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IMPACT OF *CYDIA POMONELLA* INFESTATION ON THE QUALITY PARAMETERS OF 'JONAGOLD' APPLES

Plamen Ivanov✉, **Penka Filyova**

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Abstract

The codling moth (*Cydia pomonella* L.) is a major pest in pome fruit and walnut orchards worldwide, causing significant economic losses due to fruit damage and quality deterioration. This study evaluates the impact of *C. pomonella* infestation on major commercial and physiological parameters of 'Jonagold' apples, with emphasis on the applicability of the Whiteness Index (WI) and Tissue Water Content Index (Tw) as indicators of biotic stress. Fruits from the first and second generations were classified as infested or non-infested and analyzed for weight, firmness, soluble solids (°Brix), colour coordinates (L, a, b*), WI, and Tw. Infested fruits exhibited significantly reduced weight and increased °Brix, WI, and Tw, particularly in the first generation ($p < 0.05$). ANOVA revealed significant effects of both generation and infestation status on weight, °Brix, and WI, including notable interactions. Tw showed strong sensitivity to infestation, reflecting alterations in tissue water balance, while firmness remained unaffected. The positive correlation between WI and Tw ($r = 0.65$) and their negative association with °Brix highlight their diagnostic potential. The results demonstrate that WI and Tw can serve as reliable, non-destructive indicators of physiological stress caused by *C. pomonella*, supporting early damage detection, postharvest quality assessment, and breeding programmes aimed at improving resistance.

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Introduction. The codling moth (*Cydia pomonella* L.) is one of the most destructive pests in apple orchards in temperate climates. The damage it causes leads to direct yield losses, deterioration in fruit quality, and restrictions on their commercial realization. In conditions of sustainable, organic production, where the use of insecticides is limited, the importance of this pest increases even further [1, 2].

The 'Jonagold' cultivar is widespread in Europe and Bulgaria due to its excellent taste and high commercial value. However, a number of studies have shown that it is among the most susceptible to infection by *C. pomonella* [3–5]. Morphological and physiological characteristics of the fruit, including size, firmness, and chemical composition, affect the pest's preferences in different climatic conditions [5].

Damage caused by *C. pomonella* often results in fruits that fail to meet commercial and export standards due to reductions in weight, changes in soluble solids content, and alterations in external appearance [6–8]. Colour characteristics, including anthocyanin development and surface reflectance, are also affected by biotic stress and play a key role in consumer perception [8].

In recent years, increasing attention has been directed toward non-destructive physiological and spectral-optical indicators – such as the Whiteness Index (WI) and Tissue Water Content Index (Tw) – which have shown potential for assessing ripening stage, internal quality, and stress responses in apples [9–11]. These approaches are based on non-destructive methods, including near-infrared spectroscopy, which has been successfully used to determine firmness and sugar content in apples [11]. Earlier studies have demonstrated the effectiveness of NIR spectroscopy for non-destructive assessment of acidity, soluble solids and firmness in 'Jonagold' apples [12].

Despite this progress, the physiological responses of apple fruits to *C. pomonella* infestation remain insufficiently characterized, particularly regarding spectral-optical traits that may serve as early indicators of biotic stress. Existing research has focused primarily on yield loss and external damage, while the potential of WI and Tw to detect subtle physiological alterations induced by larval feeding has not been systematically evaluated. This gap is especially relevant for breeding programmes aiming to improve cultivar resistance and for the development of rapid diagnostic tools for orchard and postharvest management [13].

This study aims to assess the impact of *Cydia pomonella* infestation on the main commercial and physiological indicators of 'Jonagold' apples, with an emphasis on the potential of the WI and Tw indices as indicators of physiological stress and poor quality. By integrating traditional quality metrics with spectral-optical indices, the study provides new insights into the physiological consequences of infestation. It evaluates the potential of non-destructive methods for early detection and quality assessment.

Material and methods. The study was conducted during the 2025 growing season in an experimental apple orchard of the Fruit Growing Institute – Plovdiv (42.1225° N, 24.7444° E), Southern Bulgaria. The experimental orchard covers 0.7 ha in total, of which 0.3 ha are planted with the cultivar 'Jonagold'. The remaining area includes the cultivars 'Fuji', 'Chadel', and 'Braeburn', which also serve as effective pollinators for the triploid and self-incompatible 'Jonagold'. Trees were planted in 2019 on MM106 rootstock, at a spacing of 4×2.5 m, and are maintained under standard agrotechnical practices. A conventional plant protection scheme against *Cydia pomonella* was applied throughout the vegetation period.

Sample sampling and grouping. The fruits were harvested by hand at the end of the first and second generations of *Cydia pomonella*. The beginning of the first generation was recorded on 24 April 2025, and the beginning of the second generation on 2 July 2025, based on pheromone trap monitoring. Each fruit is subjected to visual inspection and classified into one of the following groups:

- Fruit without visible damage (control group)
- Fruits with visible damage caused by *C. pomonella*

For each generation, three replications of 25 fruits were collected, resulting in 75 fruits per generation and a total of 150 fruits. Each replication contained both damaged and undamaged fruits, allowing for balanced comparison between groups.

Measured indicators and equipment used. The following morphological, physicochemical, and optical parameters are determined for each fruit:

- Weight (g) – electronic scale (max. 500 g, accuracy ± 0.01 g)
  Dimensions (mm) – height and two diameters, measured with a digital caliper; Average value calculated
- Firmness (N) – firmness gauge FHT-1122, two measurements on opposite sides
- Soluble dry matter content (°Brix) – digital refractometer MA871
  Colour coordinates (L\, a\, b\)* – CM-200S colourimeter, two zones of the surface
- Whiteness index (WI) – calculated automatically by the appliance according to the formula:

$$\text{WI} = 100 - \sqrt{(100 - \text{L}^*\ )^2\ + \text{a}^{*2} + \text{b}^{*2}} \tag{1}$$

- Tissue Water Content Index (Tw) – calculated using an empirical formula adapted from [9]:

$$\text{Tw} = \frac{\text{R}_{900}}{\text{R}_{970}}, \tag{2}$$

  where R_{900} and R_{970} are the values of reflected light at the respective wavelengths measured with the CM-200S.

Statistical analysis. The data were processed using Microsoft Excel and the R programming environment [14]. The following statistical methods were used:

- T-test – for comparison between the two groups of fruits
- ANOVA – to assess the impact of the generation
- Correlation analysis (Pearson coefficient) – to establish relationships between WI, Tw, °Brix, and other indicators
- Graphical representation – through boxplot and scatter plot charts

The level of statistical significance was assumed at $p < 0.05$. Statistical analyses were carried out in accordance with the methodological guidelines of [15, 16].

Results and discussion. Descriptive statistics reveal distinct differences in the main quality indicators of fruits across damage levels and pest generations. In the first generation, 'Jonagold' fruits without visible damage have an average weight of 76.7 g, while damaged fruits have an average weight of 63.1 g. A similar trend is observed in the second generation, where the weight of undamaged fruits reaches 206.4 g, whereas that of damaged ones decreases to 168.3 g. The differences are statistically significant ($p < 0.001$) and highlight the negative impact of *Cydia pomonella* on weight accumulation, particularly in later-ripening fruits (Table 1).

T-tests revealed statistically significant differences between damaged and undamaged fruit for several main quality indicators. In the first generation, damaged fruits were characterized by significantly lower weight ($p = 0.0058$) but higher values of °Brix ($p < 0.0001$), WI ($p = 0.0156$), and Tw ($p = 0.0028$). In the second generation, the weight was also statistically reduced in damaged fruits ($p = 0.0004$), whereas the remaining indicators did not reach statistical significance, despite the reported trends. The firmness and colour coordinates (L\, a\, b\)* showed no significant differences between the groups, suggesting a lower sensitivity of these parameters to biotic stress induced by *C. pomonella*.

Two-factor variance analysis (ANOVA) indicated that both generation and failure condition had a statistically significant impact on fruit weight, °Brix, and WI ($p < 0.05$). Significant interactions between the two factors were observed for weight ($p = 0.025$), °Brix ($p = 0.043$), and WI ($p = 0.004$), indicating that the impact of the damage varies across developmental phases. At Tw, strong main effects were found but no interaction, while firmness remained a relatively stable indicator, with no statistically significant differences between groups.

The visualization of the three most sensitive indicators – °Brix, WI, and Tw – using boxplots (Fig. 1) illustrates distinct differences between damaged and undamaged fruits. In the first generation, an increase in °Brix and WI was observed in damaged fruit, while Tw showed a significant increase, likely reflecting changes in water content and metabolic balance. In the second generation, the trends are maintained but with less pronounced statistical significance, consistent with t-test and variance analysis results.

T a b l e 1

Effect of the *Cydia pomonella* infestation on the main quality indicators of 'Jonagold' apples by generation and infestation status

Parameter	Generation	Not Infested (mean ± SD)	Infested (mean ± SD)	t-test p	Significance	ANOVA F (Gen)	F (Stat)	F (Int.)	p (Int.)
Weight (g)	First generation	76.7 ± 17.1	63.1 ± 11.4	0.0058	**	476.7	23.1	5.24	0.025
	Second generation	206.4 ± 27.6	168.3 ± 33.6	0.0004	***				
°Brix	First generation	7.90 ± 0.43	9.12 ± 0.72		***	459.9	23.8	4.26	0.043
	Second generation	12.0 ± 1.06	12.5 ± 0.81	0.105	ns				
WI	First generation	49.8 ± 17.5	69.3 ± 29.2	0.0156	*	37.3	3.70	8.61	0.004
	Second generation	37.0 ± 9.31	33.0 ± 6.37	0.117	ns				
Tw	First generation	−15.5 ± 80.9	60.4 ± 68.1	0.0028	**	79.4	12.0	2.00	0.162
	Second generation	−132.1 ± 81.8	−100.1 ± 38.0	0.125	ns				
Firmness (N)	First generation	8.59 ± 0.46	8.76 ± 0.39	0.221	ns	4.47	0.27	1.29	0.260
	Second generation	8.50 ± 0.39	8.43 ± 0.55	0.684	ns				

Note: Significance of *t*-test: ns – insignificant; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. ANOVA: F (Gen) – Generation Effect; F (Stat) – status effect; F (Int.) – interaction generation × status; p (Int.) – p-value for the interaction.

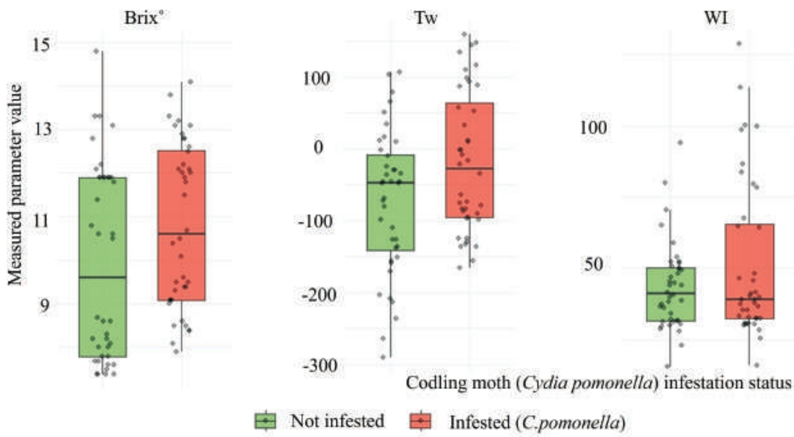

Fig. 1. Boxplot of Brix, WI, and Tw in 'Jonagold' apples depending on the status of infestation by *Cydia pomonella*

The interrelations between the main qualitative indicators are represented by a correlation matrix (Fig. 2). Strong positive correlations have been established between the weight of the fruit and the content of soluble dry matter (°Brix) ($r = 0.78$), as well as between the colour coordinates L\, a\ and b\$^*$ ($r > 0.89$), which reflects their joint dynamics during ripening. The positive relationship between WI and Tw ($r = 0.65$) indicates that the whiteness index is sensitive to changes in tissue water content. The negative correlations between WI and °Brix ($r = -0.46$), as well as between Tw and °Brix ($r = -0.56$), suggest that with an increased sugar content, a decrease in water content and changes in the optical

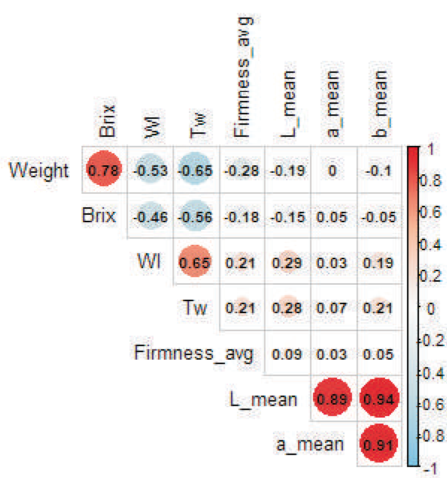

Fig. 2. Correlation matrix between quality indicators in 'Jonagold' apples

properties of the fruit are observed. Firmness showed weak associations with the other indicators ($r < 0.3$), indicating no statistically significant differences between groups as determined by t-tests and ANOVA.

The relationship between the Whiteness index (WI) and the Tissue Water Content Index (Tw) is shown in a scatter plot (Fig. 3), with points coloured by damage condition. In undamaged fruits, a wider range of WI and lower Tw values are observed, while in damaged fruits, Tw values are elevated, and WI is less dispersed around mean values. This confirms that *C. pomonella* infestation leads to physiological alterations in water balance and fruit ripeness, with a tendency towards increased ripeness at higher water content.

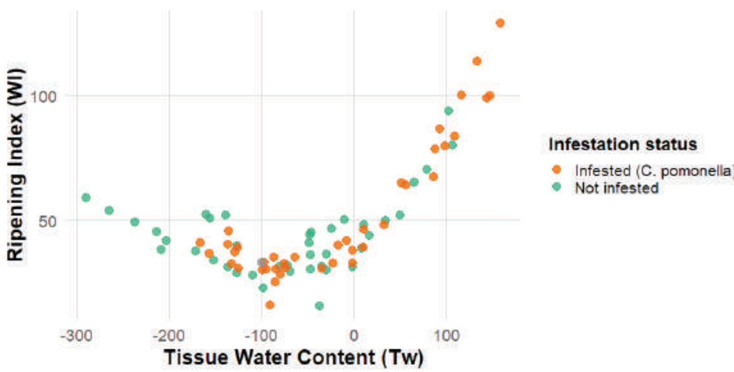

Fig. 3. Correlation between WI and Tw in 'Jonagold' apples by infestation status by *Cydia pomonella*

The results of the present study clearly demonstrate that *Cydia pomonella* infestation induces substantial alterations in the physiological and commercial characteristics of 'Jonagold' apples. The most pronounced effects were observed in fruit weight, soluble solids content (°Brix), and the spectral-optical indices WI and Tw, all of which exhibited high sensitivity to biotic stress.

The reduction in weight in damaged fruits, particularly in the second generation, is consistent with previous studies that have linked damage by *C. pomonella* to impaired development and premature ripening of fruits [4, 5, 7]. This is also confirmed by the elevated values of °Brix in damaged fruit, probably as a result of dehydration and concentration of soluble dry matter.

The tissue water content index (Tw) stands out as a particularly sensitive indicator. In undamaged second-generation fruits, their values are strongly negative, characteristic of physiologically ripe fruits with low water content. Conversely, in damaged fruit, the Tw is significantly higher, likely due to water retention caused by impaired tissue integrity or localized inflammatory processes. Similar observations have been reported by Ahmad et al. [10], who highlight the role of water indices in diagnosing stress.

The whiteness index (WI), although with a more moderate sensitivity to Tw, also showed statistically significant differences between groups. Elevated values in damaged fruits probably reflect changes in tissue reflectivity associated with phenolic compound accumulation or superficial necrosis. This is consistent with the results of [9] and the observations of [8], who associate WI and colour characteristics with physiological changes in apples under stress.

Correlation analysis confirms that Tw and WI are closely related to °Brix, highlighting their applicability as non-destructive indicators of fruit quality. Particularly notable is the strong positive correlation between Tw and °Brix ($r = +0.72$), suggesting that the increased sugar content of damaged fruits is associated with changes in the tissue water balance. Spectroscopic methods from [11] have also established similar dependencies between optical and chemical parameters, which is consistent with earlier findings on non-destructive NIR assessment of firmness, acidity and soluble solids in 'Jonagold' apples [12].

An interesting fact is that the firmness does not show statistically significant differences between the groups. This may be due to the preservation of the tissue's mechanical properties up to a certain stage of damage, or to the limited sensitivity of penetrometric measurements to localized changes characteristic of damage by *C. pomonella* [17].

In summary, the results of the current study confirm that *C. pomonella* infestation leads to complex physiological changes in the fruit, which can be reliably assessed using a combination of traditional (weight, °Brix) and spectral-optical (WI, Tw) indicators. This provides a basis for the development of non-destructive methods for early diagnosis of damage, as well as for the selection of varieties with increased resistance to biotic stress. Such approaches are in line with the goals of modern breeding programmes to improve apple genotypes [15]. The practical application of these indicators could support timely sorting and minimization of losses in storage and trading.

Conclusion. The current study demonstrates that *Cydia pomonella* infestation leads to significant changes in the physiological and commercial characteristics of 'Jonagold' apples. The most sensitive to biotic stress were the weight, Tw, and WI indicators, which showed statistically significant differences between damaged and undamaged fruits. Elevated °Brix and Tw values in damaged fruits suggest dehydration and impaired metabolic balance, while WI reflects changes in the tissue's optical properties. The correlation analysis confirmed the interrelationships between these indicators and highlighted their applicability as non-destructive indicators of qualitative change. The results obtained provide a basis for the development of rapid diagnostic methods and for the selection of varieties with increased resistance to *C. pomonella*.

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Agricultural Academy, Fruit Growing Institute - Plovdiv, 12 Ostromila St,
4004 Plovdiv, Bulgaria
e-mails: plamen280976@yahoo.com, https://orcid.org/0000-0001-8980-9583
pepi0606@abv.bg, https://orcid.org/0000-0002-0683-241X