing. **Dabbou S:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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