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Sentinel-2 Satellite Imagery for Agronomic and Quality Variability Assessment of Pistachio (*Pistacia vera* L.)

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Abstract: The objective of this work is to evaluate the agronomic, phenological, nutritional quality and organoleptic characteristics of pistachios (*Pistacia vera* L.) based on the NDVI (Normalized Difference Vegetation Index) calculated in the phenological stage of nut filling from Sentinel satellite imagery. Based on this index, three pistachio tree orchards were studied and classified into two levels of vigour: high and low. The results obtained have discriminated the production per tree, which is strongly related to yield. Regarding the nutritional quality parameters, significant differences were not observed between vigour levels, although the most vigorous trees have shown nuts with a higher percentage of fibre and protein. In terms of phenology, there have not been differences between trees of different vigour, only a slight advance of some phenological stages has been observed in several high-vigour trees. Triangular tests have been made successfully to discriminate the origin of the dry nut and the vigour of the trees. In conclusion, for a given nut quality within a given orchard, the NDVI is a good index to classify different areas according to productive capacity and can be useful to apply variable management, irrigation and fertilization according to vigour.

Keywords: Sentinel 2; NDVI; pistachio; vigour; nutritional quality

1. Introduction

In recent years, pistachio (*Pistacia vera* L.) has become one of the most interesting species in the nut sector. The viability of pistachio crops and their agronomic behaviour in a given place is conditioned by the edaphoclimatic conditions of the place [1]. In such a way, the temperature variations in different geographical locations can influence the biochemical processes during the nut development and can influence the nutritional and organoleptic characteristics of the pistachio nuts [2]. Besides, the nutritional quality of the nut is strongly affected by the composition of fatty acids present in the seed [3]. In this sense, some studies affirm that the stability and quality of the nut are greater when the concentration of oleic acid is greater, proposing the amount of iron as a useful parameter for the discrimination of pistachio varieties [4].

Another factor that determines the pistachio nuts quality is the time of harvest [2]. In this sense, it was observed that the sooner the pistachio harvest the higher the contents of potassium, calcium, magnesium, nitrogen and protein but the lower the yield [5]. Other researchers have linked the quality and production of pistachio nuts with the water regime and the rootstock used [6,7].

Moreover, the development of new technologies based on remote sensing allows information about the crops and the land surface to be obtained quickly and accurately [8]. High-resolution images can provide an estimate of the spatial variability of the vigour of many herbaceous and woody crops [9].

The images to calculate Vegetation Indexes can be obtained from various sources, such as UAV, aircraft, satellites, proximal sensing, etc. Moreover, spatial information can be obtained from several satellites, which can be classified into two main groups depending on the cost of the images: free-to-use and paid-to-use satellites [10]. Regarding free-to-use satellites, the Sentinel-2 satellite constellation provides free imagery split in several bands and it is possible to access the satellite data free of charge [11]. Besides, the periodicity of Sentinel satellite images allows to build a time series that includes the entire vegetative crop cycle.

In several fields, remote sensing has been a valuable tool, such as in the evaluation of floods or natural water flows, the determination of the areas burned by fires or the advance of desertification [12–15]. Similarly, in agriculture, the vegetation indices (NDVI, SAVI, . . .) obtained from satellite images, with a spatial resolution ranging from 10 m (Sentinel-2) to 30 m (Landsat) or obtained from UAV images whose resolution is at centimetre level (depending on the characteristics of the multispectral camera and the flight height), have been used in the decision-making process in many crops such as wheat, rapeseed, cotton, corn and woody species [16–20]. Specifically, Sentinel satellites can be very useful and they have been used to predict almond yields [21], to discriminate the quality of the walnut based on the vigour of the trees [22], to assess the bloom dynamics of almond orchards [23] and to classify vineyards according to their vigour [24,25].

At present, in the absence of an operational technological sensor that determines quality in situ, and based on past and present experience, the NDVI [26] calculated from detailed multispectral images is the best and most economical alternative for classifying differentiated management units in several woody crops such as vineyard [27] or walnut [22]. Similarly, using this vegetation index, relationships can be established to estimate the water needs in several crops such as almond or pistachio [28].

The objective of this work is to evaluate the agronomic, phenological, nutritional quality and organoleptic characteristics (triangular testing) of pistachio (*Pistacia vera* L.) based on the vigour (high and low) estimated by the vegetation index NDVI (Normalized Difference Vegetation Index) obtained from a Sentinel-2 satellite image, which is free and open access, during the phenological stage of nut filling in three pistachio orchards in 2018.

2. Materials and Methods

The experimental trials are located in three pistachio orchards in Toro (Zamora), Perales (Palencia) and Pozal de Gallinas (Valladolid) in the region of Castilla y León (Spain). The characteristics of the plots are shown in Table 1. The ground-truth data were taken during 2018. All orchards are irrigated periodically during the vegetative cycle in order to avoid the hydric stress of the trees. Each year, a regulatory pruning to control the vegetation has been made in each orchard, leaving the whole amount of flower buds.

Table 1. Characteristics of the orchards.

	Toro	Perales	Pozal de Gallinas
Coordinates	X: 301,985; Y: 4,598,920	X: 368,751; Y: 4,670,402	X: 347,997; Y: 4,577,704
Altitude (m)	740	770	737
Area (ha)	4.2	18.7	12.3
Planting pattern (m)	7 × 5	7 × 6	7 × 6
Planting date	2004	2002	2010
Male cultivar	Peter	Peter	Peter
Cultivar/rootstock	Kerman/Atlántica	Kerman/Cornicabra	Kerman/UCB

The NDVI is an index that allows quantifying the amount of vegetation in an area, as well as its health. It relates the reflected radiation in the red and Near InfraRed (NIR) bands of the electromagnetic spectrum. Its mathematical Equation (1) is the following:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad (1)$$

To calculate the NDVI, the Equation (2) was adapted to the bands provided by Sentinel 2 satellites: B8 (NIR) with a wavelength of 0.77 to 0.90 micrometres and B4 (RED) with a wavelength of 0.65 to 0.68 micrometres, both with a spatial resolution or pixel size of 10 m.

$$NDVI = (B8 - B4) / (B8 + B4) \quad (2)$$

To perform the classification of the pistachio orchards, two levels of vigour were established based on the NDVI mean values of its pixels calculated from the multispectral images. Free 2018 images were downloaded from the ESA's (European Space Agency) Copernicus project website [29]. These images, obtained from the Sentinel-2A and -2B satellites, were corrected to a level-2A product with ESA's sen2cor algorithm and were filtered manually in order to obtain cloud-free products. As a result, 24 images were assessed for each orchard, between dates 17/01/2020 and 03/11/2020, as it is shown in Figure 1.

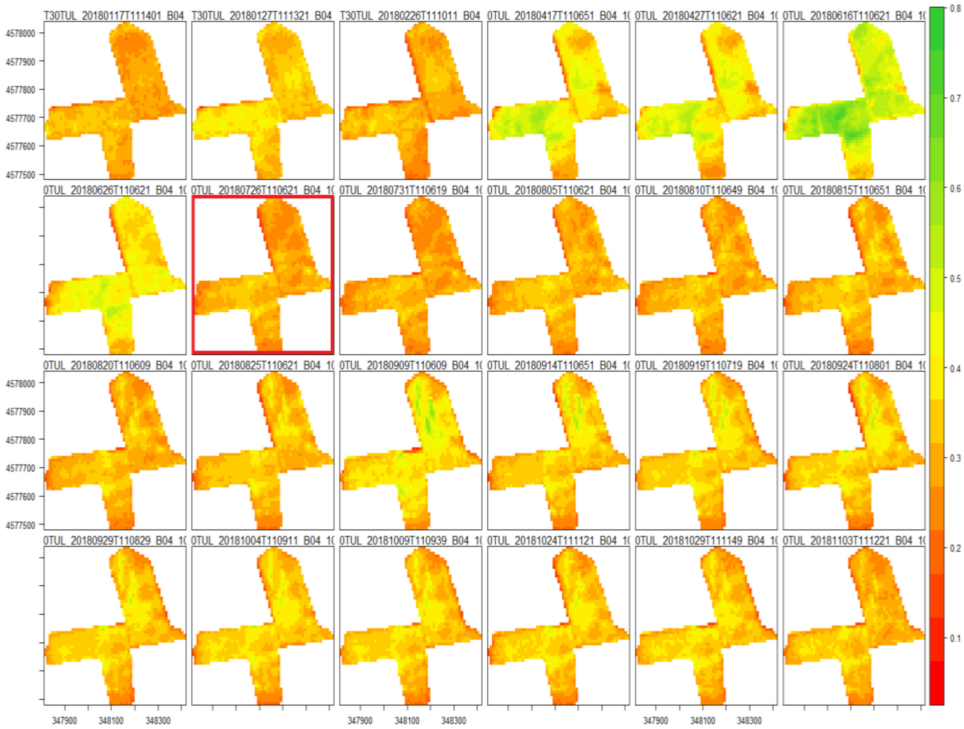
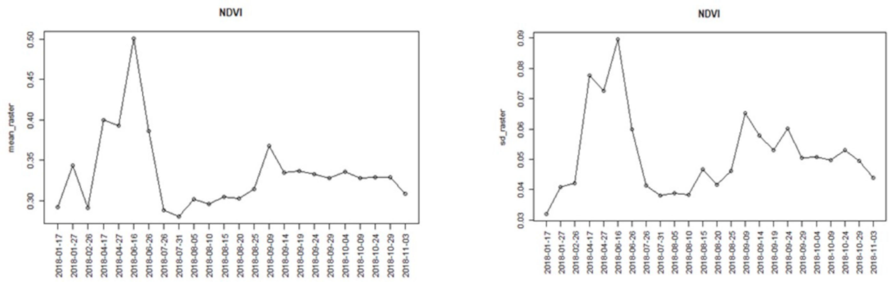


Figure 1. Normalized Difference Vegetation Index (NDVI) 2018 images of Pozal de Gallinas orchard. In red, the image chose to carry out the zoning of the pistachio orchards (26 July 2018).

The mean and the standard deviation of the NDVI of the pistachio orchards has been analysed to choose the date from which the zoning was carried out in two vigour classes (Figure 2). According to the evolution of the mean and the standard deviation of the NDVI, a minimum begins at the end of July and continues in the beginning of August (Figure 2b). According to these data, the chosen date was on July 26 because it is when the vegetation of the pistachio trees is more homogeneous. The maximum of the mean NDVI for the orchards is at the phenological state F1 (yellow colouring of the bottom of the nut mesocarp) although a maximum standard deviation has been observed suggesting a large variability of the vegetation at this moment.



(**a**) (**b**)

Figure 2. Mean (**a**) and standard deviation (**b**) of the NDVI in the pistachio orchard of Pozal de Gallinas.

Image and time series analyses were carried out using customized codes written in R statistical program (version 3.6X, R Foundation for Statistical Computing (R Core Team 2019), https://www.R-project.org/, Vienna, Austria) and QGIS software (Open Source Geospatial Foundation) version 2.18.13 was used. Finally, images were processed using an unsupervised classification clustering method (k-means), organizing each pistachio orchard into two levels of vigour, high and low, according to their NDVI values (Figure 3).

(**a**) (**b**) (**c**)

Figure 3. NDVI classification. (**a**) Toro, (**b**) Perales and (**c**) Pozal de Gallinas orchards. Two vigour levels: high (dark green) and low (light green).

Three trees per vigour were monitored in each experimental trial, establishing an experimental design of three replications per vigour, and three trees as an experimental unit. At harvest time, several variables were measured: bunch weight, number of open, closed and empty nuts per bunch, tree yield, fruit and seed weight, as well as the percentage of open, closed and empty nuts.

The main phenological stages [30] per vigour in each plot were determined (Figure 4):

- D: appearance of clusters between the bracts;
- E: cluster opening;
- F0: reddish ovaries;
- F1: yellow colouring of the bottom of the nut mesocarp;
- F2: yellow mesocarp;
- M: detachment of the nut epicarp.

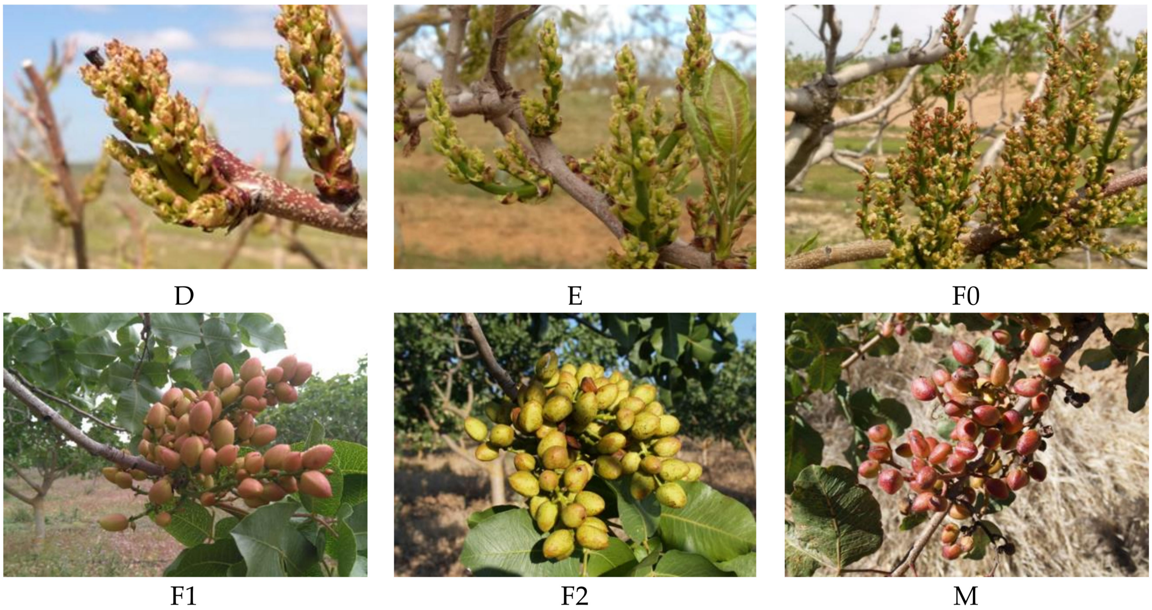


Figure 4. Main phenological stages corresponding to the appearance of clusters between the bracts (**D**), cluster opening (**E**), reddish ovaries (**F0**), yellow colouring of the bottom of the nut mesocarp (**F1**), yellow mesocarp (**F2**) and detachment of the nut epicarp (**M**).

Several nutritional parameters of a sample of pistachio nuts collected from the studied trees of each vigour were evaluated in the laboratory: grease percentages (gravimetry on soxhlet extraction), carbohydrates (gravimetrically), protein and nitrogen (Dumas combustion method), fibre (enzymatic-gravimetric method), phosphorus (UV-VIS spectrophotometry, after acid digestion by dry route), magnesium and calcium (atomic absorption spectrophotometry, after acid digestion by dry route) and the amount (mg/kg) of iron, zinc and sodium (atomic emission spectrophotometry, after acid digestion by dry route).

Finally, organoleptic tests were carried out in a tasting room equipped with ten individual boxes, according to ISO 8589: 2007 (Figure 5). In compliance with ISO 4120: 2004, a triangular test was carried out to determine if there was a perceptible sensory difference or similarity between samples of two products. The method was a forced-choice procedure and it can be used whether there are differences in several sensory attributes or only in one of them. This test was carried out among the nuts belonging to different vigour trees to find out if the consumer was able to detect differences between the experimental treatments corresponding to high and low vigour.

(**a**) (**b**) (**c**)

Figure 5. Standard tasting room where the triangular test (**a**) and process of the pistachio nut sample (**b**,**c**) was carried out.

The statistical analysis was performed using analysis of variance (ANOVA) in Statgraphics Centurion 17.2 software.

3. Results

3.1. Agronomic Study

The parameters related to the cluster have not shown statistical significance differences. The higher values were observed for high vigour, in all the components of the cluster (Figure 6).

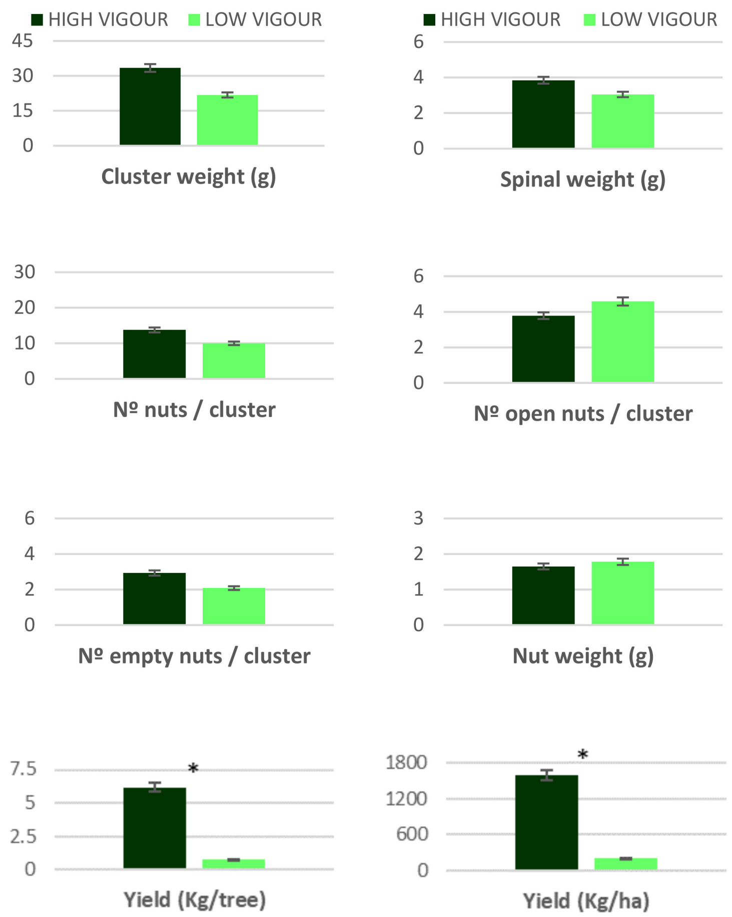
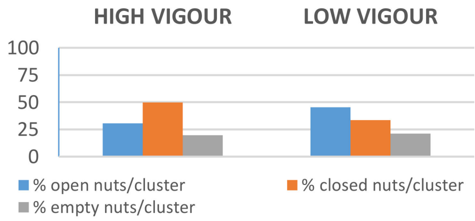
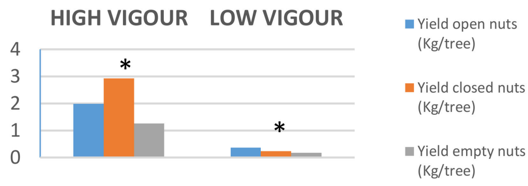


Figure 6. Averages corresponding to cluster, nut and yield parameters for the experimental treatments: High Vigour and Low Vigour. Statistical significance level: *, $p < 0.05$.

Likewise, the number of nuts per cluster has been higher in the high vigour, showing 13.8 nuts per cluster compared to the 10 nuts per cluster in the low vigour, although without finding statistically significant differences. It has been observed that the low vigour has presented a greater number of open nuts and a lower number of closed and empty nuts per cluster, showing percentages of 45.5%, 33.4% and 21.1%, respectively, compared to those shown in the high vigour (30.5%, 49.9% and 19.6%, respectively) (Figure 7). The number of open nuts is an important aspect regarding the quality of the nut [1,30].



(**a**)



(**b**)

Figure 7. Averages corresponding to (**a**) open, closed and empty nut percentage and (**b**) yield corresponding to open, closed and empty nuts for the experimental treatments: High Vigour and Low Vigour. Statistical significance level: *, $p < 0.05$.

It has been observed that the higher the nut or seed size the less the vigour of the individual trees, although the production of these trees has shown statistically significant differences in favour of the high vigour (Figure 6). It has been observed that the higher the individual vigour of the trees the lower the percentage of open nuts they present, although the yield per hectare is almost 88% higher, which would offset the lower percentage in the number of open nuts in high vigour. Similarly, the production of closed nuts per tree has shown statistical significance differences in favour of high vigour, observing a value of 2.93 kg/tree compared to 0.24 kg/tree of low vigour (Figure 7).

3.2. Phenological Study

The dates of the several phenological stages evaluated have not presented significant differences or lags. Only a slight delay in the F2 phenological stage (yellow mesocarp) was observed in one of the experimental trials (Table 2). The harvest maturity date was determined by evaluating the difficulty to detach the epicarp of the nut, and this is the day of nut collection. In this sense, certain differences have been observed between experimental trials, probably due to the differences in heat hours in the Toro orchard compared to the other orchards, showing a 9-day advance in the harvest maturity date.

Table 2. Date of the main phenological stages [30] depending on the vigour and the location.

Phenological Stage	High Vigour			Low Vigour		
	Toro	Perales	Pozal	Toro	Perales	Pozal
D	May 1th	May 4th	May 1th	May 1th	May 4th	May 1th
E	May 6th	May 9th	May 6th	May 6th	May 9th	May 6th
F0	May 11th	May 16th	May 11th	May 13th	May 16th	May 13th
F1	May 27th	May 29th	May 25th	May 27th	May 29th	May 25th
F2	Jun 25th	Jul 11th	Jun 19th	Jun 22th	Jul 23th	Jun 20th
M	Oct 15th	Oct 24th	Oct 24th	Oct 15th	Oct 24th	Oct 24th

3.3. Nutritional Quality Study

The nutritional and quality parameters of the pistachio nuts have not shown statistically significant differences between different vigour (Figure 8). On one hand, the higher the vigour, the higher the percentages of fibre, protein and nitrogen, and the higher the amount of sodium. On the other hand, the low vigour has shown the highest percentage of humidity, although without being significant. Concerning the rest of the nutritional and quality parameters, no statistically significant differences have been found (Figure 8).

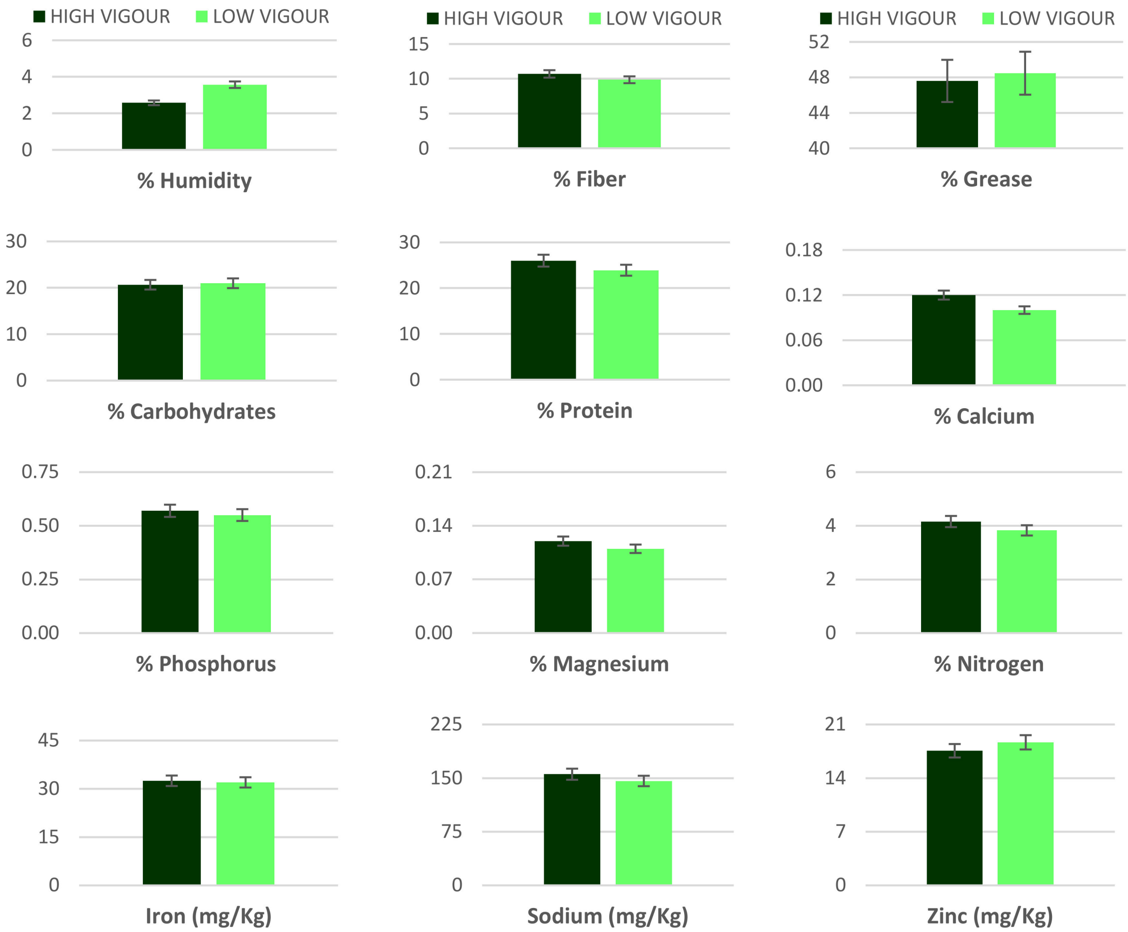


Figure 8. Averages corresponding to the nutritional and quality parameters of the pistachio nut for each experimental treatment: High Vigour and Low Vigour. Statistical significance level: *, $p < 0.05$.

3.4. Triangular Tasting

Regarding the sensory analysis, triangular tests have shown that consumer was able to detect pistachio nuts from different vigour trees at a 95% probability level in a total of 68 trials, and pistachio nuts from different provenances or experimental trials at a 99% probability level in a total of 66 trials (Table 3).

Table 3. Triangular test results for the vigour factor and the provenance factor. Statistical significance level (SL): ns, not significant; *, $p < 0.05$; **, $p < 0.01$.

Factor	Number of Trials	Hits	SL
Vigour (high–low)	68	34	*
Provenance	66	40	**

4. Discussion

On the one hand, the NDVI calculated from the Sentinel-2 satellite image taken on July 26 has delimited two areas of vigour in the phenological stage of nut filling, showing that the vigour of trees is related to the yield. This aspect may allow using the zoning calculated from the vegetation indices (NDVI, SAVI, etc.) to forecast the pistachio harvest and the more complete the time series of raster images (number of images, date of the first image, etc.), the better the harvest forecast will be.

On the other hand, this classification did not discriminate the quality of the nuts since the percentage of open pistachio nuts and the nutritional and quality parameters did not show significant differences between experimental treatments. However, the higher the vigour of the tree, the higher the percentage of proteins. Therefore, the quality of the pistachio nut is not related to the amount of vegetation on the trees. Besides, research suggests that the nutritional quality of pistachio nuts is affected by the concentration of fatty acids and the amount of iron present in the seed [3,4], although a relationship between these parameters and the vigour of pistachio trees has not been observed.

These results are consistent with those observed in other crops classified using Sentinel-2 satellite NDVI, such as vineyard [24,27,31] or walnuts [22]. In addition, some authors have observed differences in pistachio nut yields due to different NPK fertilization [32], water regime [33,34], the use of male trees [35,36] or different rootstocks [37]. The small differences observed in some parameters may be due to temperature variations between the different geographic locations that influence the biochemical processes during the development of the fruit and the nutritional characteristics of the pistachio [2].

Regarding the dates of the phenological stages, different vigour trees have not shown differences between them, showing that even with such differences in the yields the dates of the phenological stages have been maintained stable. However, some non-significant differences were observed between trees from different geographic locations, probably due to the different accumulation of hot hours. In this sense, the amount of vegetation of the trees does not imply that the vegetative cycle varies. The phenological development of the pistachio orchard being uniform over time. Other authors found differences in some phenological stages due to other factors, such as the variety [36], water regime [38], geographic location [39] or leaf nitrogen foliar applications [40].

Finally, the triangular test showed that the consumer was able to discriminate the origin of the pistachios (different orchards) and, therefore, the vigour of the trees. Pistachio tasters have detected organoleptic differences between nuts from trees of different vigour and trees from different pistachio orchards. It would have been interesting to carry out a descriptive tasting of the pistachio nut and observe what attributes are different depending on the vigour or origin of the pistachio nut.

In this sense, other investigations have managed to discriminate pistachios under different water regimes [34,37].

5. Conclusions

The results obtained show that the vigour of the trees or the amount of vegetation is related to the production per pistachio tree. For this, these results suggest that for a given nut quality, the NDVI is a good index to classify different areas according to productive capacity. The proposed methodology may be interesting to apply to variable management, irrigation and fertilization according to the vigour of the pistachio trees.

It would also be interesting to know the sensory differences of the pistachio nut through descriptive tastings or ordering tastings since the consumer can distinguish nuts from trees of different vigour or origin.

In further studies, it might be interesting to explore the possibility of measuring the leaf area and geopositioning the trees to correlate ground-truth data and Sentinel satellite information, using techniques that have been carried out in other crops [8]. Besides, it would be interesting to combine ground measured data with Sentinel satellite information to forecast other variables such as yields.

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