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ORIGINAL RESEARCH ARTICLE

Modeling and optimizing the changes in physical properties of olives in response to attacks of olive fruit fly (*Bactrocera oleae* (Gmelin))

Tuba Öncül Abacigil[1,2]

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Abstract

Response Surface Methodology (RSM) was used to establish a predictive model for the effects of olive fruit fly attacks on the physical properties of olives at different orchard altitudes and harvesting periods. The physical properties investigated included the maturity index, fruit removal force, and change ratios of weight, density, hardness, and crushing force of olives. This study was conducted using the Ayvalık olive cultivar at three orchards in the Edremit district, Balıkesir (Turkey), at altitudes of 84, 126, and 168 m. The olives were harvested at 50-day intervals during the months of September to December for three years repeatedly (2016–2018). A Box–Behnken experiment design (BBD)-based optimization model was used to minimize the responses and obtain the optimum factors. Using the desirability function method, the ratio of damaged olives was 0.10, the harvesting time was 72 days after the first harvest, and an altitude of 168 m was found to be the optimal condition. In this condition, the dependent variables were predicted as follows: the maturity index, 3.56; fruit removal force, 2.73 N; the change ratio of weight, -0.0767; density, -0.1989; hardness, 0.0504; and crushing force, 0.0205. The results indicated that the losses in the physical properties were severely affected by the damage caused by the attacks of the olive fruit fly. These losses were also caused by orchard altitude and harvesting dates. The results demonstrated that the change ratios of the physical properties of olives can be used as ripening criteria.

Keywords Attacks of olive fruit fly *(Bactrocera oleae)* · Maturity index · Physical properties · Optimization · Response surface methodology

Abbreviations

Olive fruit fly	(*Bactrocera oleae or B. oleae*)
MI	Maturity index
FRF	Fruit removal force
CRW	The change ratio of weight
CRD	Density
CRH	Hardness
CRCF	Crushing force
RDO	The ratio of damaged olive
HAP	Harvesting period
OAL	Orchard altitude
RSM	Response surface method

✉ Tuba Öncül Abacigil
abacigil@balikesir.edu.tr

[1] Edremit Olive Cultivation Institute, Balıkesir University, 10300 Edremit, Balıkesir, Turkey

[2] Department of Plant and Animal Production, Olive Cultivation and Processing Technology Program, Edremit Vocational School of Higher Education, Balıkesir University, 10300 Edremit, Balıkesir, Turkey

Introduction

An olive fruit fly *(Bactrocera oleae* (Gmelin) (Diptera: Tephritidae)) which feeds only on olive fruits, is the most important olive pest in Mediterranean countries, such as Turkey. The olive fruit fly damages olive fruits during its reproductive process. A female adult fruit fly lays eggs in the olive fruit, leaving behind a distinguishable mark on the surface of the olive, called ovipositional sting. As the larvae develop inside the olive, they feed on the pulp of the fruit, causing it to drop early or rot. The larvae may pupate within the fruit or exit the fruit to pupate in the soil. The physical damage caused by the olive fly translates into economic damage in several ways (Baerenklau et al. 2014).

Olive fruit flies result in a decrease in oil rate, an increase in acid content, and a product loss between 30 and 100% in some years (Shahzad et al. 2017). It lives in a pupal state during winter in dry grass and clods. Adults may lay between 200 and 250 eggs on fruits the following June. Hatched larvae eat the fruit pulp, leading to bruising and defoliation, decreasing the oil rate and increasing the acid content (Daane and Johnson 2010; Abrol 2015). Cultural control of the fly involves tilling the soil in the months of February and March and removal of fallen wormy olives during the months of August and September (Mete and Pekcan 2017). The use of chemical pesticides such as Fenthion, Dimethoate, Trichlorfon, Ethanoate-methyl, Triazophos, Formation and Malathion are also recommended for ground control. Extensive pesticide administration in accordance with the system and partial administration via toxic fodder should also be carried out. Aerial sprays were based on malathion ULV (Ultra Low Volume) at 1–1.5 L/ha (Boulahia-Kheder 2021). Synthetic pesticides have been used in addition to cultural measures in the event of an olive fruit fly in Turkey. Although these pesticides improve olive fruit health and production, their continued application can lead to pest resistance and human and environmental health impairments (Gaforio et al. 2019). *B. oleae* may produce 4–5 generations per year (Hamdan 2016). Unfortunately, this number has increased in recent years owing to global warming effects, and known chemical control methods are no longer sufficient to control pests and are very costly in Turkey. Due to its increasing population and damage to the fruit, the olive fly is considered to be the most important economic pest in the olive agroecosystem in Turkey today. New scientific studies aimed at reducing the economic and quality losses caused by *B. oleae* are very important.

Important factors in *B. oleae* preference for oviposition include physical properties such as olive fruit size, color, and hardness of the olive fruit epicarp and mesocarp (Gonçalves et al. 2012). The larvae of the pest cause the fruits to decay and fall, which reduces the olive oil amount in those collected without spillage, and partly causes an increase in the acidity of the oil. Olive damage (sting) by *B. oleae* reduces the quality of olive oil when it enters a malaxer with healthy olives for olive oil production (Gómez-Caravaca et al. 2008; Tamendjari et al. 2009; Mraicha et al. 2010).

Fruit size, weight, volume, water content, fruit epicarp parameters (break force, elasticity, tissue firmness, and break energy), and fruit color are among the studied physical factors (Malheiro 2015; Huwei et al. 2021). Studies have been conducted on the optimal harvesting time (Lazzez et al. 2011; Sousa et al. 2015; Gamlı and Eker 2017) and changes in olive characteristics during ripening (Beltrán et al. 2004; Yorulmaz et al. 2013). These studies are usually related to the chemical changes in olives and oil. In some studies, the physical and chemical properties have been emphasized in terms of the damage caused to the fruit by olive flies during the ripening period (Tamendjari et al. 2009; Mraicha et al. 2010; Gonçalves et al. 2012; Malheiro et al. 2015; Rojnić et al. 2015). However, the quality of olives and olive oil is related not only to the changes in chemical properties of olive fruit during ripening, but also to physical properties such as maturity index, removal force, size, weight, volume and density changes, hardness, and breaking strength. The timing of the olive fruit harvest is also directly related to these features. Rizzo et al. (2012) studied the relationship between olive fly infestation and fruit color, shape change (elongation), hardness, and volume in olive varieties. In another study, the effect of ripening on the mechanical properties of olives was investigated (Georget et al. 2001). Çetin et al. (2011) studied the influence of *Eriophid* mites (*Aculusolearius* Castagnoli and *Aceriaoleae* (Nalepa) (Acarina: Eriophyidae)) on physical and chemical properties of Ayvalık olive cultivar. Researchers have studied the effect of olive fly attack on the phenolic profile (content), chemical parameters, and quality of olive oil (Gómez-Caravaca et al. 2008; Topuz and Durmusoglu 2008; Koprivnjak et al. 2010). Studies on olive orchard altitudes have shown that there are differences in the levels of damage caused by olive flies (Yasin et al. 2014) (Noori and Shirazi 2012). Accordingly, the olive fly population and the damage caused by the olive fly to the fruit are significantly related to altitudes between 0 and 700 m altitude (Kounatidis et al. 2008). Regional studies have focused on the resistance of some Sicilian (Italian) olive varieties to *B. oleae* attack (Rizzo and Caleca 2006) and the damage caused by olive fruit flies in the Tlemcen region of Algeria (Gaouar and Debouzie 1991).

Studies on the effects of olive flies on the physical properties of olive fruit are very limited (Gümüşoğlu et al. 2006; El-Soaly 2008; Kılıçkan and Güner 2008; Öztürk et al. 2009; Saracoglu et al. 2011; Zare et al. 2012; Mirzabe et al. 2013). In particular, there are only a limited number of studies on optimizing the change ratios of the physical properties of olives caused by olive fruit fly attacks. Olive cv. Ayvalık is a major Turkish variety used for oil extraction and is also used as a source of table olives. Edremit, in the district of Balıkesir province in western Turkey, is known for its origin (Toker et al. 2016). In the literature, studies on the determination of certain physical properties of olive fruit, the effect of olive fly damage on fruit maturation (Vatansever Sakin 2019, 2022), and the sensitivity of olive fly to important edible and oily olive varieties (Gümuşay et al. 1989) were carried out in the Ayvalık olive cultivar in the Edremit (Balıkesir, Turkey) district.

A similar study was also conducted by Vatansever Sakin (2022). However, the maturity index was not considered in Vatansever Sakin (2022). In this study, both the maturity index was taken into account and the Box-Behnken statistical model, which is a different model in response surface methodology (RSM), were used. In addition, the effect of the three factors on the six responses was examined using the Box-Behnken experiment design (BBD). In the literature, 15 experimental trials with three factors were conducted, and satisfactory results were obtained from these studies (Szydłowska-Czerniak et al. 2010, 2011). However, there are no studies on 15 experimental trials in which six responses

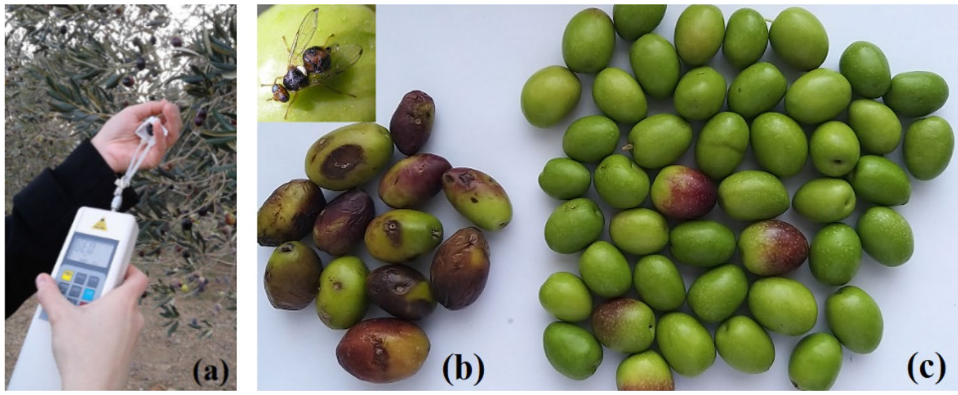

Fig. 1 **a**) Measurement of olive fruit removal force. **b**) Damaged olives **c**) Undamaged olives (October 20th)

were analyzed with three factors, providing meaningful results for each.

In this study, we examined the effect of olive fruit fly attacks on the physical properties and maturity index of Ayvalık olive cultivars and determined the optimum conditions (harvesting time, orchard altitude, and ratio of damaged olives) using response surface methodology. Another purpose of this study was to determine the physical damage caused by olive flies to the fruit. In addition, for this olive cultivar in the Edremit district, the effect of fruit damage due to olive fly damage on fruit ripening, depending on the harvest period, was investigated.

Material and methods

The study was carried out during 2016–2018 in different olive orchards at altitudes of 84, 126, and 168 m. Approximately 1 kg of olives were randomly collected on September 1st, October 21st and December 10th, with periods of 0–50–100 days after the first harvest. One hundred of these olives were randomly used for the MI calculation. Sixty olives, which were also randomly selected, were grouped as damaged (D) and undamaged (U) according to the amount of damage caused by the olive fly during the ripening period. Minimum, medium, and maximum *B. oleae* infestation rates, that is, ratios of damaged olives of 0.10, 0.25 and 0.40 were used to comply with the experimental design in the analysis. For this grouping, a stereomicroscope was used to control for the presence of spawning holes (i.e., olive damage) in all olive samples. Sampling took place over three years, starting on September 1st and continuing until December 10th each year. Physical tests of the olives in each group were performed during a working period of approximately 100 days after the first harvest. First, the fruit removal forces of olives from the branch were measured. Second, for the olive fruits, the weight, size (width, height, and thickness), density, MI, hardness, and maximum crushing forces (flesh and seed together) were determined. Subsequently, the change ratio values of weight, density, hardness (firmness), and crushing force were calculated for damaged and undamaged olives.

Olive fruit removal force

When olive fruits were picked from the branches, a Macrona (HP-200) digital force gauge with a capacity of 200 N, as shown in Fig. 1a, was used. As mentioned, the collected fruits were classified into two groups according to undamaged (U) and damaged (D) olive flies, as shown in Fig. 1b, c after they were brought to the laboratory.

Hardness measurement tests

Using the hardness tester shown in Fig. 2a and V-block for fixing the olive in Fig. 2b, at least five fruits from each damaged (D) and undamaged (U) group were measured (Vatansever Sakin 2022). The olive fruit (peel and flesh) hardness was measured by HT-6510A Shoremeter with a tip of 1.2 mm of indenter diameter.

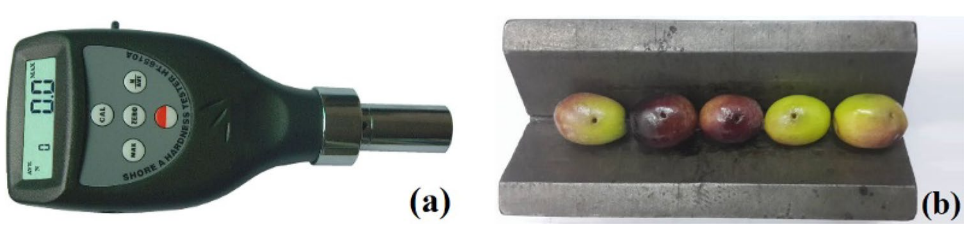

Fig. 2 **a**) The hardness tester is called Shoremeter (Shore-A). **b**) V-block for fixing the olive

The olive crushing test

Öztürk et al. (2009) studied the physical properties of various olive varieties and Özdemir et al. (2018) conducted similar research on the fruit properties of six olive varieties. Kılıçkan and Güner (2008) studied the mechanical behavior of olive fruits under compression loading. In this study, a biological material test device in the Edremit Olive Cultivation Laboratory was used to measure the crushing force of olives. A biological material testing device was also used by Vatansever Sakin (2022)

Measuring weight, determination of sizes and maturity index through an image processing method

The mini loadcell with a maximum measurement capacity of 100 g (Fig. 3) was placed in the section of the device used to measure the size and weight of the olive. The olive was placed in an elliptical hole on the loadcell and fixed, and its size and weight were measured. LED high-resolution cameras were placed 10 cm from the olive with lenses at 90º to each other. The cameras recorded views from both the front and side cross-sections of the olive, and real-time images were sent to the PC. The visual image, colors, and outline of the olives were analyzed using image processing software. Thereafter, the size variables of the olive (width, length, thickness, and color) were calculated and recorded (Vatansever Sakin 2022).

Maturity index (MI)

The maturity (ripening) index (MI) was determined by evaluating the color of 100 olives randomly selected from olive samples (one kg each) during the harvesting period, according to the method based on color changes of peel and pulp (Guzman et al. 2015). The technique used to estimate the MI was segmentation, which is based on identifying regions and edges using clusters of pixels selected according to various criteria (colors, boundary, texture, etc.) In this study, a similar operation was performed by using the device shown in Fig. 3b, and the MI for each olive group was calculated. MI was calculated as follows:

Fig. 4 Ripening in the olive (cv. Ayvalık) (cross section of an olive)

$$\text{Maturity Index (MI)} = \frac{[(0 \times n_0) + (1 \times n_1) + (2 \times n_2) + \cdots + (7 \times n_7)]}{100} \tag{1}$$

Therefore, n_0, n_1, n_2…, n_7 are the numbers of olives in each color category listed.

The International Olive Council (IOC) has determined the color scale used to calculate the MI in olive samples (IOC 2007; Dag et al. 2011, 2014; Guzman et al. 2015; Koseoglu et al. 2016). Nine-year-old cvs. Barnea and Manzanillo trees have also conducted research on olive MI and studied the effects of yield, harvest time, and fruit size on oil content in olive trees irrigated during the 105-day harvest (September 1st to December 14th) (Lavee and Wodner 2004). Similarly, in this study, olives collected during the 100-day harvest period were divided into seven categories according to MI, and the data for each category are provided in the Results section. The fruits of the Ayvalık olive cultivar used for oil production, ideally, harvesting starts as a maroon color of 2 mm depth occurring on the flesh closest to the skin, after the skin has taken on a purple color (olive on the right side in Fig. 4. This case corresponds to the 3.5–4 value of MI (Efe et al. 2013).

Experimental design and statistical analysis

In this study, Response Surface Methodology (RSM) was used to establish a predictive model for the effects of olive fruit fly attacks at different orchard altitudes and harvesting periods

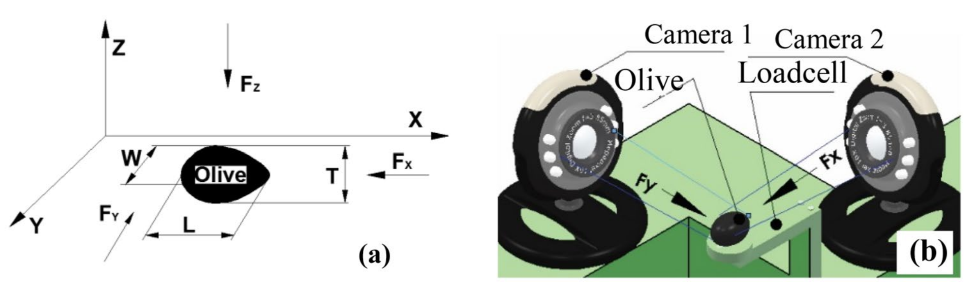

Fig. 3 **a**) Representational image of the three perpendicular dimensions of the olive fruit, **b**) Olive weight measured by the loadcell, and olive sizes and colors measured by the camera system

Table 1 Actual and coded experimental variables in Box–Behnken experimental design

Independent variables (factors)	Units	Symbol Code	Experimental values		
			Lower (-1)	Center (0)	Higher (+1)
Bactrocera infestation	ratio	RDO	0.10	0.25	0.40
Harvesting period	number of days	HAP	0	50	100
Altitudes of olive orchard	meter	OAL	84	126	168

as independent variables (factors) on the dependent variables (responses), such as the physical properties of olives. Using Minitab-19 and Statistica-12 software, 15 experiments were designed and physical tests were conducted on the olives. The Box-Behnken Design (BBD) is considered an experimental design for RSM, which was developed in 1960 by Box and Behnken (1960). The BBD must contain an equal number of replicates for all possible factor level combinations. In the optimization and modelling process data, linear, square, interaction, or quadratic models can be used to correlate responses with selected factors. In the RSM, the most commonly used second-order polynomial equation for the placement of experimental data and the determination of related model terms are expressed as follows:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon \quad (2)$$

y: Response of the system (estimated response)
b_0: Model constant (constant coefficient)
b_i, b_{ii},b_{ij}: coefficients of variables
x_i, x_j: Coded independent variables (factors)
ε: error value

The Box-Behnken design used in this study is an important statistical method in the design of experiments. This design was used to analyze factors (-1, 0, +1) on three levels, as listed in Table 1 (Olajide et al. 2014; Akubude et al. 2017). In this study, a matrix containing 15 experimental studies was determined using BBD, and the corresponding responses were obtained through simulation. Based on this coding, the results of 15 experimental studies that fit the design from the data obtained over the course of three years are presented in Table 2. The encoded versions of the factors and the corresponding responses for each test are also shown. Through further analysis, the second-order model shown in Eq. (2) was generated.

The design was composed of six responses: maturity index (MI), fruit removal force (FRF), change ratio of weight (CRW), density (CRD), hardness (CRH), and crushing force (CRCF), and three factors: the ratio of damaged olives (RDO), harvesting period (HAP), and orchard altitude (OAL). The factors or independent variables, such as the ratio of damaged olive*s,* harvesting period, and altitudes, were examined in the range of 0.10–0.40, 0–100 days and 84–168 m, respectively, as shown in Table 1, based on preliminary studies.

Table 2 Formulations of samples according to Box–Behnken experimental design

Run no	Year	Independent variables (factors)			Dependent variables (responses)					
		RDO	HAP	OAL	MI	FRF	CRW	CRD	CRH	CRCF
1	1th year	-1	-1	0	0.50	4.24	0.031	-0.269	0.020	0.008
2	2th year	0	-1	1	0.00	5.34	0.039	-0.031	0.081	0.013
3	2th year	0	-1	-1	1.00	5.30	0.040	-0.140	0.105	0.018
4	3rd year	1	-1	0	0.75	4.51	0.085	0.024	0.179	0.100
5	1th year	-1	0	1	2.75	3.36	-0.129	-0.292	0.033	0.008
6	2th year	-1	0	-1	2.85	4.21	0.037	-0.059	0.049	0.009
7	2th year	0	0	0	3.00	3.80	0.041	-0.038	0.146	0.019
8	3rd year	0	0	0	2.90	3.85	0.045	-0.026	0.156	0.022
9	3rd year	0	0	0	3.00	3.54	0.047	-0.007	0.158	0.035
10	1th year	1	0	-1	3.50	1.50	0.098	-0.044	0.189	0.125
11	3rd year	1	0	1	3.25	3.08	0.111	0.061	0.202	0.150
12	2th year	-1	1	0	4.50	2.26	0.038	0.013	0.072	0.012
13	1th year	0	1	-1	5.50	0.92	0.075	-0.001	0.169	0.037
14	3rd year	0	1	1	5.00	2.32	0.084	0.006	0.172	0.088
15	1th year	1	1	0	5.50	1.22	0.115	-0.020	0.203	0.177

ANOVA and Regression Models

All measurements were analyzed statistically using Minitab-19 software with ANOVA tools. Six physical properties (output parameters or responses) were estimated to be equivalent to three factors (input factors) that affect the important characteristics of olive fruit.

Results

Figure 5 shows the charts obtained as a result of the crushing test of the olives picked up from the trees at orchard altitudes of 84, 126, and 168 m and worked on for three years. The charts indicate the compression force–deformation graphics of four groups of olives, damaged (D) and undamaged (U), from olive fruit flies collected on the 1st and 100th days of harvest. Graphs displaying the test data from the three altitudes on two different days during the ripening season are shown in Fig. 5.

The physical properties obtained during the harvesting period of 100 days are listed in Table 3. The average physical properties of olives during the specified 100 days ripening period are listed in Table 4.

The initial ANOVA results of the MI, fruit removal force, change ratio of weight, density, hardness, and crushing force are listed in Table 5. The ANOVA results show that the R^2 value is close to 100% ($R^2 = 84.54–99.52\%$), and the model is in close agreement with the current and experimental data. The R^2 values indicated that the model had good predictability. The initial equations of the models are presented in Table 6. These equations refer to the overall estimation model for the variables.

At this stage, to evaluate the influence of these independent factors on the corresponding responses, analysis of variance was performed using Minitab-19 software according to the BBD model, and results were determined based on a confidence level of 95% ($\alpha = 0.05$). The significance of each term was evaluated based on its probability value (p-value). If the terms have a significant effect on the response, the probability value would be more than 95% ($\alpha \leq 0.05$); otherwise, the probability value will be less than 95% ($\alpha \geq 0.05$), and those terms should be eliminated from the final analysis and equations. However, attention should be paid to this point: the importance of the experimental design methodology is demonstrated by the fact that the response is influenced by factors as well as by the interaction between factors. In this study, the squares and 2-way interactions between the factors were also considered.

Analysis of variance and fitting regression model

As seen in Table 5, the term RDO is significant with probabilities of P > 98% (MI), P > 95% (FRF), P = 99% (CRW), P > 99% (CRD), P > 99% (CRH), and P > 99% (CRCF). While the term HAP is significant with probabilities of P > 99% (MI), P > 99% (FRF), P > 97% (CRD), P > 99% (CRH) and P > 99% (CRCF), respectively, it is insignificant in CRW analysis with a result of $\alpha \geq 0.05$ (0.327). The term OAL was significant with a probability of P > 96% (MI) and P > 98% (CRCF). However, the probability values of the OAL term are 0.193, 0.232, 0.927, and 0.564 for the FRF, CRW, CRD, and CRH analyses, respectively. Because $\alpha \geq 0.05$, in these analyses, the term OAL is insignificant. Because the OAL term is less than 0.05 (0.000), it is significant with a probability of P > 99% only in the CRCF analysis. Additionally, this table shows that the squares of the terms RDO, HAP, and OAL are usually insignificant ($\alpha \geq 0.05$), and only in the CRCF analysis, RDO × RDO is significant with a probability of p > 99%. Similarly, the two-way interaction between the terms RDO, HAP, and OAL was often found to be insignificant. Only the probability values of RDO × HAP and RDO × OAL, CRCF analysis, and RDO × HAP and HAP × OAL multiplication ($\alpha \leq 0.05$) were significant in the CRD analysis. In addition, the p-values (α) of the lack-of-fit terms are greater than 0.05, except for MI and CRW. Nevertheless, the data demonstrate that the model complied satisfactorily. Therefore, the BBD experimental design is a good choice for analyzing the results. After

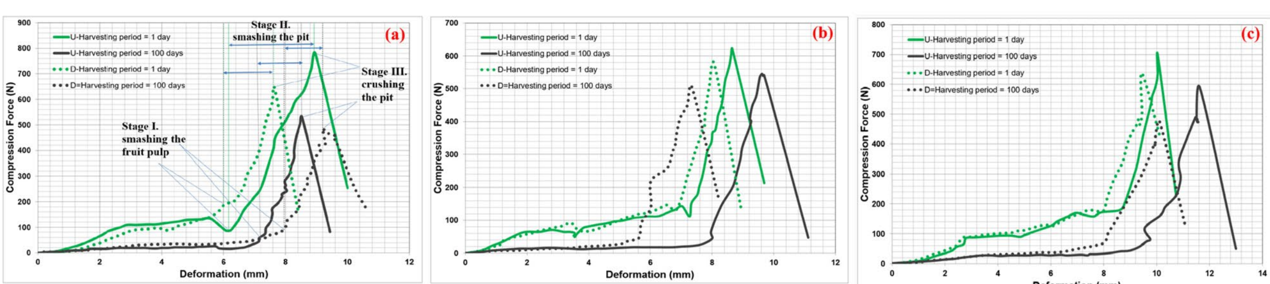

Fig. 5 Compression force–deformation graphs. **a**) 1st year, altitude: 84 m, **b**) 2nd year, altitude: 126 m, **c**) 3rd year, altitude: 168 m

Table 3 Physical properties obtained from the Ayvalık olive cultivar for three years

Year	1th year	2th year	2th year	3rd year	1th year	2th year	2th year	3rd year
Altitude (m)	126	168	84	126	168	84	126	126
Maturity Index (MI)	0.50	0.00	1.00	0.75	2.75	2.85	3.00	2.90
Skin color	hard green	hard green	color < 1/2	yellow-green	color > 1/2	color > 1/2	white	color > 1/2
Date of harvest	September 1	September 1	September 1	September 1	October 21	October 21	October 21	October 21
Number of days after first harvest	0	0	0	0	50	50	50	50
Number of Undamaged olive	6	15	15	24	6	6	15	15
Number of Damaged olive	0.10	0.25	0.25	0.40	0.10	0.10	0.25	0.25
Olive-fruit removal force (N)	4.24[a] ± 1.42[b]	5.34 ± 1.41	5.30 ± 1.58	4.51 ± 1.56	3.36 ± 1.15	4.21 ± 1.84	3.80 ± 1.35	3.85 ± 1.48
U- Fruit weight (g)[c]	2.86 ± 0.52	2.31 ± 0.41	2.24 ± 0.82	2.71 ± 0.74	2.95 ± 0.60	2.95 ± 0.41	3.16 ± 0.59	3.32 ± 0.82
D- Fruit weight (g)[d]	2.77 ± 0.21	2.22 ± 0.43	2.15 ± 0.50	2.48 ± 0.10	3.33 ± 0.24	2.84 ± 0.75	3.03 ± 0.43	3.17 ± 0.41
U- Length (mm)	19.19 ± 1.55	18.39 ± 2.71	19.61 ± 1.55	20.46 ± 1.15	19.68 ± 1.43	19.85 ± 1.43	20.27 ± 1.62	20.67 ± 1.62
D- Length (mm)	17.30 ± 1.90	18.03 ± 1.47	18.38 ± 1.21	19.65 ± 1.30	18.43 ± 1.06	19.41 ± 1.30	19.87 ± 1.47	20.21 ± 1.32
U- Width (mm)	15.04 ± 1.20	13.87 ± 1.06	15.06 ± 0.67	14.70 ± 1.12	15.89 ± 1.73	15.25 ± 1.12	15.64 ± 1.43	15.27 ± 1.02
D- Width (mm)	13.93 ± 1.94	13.54 ± 1.20	14.24 ± 1.18	14.55 ± 1.21	15.46 ± 1.47	14.46 ± 1.05	15.04 ± 1.09	14.75 ± 1.20
U- Thickness (mm)	14.38 ± 1.12	13.76 ± 1.57	15.02 ± 1.47	15.08 ± 1.47	15.32 ± 0.67	15.37 ± 1.15	15.72 ± 0.45	15.44 ± 0.51
D- Thickness (mm)	13.14 ± 1.70	13.40 ± 1.62	14.27 ± 1.73	14.88 ± 1.70	14.69 ± 0.74	15.07 ± 1.73	15.41 ± 1.71	15.22 ± 1.73
U- Hardness (Shore-A)[e]	13.12 ± 5.44	20.81 ± 4.53	16.37 ± 7.99	17.02 ± 5.53	26.22 ± 7.26	28.51 ± 10.31	20.03 ± 5.74	35.90 ± 10.73
D- Hardness (Shore-A)[e]	12.86 ± 5.48	19.12 ± 9.66	14.65 ± 7.63	13.98 ± 4.96	25.35 ± 9.42	27.11 ± 10.71	17.11 ± 8.97	30.30 ± 9.04
U- Crushing force (N)	780.63 ± 9.18	604.70 ± 7.46	664.40 ± 8.96	667.53 ± 8.62	615.20 ± 8.05	635.40 ± 8.97	584.10 ± 8.25	800.80 ± 11.57
D- Crushing force (N)	774.23 ± 8.96	596.80 ± 7.11	652.70 ± 8.25	601.10 ± 9.18	610.00 ± 9.42	629.50 ± 8.42	573.28 ± 8.18	783.35 ± 8.18

Year	3rd year	1th year	3rd year	2th year	1th year	3rd year	1th year
Altitude (m)	126	84	168	126	84	168	126
Maturity Index (MI)	3.00	3.50	3.25	4.50	5.50	5.00	5.50
Skin color	white	white	white	purple < 1/2	purple > 1/2	purple < 1/2	purple > 1/2
Date of harvest	October 21	October 21	October 21	December 10	December 10	December 10	December 10
Number of days after first harvest	50	50	50	100	100	100	100
Number of Undamaged olive	15	24	24	6	15	15	24
Number of Damaged olive	0.25	0.40	0.40	0.10	0.25	0.25	0.40
Olive-fruit removal force (N)	3.54 ± 1.42	1.50 ± 1.18	3.08 ± 1.62	2.26 ± 1.78	0.92 ± 0.92	2.32 ± 1.39	1.22 ± 1.35
U- Fruit weight (g)[c]	2.35 ± 0.24	2.75 ± 0.68	2.52 ± 0.82	2.08 ± 0.68	2.68 ± 0.43	2.75 ± 0.65	2.70 ± 0.74
D- Fruit weight (g)[d]	2.24 ± 0.25	2.48 ± 0.48	2.24 ± 0.87	2.00 ± 0.51	2.48 ± 0.82	2.52 ± 0.50	2.39 ± 0.68
U- Length (mm)	21.02 ± 1.18	20.32 ± 2.15	21.05 ± 1.55	20.47 ± 1.26	20.69 ± 2.08	21.17 ± 2.71	20.68 ± 1.37
D- Length (mm)	20.57 ± 1.21	19.76 ± 1.58	20.67 ± 1.47	20.22 ± 1.05	20.27 ± 1.09	20.80 ± 1.26	20.09 ± 1.71
U- Width (mm)	15.54 ± 0.67	16.25 ± 1.18	15.61 ± 1.04	15.75 ± 1.21	16.98 ± 1.34	15.74 ± 1.06	16.91 ± 1.26
D- Width (mm)	15.25 ± 1.57	15.48 ± 1.58	15.30 ± 1.23	15.42 ± 1.05	16.27 ± 1.44	15.42 ± 0.88	15.89 ± 1.37
U- Thickness (mm)	15.87 ± 0.57	16.23 ± 1.21	15.93 ± 1.15	15.89 ± 0.24	16.35 ± 1.05	16.44 ± 0.68	16.32 ± 1.23
D- Thickness (mm)	15.65 ± 1.73	15.13 ± 1.09	15.66 ± 1.62	16.00 ± 1.22	16.10 ± 0.85	15.75 ± 0.51	15.51 ± 1.19
U- Hardness (Shore-A)[e]	29.05 ± 8.13	13.63 ± 6.21	12.53 ± 4.93	13.27 ± 5.73	32.75 ± 7.89	18.62 ± 8.88	15.20 ± 6.38
D- Hardness (Shore-A)[e]	24.46 ± 14.07	11.06 ± 4.72	10.00 ± 2.81	12.31 ± 5.81	27.20 ± 11.27	15.42 ± 5.71	12.12 ± 4.87
U- Crushing force (N)	676.80 ± 9.52	574.06 ± 5.81	603.49 ± 8.25	712.52 ± 11.50	598.10 ± 7.36	708.99 ± 10.22	669.10 ± 8.62
D- Crushing force (N)	653.40 ± 9.18	502.15 ± 5.71	512.85 ± 8.05	704.30 ± 8.18	575.80 ± 7.63	646.80 ± 9.22	550.43 ± 8.46

[a][Results are given as the mean]

[b][± standard deviation]

[c][U-: Undamaged]

[d][D-: Damaged olive fly], ∅D : indenter diameter (mm)

[e][$H = (0.55 + 0.075 \times \text{Shore-A})/(\pi \times \varnothing\ D^2/4) = N/mm^2$, Example: N = 30 $\text{Shore-A} = (0.55 + 0.075 \times 30)/(\pi \times 1.2^2/4) = 2.475\ N/mm^2 = 25.237\ kg/cm^2$]

Table 4 Physical characteristics of Ayvalık olive cultivar for 100 days ripening period*

Fruit Removal Force (N)	Weight (g)	Length (mm)	With (mm)	Thickness (mm)	Hardness (Shore-A)	Crushing Force (N)
3.40 ± 1.43	2.58 ± 0.54	19.81 ± 1.44	15.20 ± 1.17	15.22 ± 1.13	20.03 ± 7.68	647.79 ± 8.43

*These data for three years are the averages of the 100 days ripening period from September 1 to December 10

eliminating ineffective terms (α ≥ 0.05), the analysis process was repeated; the ANOVA results are presented in Table 7. The P-values of important terms and lack-of-fit values changed after the insignificant terms were removed. The sequence of significant variables was RDO > HAP > OAL > RDO × RDO = RDO × HAP = RDO × OAL > HAP ×

Table 5 Initial analysis of variance for physical properties of olives

	MI			FRF			CRW		
Source	DF	Adj SS	P-Value	DF	Adj SS	P-Value	DF	Adj SS	P-Value
Model	9	43.1598	0.000	9	25.9706	0.008	9	0.039013	0.117
Linear	3	42.7806	0.000	3	22.4219	0.001	3	0.027500	0.036
RDO	1	0.7200	0.012	1	1.7672	0.048	1	0.023174	0.010
HAP	1	41.6328	0.000	1	20.0661	0.000	1	0.001684	0.327
OAL	1	0.4278	0.031	1	0.5886	0.193	1	0.002642	0.232
Square	3	0.1704	0.410	3	1.1810	0.319	3	0.003343	0.553
RDO × RDO	1	0.0031	0.810	1	1.1271	0.092	1	0.000044	0.868
HAP × HAP	1	0.1241	0.171	1	0.0532	0.670	1	0.002587	0.236
OAL × OAL	1	0.0310	0.461	1	0.0724	0.621	1	0.000488	0.584
2-Way Interaction	3	0.2087	0.339	3	2.3676	0.132	3	0.008171	0.246
RDO × HAP	1	0.1406	0.150	1	0.4290	0.255	1	0.000132	0.774
RDO × OAL	1	0.0056	0.748	1	1.4762	0.063	1	0.008013	0.064
HAP × OAL	1	0.0625	0.309	1	0.4624	0.240	1	0.000026	0.898
Error	5	0.2435	-	5	1.3016	-	5	0.007136	-
Lack-of-Fit	3	0.2369	0.041	3	1.2462	0.063	3	0.007119	0.004
Pure Error	2	0.0067	-	2	0.0554	-	2	0.000017	-
Total	14	43.4033	-	14	27.2721	-	14	0.046149	-
	CRD			CRH			CRCF		
Source	DF	Adj SS	P-Value	DF	Adj SS	P-Value	DF	Adj SS	P-Value
Model	9	0.135825	0.019	9	0.054677	0.001	9	0.046453	0.000
Linear	3	0.070717	0.010	3	0.051367	0.000	3	0.037597	0.000
RDO	1	0.049323	0.004	1	0.044591	0.000	1	0.033135	0.000
HAP	1	0.021376	0.022	1	0.006704	0.002	1	0.003850	0.000
OAL	1	0.000018	0.927	1	0.000072	0.564	1	0.000612	0.014
Square	3	0.007320	0.388	3	0.002720	0.062	3	0.006546	0.000
RDO × RDO	1	0.006234	0.135	1	0.002182	0.019	1	0.006447	0.000
HAP × HAP	1	0.000005	0.962	1	0.000415	0.199	1	0.000202	0.087
OAL × OAL	1	0.001384	0.440	1	0.000427	0.193	1	0.000158	0.119
2-Way Interaction	3	0.057788	0.016	3	0.000590	0.451	3	0.002309	0.005
RDO × HAP	1	0.026681	0.014	1	0.000203	0.348	1	0.001388	0.003
RDO × OAL	1	0.028531	0.013	1	0.000214	0.336	1	0.000166	0.113
HAP × OAL	1	0.002576	0.304	1	0.000172	0.384	1	0.000756	0.009
Error	5	0.009841	-	5	0.000946	-	5	0.000225	-
Lack-of-Fit	3	0.009349	0.074	3	0.000861	0.133	3	0.000081	0.784
Pure Error	2	0.000493	-	2	0.000086	-	2	0.000144	-
Total	14	0.145667	-	14	0.055624	-	14	0.046678	-

Table 6 Initial regression equations for responses

Responses		Regression Equation in Uncoded Units
MI	=	2.10 + 0.85 × RDO + 0.03921 × HAP—0.0201 × OAL + 1.30 × RDO × RDO—0.000073 × HAP × HAP + 0.000052 × OAL × OAL + 0.0250 × RDO × HAP—0.0060 × RDO × OAL + 0.000060 × HAP × OAL
FRF (N)	=	5.88—0.82 × RDO—0.0364 × HAP—0.0057 × OAL—24.6 × RDO × RDO—0.000048 × HAP × HAP - 0.000079 × OAL × OAL—0.0437 × RDO × HAP + 0.0964 × RDO × OAL + 0.000162 × HAP × OAL
CRW	=	0.149—0.498 × RDO—0.00111 × HAP—0.00063 × OAL—0.153 × RDO × RDO + 0.000011 × HAP × HAP - 0.000007 × OAL × OAL + 0.00077 × RDO × HAP + 0.00710 × RDO × OAL + 0.000001 × HAP × OAL
CRD	=	-0.278 + 0.292 × RDO + 0.00523 × HAP—0.00002 × OAL—1.83 × RDO × RDO + 0.000000 × HAP × HAP - 0.000011 × OAL × OAL—0.01089 × RDO × HAP + 0.01341 × RDO × OAL—0.000012 × HAP × OAL
CRH	=	-0.1217 + 0.939 × RDO + 0.000847 × HAP + 0.00102 × OAL—1.080 × RDO × RDO—0.000004 × HAP × HAP - 0.000006 × OAL × OAL—0.000950 × RDO × HAP + 0.00116 × RDO × OAL + 0.000003 × HAP × OAL
CRCF	=	0.1564—0.752 × RDO—0.001303 × HAP—0.001310 × OAL + 1.857 × RDO × RDO + 0.000003 × HAP × HAP + 0.000004 × OAL × OAL + 0.002483 × RDO × HAP + 0.001022 × RDO × OAL + 0.000007 × HAP × OAL

OAL. It is obvious that the linear terms are more effective than their squares (square) and two-way interactions. The equations in Table 8 show the reduced regression patterns after eliminating the trivial terms.

Table 9 indicates the regression coefficients for the three independent factors, squares, and interaction between factors for the initial and final analyses. Meaningful terms with a P value of less than 0.05 are marked with a single star, and those with a probability of $P < 0.001$ are shown with two stars. According to the regression coefficients in Table 9, the regression models based on BBD are shown in Table 8.

Table 9 also shows the decision-making coefficient (R^2), which is another criterion for evaluating the ability of the reduced model to predict results. However, the closer these values are to 100%, the more accurately the results can be predicted. As it is seen, R^2 values range from 84.54–99.52% and 73.30–98.57%, respectively, for the overall and reduced models. Only the CRW model did not explain approximately 26.7% of the total variability; however, these high values for other R^2 values showed that the selected model gave a good estimate at the intervals examined.

The results showing the effectiveness of the analyzed terms are shown in Fig. 6 in the form of Pareto graphs. These charts show the degree of significance of the factors according to the responses.

Optimizations

The physical properties were optimized using the response optimizer part of the Minitab-19 software. Because the goal of this study is to minimize the responses, the change ratios of the physical properties were set to the minimum or target values of the data. Therefore, the target value for MI was 4, and the maximum value obtained from software optimization was 3.56. To achieve the lowest level of harvest labor force, the fruit removal force was aimed at a minimum value. At the optimum harvesting day, the ratio of damaged olives and orchard altitude estimation and change ratios of physical properties in the fruit were considered to be minimum to improve the quality of table olive and olive oil. As a result of optimization, the responses were as follows: maturity index, 3.56; fruit removal force, 2.73 N; change ratio of weight, -0.0767; density, -0.1989; hardness, 0.0504; and crushing force, 0.0205. The optimum RDO, HAP and OAL values corresponding to these results were 0.10 on the 72nd day and at 168 m, respectively. The optimization graph and results obtained according to these data are shown in Fig. 7. As mentioned above, in mid-November, the MI of Ayvalık cv olives was 4. Therefore, MI = 4 was considered the target in the optimization.

The actual benchmark values that were not included in the analysis are as follows: MI = 3.5, FRF = 2.84 N, CRW = 0.0315, CRD = -0.0439, CRH = 0.0723 and CRCF = 0.0185. Compared to the values obtained from the optimization, a 1.69% decrease in MI, 4.03% improvement in FRF, 141% improvement in CRW, 77.91% improvement in CRD, 43.54% improvement in CRH, and 9.64% decrease in CRCF were observed. The weight and density loss values in the results were negative because olive flies prefer fruits that have a high mass (heavy) and hard (low elasticity) outer shell.

It was determined that olive fruit flies caused a high degree of damage to the Ayvalık olive cultivar, and the damage reached 40% in the first and third years of the study. Additionally, pests have been found to cause more damage at low orchard altitudes. Variance analysis results indicated that the ratio of damaged olives had a significant effect on the physical properties. Harvesting period and altitude were observed to have a lesser effect on the ratio of damaged olives in terms of adversely affecting their physical properties. Mutual interaction effects occurred between the following factors: RDO × HAP in CRCF analysis, RDO × OAL in CRW analysis, RDO × OAL and RDO × HAP in CRD analysis. Eliminating ineffective terms increased the impact percentage

Table 7 Final analysis of variance for physical properties of olives

	MI			FRF			CRW		
Source	DF	Adj SS	P-Value	DF	Adj SS	P-Value	DF	Adj SS	P-Value
Model	3	42.7806	0.000	2	21.8333	0.000	3	0.033829	0.002
Linear	3	42.7806	0.000	2	21.8333	0.000	2	0.025816	0.002
RDO	1	0.7200	0.004	1	1.7672	0.072	1	0.023174	0.001
HAP	1	41.6328	0.000	1	20.0661	0.000	-	-	-
OAL	1	0.4278	0.019	-	-	-	1	0.002642	0.153
Square	-	-	-	-	-	-	-	-	-
RDO × RDO	-	-	-	-	-	-	-	-	-
2-Way Interaction	-	-	-	-	-	-	1	0.008013	0.022
RDO × HAP	-	-	-	-	-	-	-	-	-
RDO × OAL	-	-	-	-	-	-	1	0.008013	0.022
HAP × OAL	-	-	-	-	-	-	-	-	-
Error	11	0.6227	-	12	5.4388	-	11	0.012320	-
Lack-of-Fit	9	0.6160	0.047	10	5.3834	0.050	9	0.012303	0.006
Pure Error	2	0.0067	-	2	0.0554	-	2	0.000017	-
Total	14	43.4033	-	14	27.2721	-	14	0.046149	-

	CRD			CRH			CRCF		
Source	DF	Adj SS	P-Value	DF	Adj SS	P-Value	DF	Adj SS	P-Value
Model	5	0.125930	0.001	3	0.053233	0.000	6	0.045952	0.000
Linear	3	0.070717	0.002	2	0.051295	0.000	3	0.037597	0.000
RDO	1	0.049323	0.001	1	0.044591	0.000	1	0.033135	0.000
HAP	1	0.021376	0.012	1	0.006704	0.000	1	0.003850	0.000
OAL	1	0.000018	0.929	-	-	-	1	0.000612	0.032
Square	-	-	-	1	0.001938	0.012	1	0.006211	0.000
RDO × RDO	-	-	-	1	0.001938	0.012	1	0.006211	0.000
2-Way Interaction	2	0.055212	0.002	-	-	-	2	0.002143	0.004
RDO × HAP	1	0.026681	0.007	-	-	-	1	0.001388	0.004
RDO × OAL	1	0.028531	0.006	-	-	-	-	-	-
HAP × OAL	-	-	-	-	-	-	1	0.000756	0.020
Error	9	0.019737		11	0.002390	-	8	0.000726	-
Lack-of-Fit	7	0.019244	0.085	9	0.002305	0.152	6	0.000582	0.484
Pure Error	2	0.000493	-	2	0.000086	-	2	0.000144	-
Total	14	0.145667	-	14	0.055624	-	14	0.046678	-

of the effective factors. For instance, in MI, the probability value of RDO increased from 98.8 to 99.6%, the probability value of OAL increased from 96.9 to 98.1%, the probability value of RDO in CRD increased from 99.6 to 99.9%, the probability value of HAP increased from 97.8 to 98.8%, the probability value of RDO × HAP interaction increased from

Table 8 Final regression equations for responses

Responses		Regression Equation in Uncoded Units
MI	=	0.846 + 2.000 × RDO + 0.04562 × HAP—0.00551 × OAL
FRF (N)	=	5.664—3.13 × RDO—0.03167 × HAP
CRW	=	0.2391—0.536 × RDO—0.002209 × OAL + 0.00710 × RDO × OAL
CRD	=	0.053—0.621 × RDO + 0.003756 × HAP—0.00339 × OAL—0.01089 × RDO × HAP + 0.01341 × RDO × OAL
CRH	=	-0.0756 + 1.004 × RDO + 0.000579 × HAP—1.013 × RDO × RDO
CRCF	=	0.0631—0.602 × RDO—0.001007 × HAP—0.000119 × OAL + 1.813 × RDO × RDO + 0.002483 × RDO × HAP + 0.000007 × HAP × OAL

Table 9 Regression coefficient and percentage of R^2 for both steps of analysis of variance for physical properties

		Coefficients										
		b_0	b_1	b_2	b_3	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}	R^2 (%)
MI	Initial analyze	2.1000	0.850*	0.03921**	-0.02010*	1.300	-0.000073	0.000052	0.02500	-0.0060	0.000060	99.44
	Final analyze	0.8460	2.000**	0.04562**	-0.00551*	-	-	-	-	-	-	98.57
FRF	Initial analyze	5.8800	-0.820*	-0.03640**	-0.005700	-24.60	-0.000048	-0.000079	-0.04370	0.0964	0.000162	95.23
	Final analyze	5.6640	-3.130	-0.03167**	-	-	-	-	-	-	-	80.06
CRW	Initial analyze	0.1490	-0.498**	-0.001110	-0.000630	-0.153	0.000011	-0.000007	0.00077	0.0071	0.000001	84.54
	Final analyze	0.2391	-0.536	-	-0.002209	-	-	-	-	0.00710*	-	73.30
CRD	Initial analyze	-0.2780	0.292**	0.005230*	-0.000020	-1.830	0.000000	-0.000011	-0.01089*	0.01341*	-0.000012	93.24
	Final analyze	0.0530	-0.621**	0.003756*	-0.003390	-	-	-	-0.01089**	0.01341**	-	86.45
CRH	Initial analyze	-0.1217	0.939**	0.000847**	0.001020	-1.080*	-0.000004	-0.000006	-0.00095	0.00116	0.000003	98.30
	Final analyze	-0.0756	1.004**	0.000579**	-	-1.013*	-	-	-	-	-	95.70
CRCF	Initial analyze	0.1564	-0.752**	-0.001303**	-0.001310*	1.857	0.000003	0.000004	0.002483**	0.001022	0.000007**	99.52
	Final analyze	0.0631	-0.602**	-0.001007**	-0.000119*	1.813**	-	-	0.002483**	-	0.000007*	98.44

*Significant at $P \geq 95\%$

**Significant at $P \geq 99\%$

98.6 to 99.3%, the probability value of RDO×OAL increased from 98.7 to 99.4% and in CRH, the probability value of HAP increased from 99.8 to 100%, and the probability value of RDO×RDO increased from 98.1 to 98.8%.

In accordance with the optimization results, the least damaged olives were obtained on the 72nd day from the first harvesting day, which was September 1st, at an altitude of 168 m. It was observed that on this harvesting day, the olive fruits were 19.98 mm in length, 15.85 mm width and 15.90 mm in thickness with a weight of 2.82 g. This study indicates that as the altitude of the olive orchard increases, the olive fruit damage caused by *B. oleae* larval infestation rate decreases. As a result, it was determined that the change ratio of each physical property, such as the fruit removal force, hardness, weight, density, and crushing force, could be used as ripening criteria. The effects of MI have been reported in the literature. The change ratio of each physical property depended on the ripening period, intensity of the olive fly attacks, and altitude of the orchard. The study results reveal important data in terms of olive maturity determination, determining the correct harvesting time, choosing a place, and selection of variety in creating a new olive facility, contributing to the olive economy, and developing new harvesting tools. Based on the main results of this study, we plan to minimize the negative effects of olive fruit fly, which is accepted as the primary olive pest in Turkey, with the correct harvest time and new olive orchard facility. The findings will also be indirectly useful in future studies on the improvement of olive oil quality and the reduction of pesticides used for olive fruit fly control. It would also be beneficial to conduct similar studies by considering cultivars other than Ayvalık and comparing the results for a better interpretation of olive agroecosystems.

3D surfaces and 2D contour plots for the physical properties

In this section, 3D surface and 2D contour drawings of physical properties are used to illustrate the relationship between the designed factors and activity parameters. While 2D contours are drawn simultaneously as a function of two factors, the other factors are maintained at constant levels (usually at the zero level). These graphs are useful for examining the effects of both the main factors and their interactions with each other. The 3D surface and 2D contour drawings shown in Fig. 8 were obtained using the Statistica-12 software.

Effect of the ratio of damaged olive (RDO) and harvesting period (HAP) on the physical properties of olive fruits

Figure 8a, b show the 3D surface and 2D contour chart for the MI versus the ratio of damaged olives and the

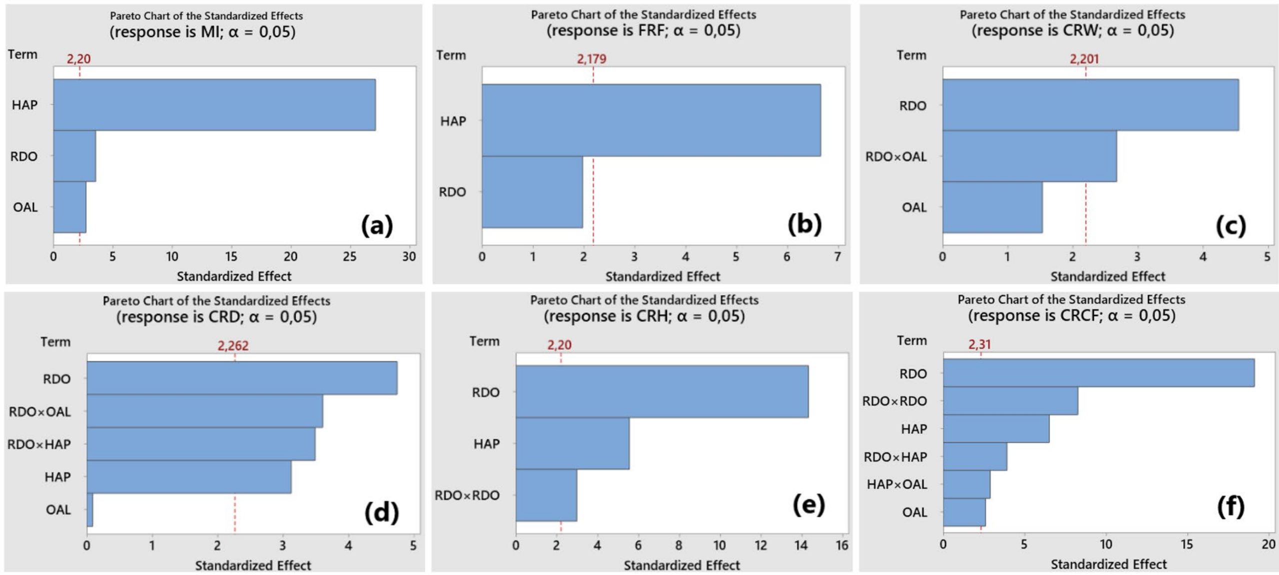

Fig. 6 Effectiveness of analyzed terms in the form of a Pareto chart

harvesting period, respectively, and the orchard altitude is accepted as 126 m (zero level). As the harvesting period increased, the MI also increased significantly. It has also been observed that with the increase in the ratio of damaged olives, the MI increased somewhat, but this level of increase was much lower than the increase in the harvesting period. As can be seen here, harvest period was the factor that most affected MI. As seen in Fig. 8c, d, while the fruit removal force decreased significantly with an increase in the harvest period, the increase in the ratio of damaged olives showed little change. As the harvesting period increased, the olive removal force decreased from 5 to 1 N. After the 72nd day, the fruit removal force also dropped below 2.7 N. Between the 98th and 100th days of the harvesting period, FRF was less than 1.25 N in the daytime and fruits had fallen because of their own weight or in natural ways. The minimum loss in fruit weight was observed during the harvesting period, when the ratio of

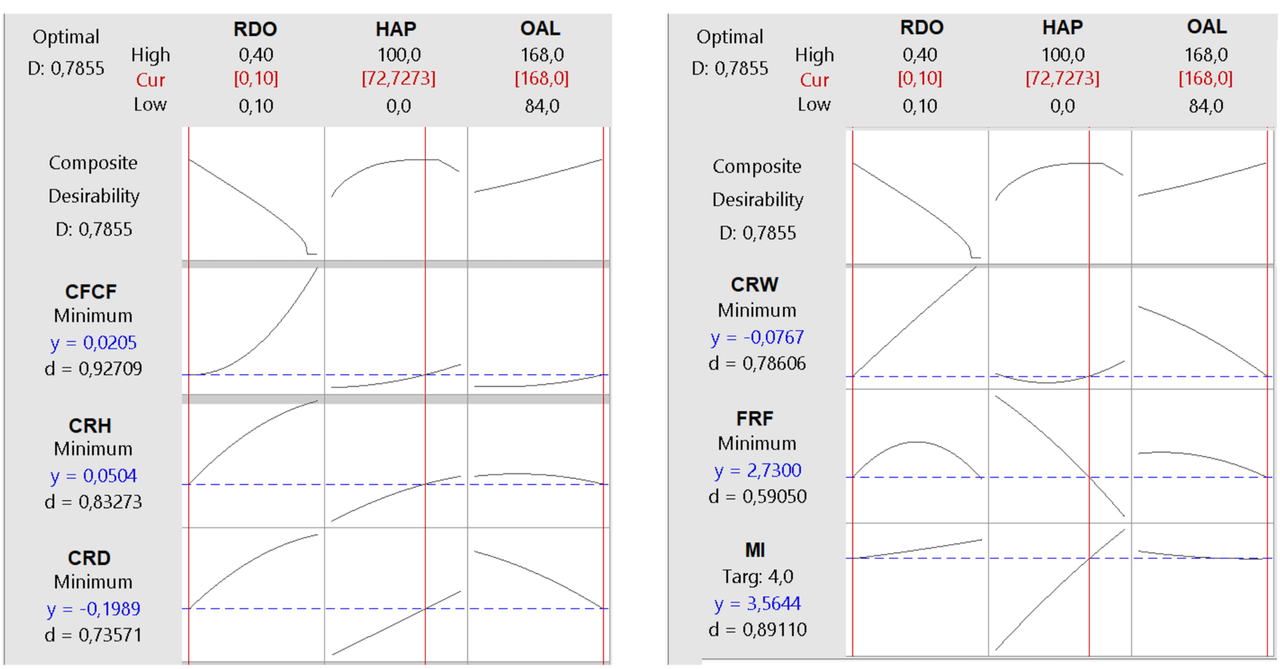

Fig. 7 Response optimization graphs

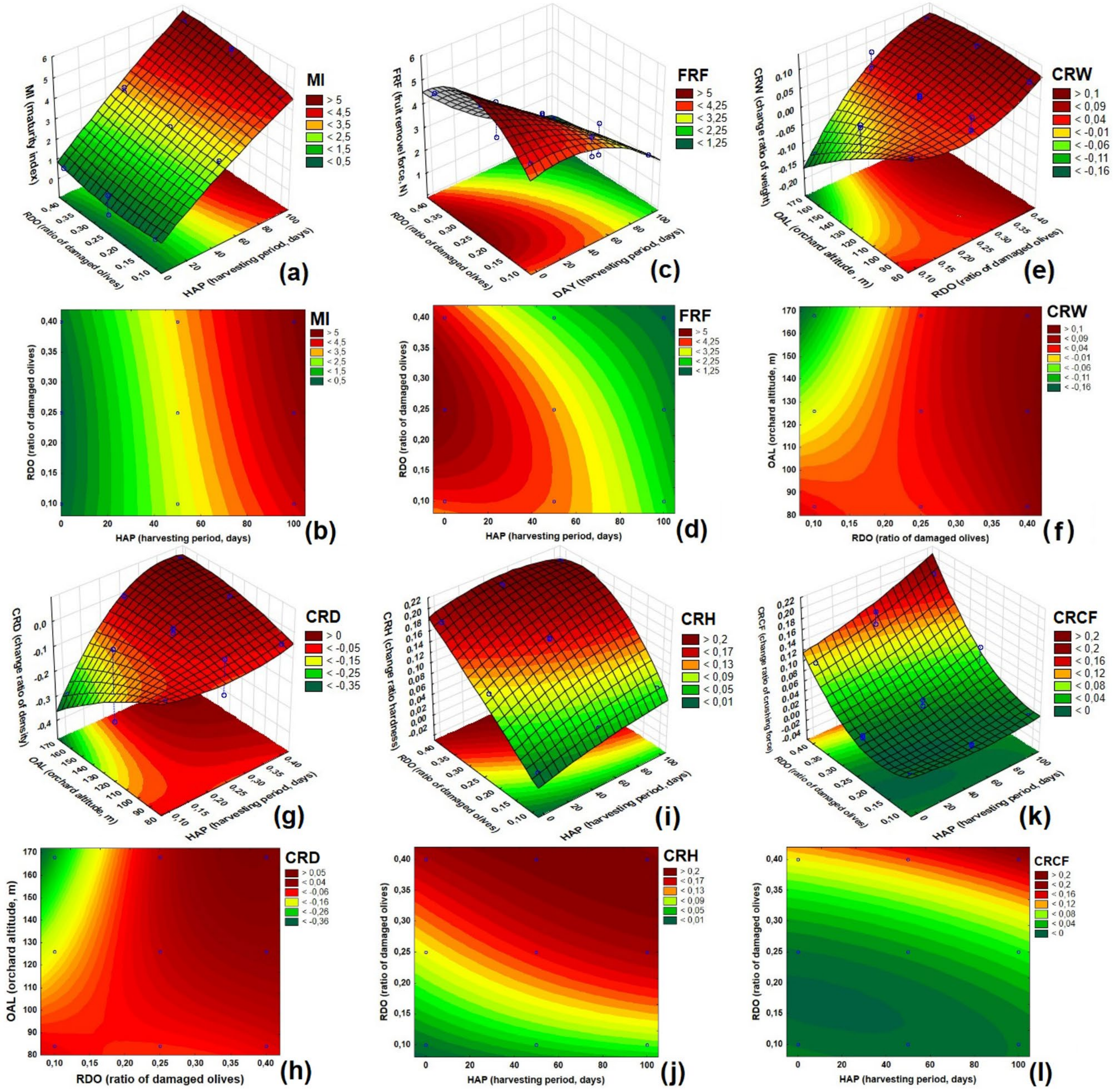

Fig. 8 3D surface and 2D contour plots for change ratios of the physical properties of olive fruits

damaged olives was the lowest. As shown in Fig. 8I, j, the change ratio of the hardness increased significantly with an increase in the ratio of damaged olives. It was observed that the change ratio of hardness increased with an increase in the harvesting period, but this increase was lower than the increase in the ratio of damaged olives caused by olive fly attacks. While the ratio of damaged olives was in the range of 0.30–0.40 during the harvesting period, the change ratio of hardness was in the range of 0.17–0.20, and maximum losses of the physical properties were observed. In the last days of harvesting, while the ratio of damaged olives was in the range of 0.18–0.40, the change in the ratio of fruit hardness was also observed at the maximum level. The loss of hardness in the fruit occurred mostly during the 95th and 100th day of the harvesting period. When the ratio of damaged olives increased above 0.35, the change ratio of fruit hardness increased above 0.17. In addition to using the MI and fruit removal force for harvesting time, the change ratio of fruit hardness, which is an expression of maturity, can also be used as a criterion. As seen in Fig. 8k, l, the change ratio of the fruit crushing force shows an obvious increase in the ratio of damaged olives. Similarly, the loss of fruit crushing force increased with an increase in harvesting period. It is also clear that changing these two variables simultaneously affected the loss of fruit crushing force in an increasing manner. For this reason, there is a mutual interaction effect between RDO and HAP. The loss of crushing force was naturally at its maximum in the period between the 80th and 100th day of harvesting. In addition, the ratio of damaged olives reached a maximum of 0.35–0.40. Until the 45th day of harvesting, the losses in crushing force were at a minimum.

Effect of the ratio of damaged olive (RDO) and orchard altitude (OAL) on the physical properties of olive fruits

As shown in Fig. 8e, f, the change ratio of fruit weight increased with the ratio of damaged olives and decreased with increasing orchard altitude. In addition, changing these two variables at the same time has affected the weight loss in the increased format. As shown in Fig. 8g, h, the change ratio of fruit density increased with the ratio of damaged olives and decreased with increasing orchard altitude. In addition, changing these two variables simultaneously affects the loss of density in the increased format. For these reasons, there is a mutual interaction effect between the RDO and OAL. The maximum density loss occurred on the last day of harvest. On the first day of harvesting, density decreased with an increase in orchard altitude. The change ratio of density decreased as the orchard altitude increased, particularly when the ratio of damaged olives was between 0 and 0.15.

The results of this study will be useful for determining the optimal harvest time for the Ayvalık olive cultivar to achieve the highest quality of fruits and maximum quantity and quality of olive oil. Therefore, this study can serve as a guide for future studies.

Discussion

Olive fruits that are still green at the beginning of September change to a yellow-green color in October. The color first turned purple in December. When it is fully ripened at the end of December, it turns into a color close to black. During the ripening process, the hardness of the fruit epicarp (bark) and fruit mesocarp (flesh) gradually decreased, and the olives were ready for harvest. Infestation with *B. oleae* larvae considerably reduces the hardness of olive fruits (Vatansever Sakin 2022). The results obtained from this study confirm this observation, as the hardness of the damaged fruits also decreased in three consecutive years compared to that of the undamaged fruits. This decrease in hardness leads to the fugacity of the fruit; thus, it cannot be considered edible. Some studies have reported that *B. oleae* prefers olives with hard fruit flesh because of their low elastic properties (Gonçalves et al. 2012; Rizzo et al. 2012; Malheiro et al. 2015), whereas olive fruit fly outflows in olive groves are related to fruit ripening, and larvae form high populations during the fruit ripening period (Tzanakakis 2003). Research indicates that, as the altitude of an olive orchard increases, fruit damage caused by *B. oleae* larval infestation decreases (Gaouar and Debouzie 1991; Vatansever Sakin 2022). Yokoyama and Miller (2004) and Vatansever Sakin (2022) reported that coastal regions, which are cooler and have much more humidity than inland areas, are more accessible areas for the development of olive fruit flies, and the pest population decreases as the altitude increases away from the coastal regions.

The Ayvalık olive cultivar is harvested from October to November, when the skin begins to change color, without waiting for full maturation, and is used to make high-quality scratched olives. Those harvested from January to February, when fully ripened, are consumed as black table olives (Vatansever Sakin 2022). The fruits of the Ayvalık olive cultivar harvested from October to November provide high-quality olive oil with pleasant scent and aroma (Efe et al. 2013). According to Beltrán et al. (2004), olive fruit harvesting should be conducted from the middle of November to obtain the highest oil yield and avoid natural fruit drop. This corresponds to the 75th day of the first harvest on September 1st. In the study by Vatansever Sakin (2022), which was conducted without considering the MI, this period corresponds to the 62nd day from the first day of harvest. In this study, the optimum harvesting day corresponded to November 12th which is the 72nd day from the first harvest. This analysis with Minitab and Statistica software can be repeated by changing the targets at any time. In the current optimization, the RDO, HAP, and OAL data can be manually modified to obtain new responses. According to a study by Toker et al. (2016), the total phenol concentration of oil decreases as the fruit matures, in agreement with related studies. The hexanal concentration of the oil also decreased as fruit maturity progressed. Total carotenoid content in the fruit of olive cultivars increased slowly especially between the 3.5–4.5 MI stages. However, the total chlorophyll content decreased during ripening in the 3–4 MI stages. Therefore, there is an inverse relationship between chlorophyll and carotenoid content in olive fruit (Gundogdu and Kaynas 2016).

As mentioned in the optimization results, the dependent variables (responses) were as follows: MI = 3.56, FRF = 2.73 N; CRW = -0.0767, CRD = -0.1989, CRH = 0.0504, and CRCF = 0.0205. Based on these results, the optimum independent variables (factors) were estimated to be RDO = 0.10, HAP = 72nd day and OAL = 168 m. However, according to the final regression results presented in Table 8, if the ratio of damaged olive (RDO) and orchard altitude (OAL) is equal to 0.2 and 168 m, respectively, on the 72nd day estimated to be the optimal harvesting time, the removal force of olive oil is calculated as 2.75 N. By using the same data, on the other hand, the maturity index representing a critical parameter is calculated as MI = 3.60 in order to define the most available harvesting time. These data, which are similar to the results of this study, were also reported by Mafrica et al. (2019) and Vatansever Sakin (2022).

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Declarations

Ethics approval and consent to participate Not applicable.

Conflict of interest The author declares that there is no conflict of interest.

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