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Early Nut Drop in the Hazelnut Cultivar 'Tonda Gentile Trilobata' in Northwest Italy: Quantification of Yield Loss and Environmental Factors Involved

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Highlights

What are the main findings?

- The four orchards of 'Tonda Gentile Trilobata' showed substantial variation in nut loss among sites and years.
- Single environmental factors cannot explain the incidence of early nut drop.
- Poor soil fertility, high soil pH, and active limestone are candidate factors associated with the increase in nut loss.
- Climatic variables have a complex effect on early nut drop depending on the timing of reproductive stages.

What are the implications of the main findings?

- The study of the environmental and nutritional factors associated with early nut drop suggests some candidate factors that should be tested in future experimental trials.

Abstract

The investigation aimed to estimate the extent of early nut drop in the hazelnut cv. 'Tonda Gentile Trilobata' during a three-year period (2022–2024). Four orchards located at different sites in the Piedmont Region, NW Italy, were chosen for their different soil and climate conditions. All the material dropped from the plants from early June to early September (including nuts at maturity) was collected and counted to estimate the percentage of early nut drop. The nutritional status of plants (by leaf analysis), the soil parameters (by soil analysis), as well as the main climatic variables (rainfall, temperature, relative humidity), were monitored and used to investigate their relationship with the percentage of early nut drop using principal component analysis (PCA) and linear regression analysis. The percentage of early nut drop ranged from 3.2% to 64.9%, with an overall average percentage that increased over the three years, from 14.2% to 36.4%. Our regression analyses associated soil-related and climatic variables with early nut drop, highlighting that favorable soil conditions, with higher organic matter content, greater cation exchange capacity, and better nutrient availability, consistently showed lower early nut drop and higher productivity. The results also suggest that climatic events may affect hazelnut productivity and early nut drop with complex interactions that require validation over years.

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Keywords: *Corylus avellana* L.; climate variables; soil and foliar analysis; principal component analysis; regression model

1. Introduction

European hazelnut (*Corylus avellana* L.) is one of the most important tree nut crops in terms of worldwide production, with a continuous increment in planted area due to the strong demand for nuts from the confectionery industry [1]. In 2024, the largest producer was Turkey with 717,000 t, followed by Italy (120,520 t) and the United States (87,820 t) [2].

The wide distribution of the species *C. avellana* underlines its large genetic and morphological variability and climatic adaptation. However, its profitable area of cultivation is limited to mild climates in temperate regions, often characterized by their proximity to the sea or other large bodies of water [1]. European hazelnut is a temperate-climate species characterized by good cold tolerance during winter and a lower tolerance to heat, humidity, and wind stress during spring and summer [3].

Hazelnut is a wind-pollinated, monoecious species that exhibits a sporophytic self-incompatibility system. Transition to flowering starts in early June, and flowers develop across summer and early autumn. Flowering takes place during the winter months (December to March in the Northern Hemisphere) but, at the time of bloom, the pistillate flower consists of a rudimentary ovary with two short styles ending with a red-colored stigma emerging from the bud scales of a mixed floral and vegetative bud. After pollination, the stigma dries while the formation of the ovary begins at the time of leaf budburst (March) and is completed in May when fertilization of the egg cell occurs [1]. A lack of pollination causes the inflorescence to drop, which occurs in May. A study conducted on four hybrid hazelnut cultivars of *Corylus heterophylla* Fisch. showed that ovary abortion was due to the absence of a mature embryo sac in the ovule and to the inability of pollen tubes to penetrate the ovule, likely associated with insufficient resource availability to support fruit set, whereas ovary abortion in *C. heterophylla* is at least partly determined by pollen availability [4]. Following fertilization, hazelnut is known to be affected by a certain quantity of early cluster drop (ECD), but the real extent of this phenomenon and its causes have been poorly investigated [5–7] due to its complexity. Early cluster drop was associated with the high presence of blanks (nuts without seed or with aborted seed) at harvest [8]. Another study conducted on *C. heterophylla* concluded that formation of blank nuts is closely related to embryo abortion, but not to the incompatibility between the pollen and stigma [9].

Several factors were related to pre-harvest cluster drop [10]; more recent papers suggest a relationship between cluster drop and nutritional deficiencies [6,7], insufficient soil moisture [11], climatic conditions [8] and damage due to early feeding of bugs [12]. The cited studies considered the extent of ECD in relation to environmental, physiological, and agronomical factors, but the quantification of yield loss due to ECD remains uncertain.

Another factor that may affect hazelnut crop production is the content of non-structural carbohydrate (NSC) throughout the year. A deficiency in NSC in one of the critical periods related to pollination, fertilization, and nut growth may play a major role in the abscission of pollinated pistillate flowers and nut clusters, reducing the crop size [13]. In addition, physiological studies indicate a high susceptibility of hazelnut to heat stress due to a limited stomatal regulation capacity [14,15] for a narrow range of optimal stomatal conductance in comparison to other crops [16]. Consequently, a high physiological sensitivity to water stress is reported, particularly during the kernel-filling period [17], also due to a typically shallow root system of hazelnut [18]. The occurrence of climatic stressors, in particular heat and drought, is expected to become frequent in Europe. In fact, the climatic projections show

an increase in temperatures and radiation, and a decrease in rainfall. A global atmospheric temperature increase of 2 °C is expected, probably accompanied by a reduction in summer precipitation of around 10–15% in several areas of southern Europe. This increase will be very likely associated with more frequent high-temperature events and heatwaves [19]. The rise in summer temperatures, together with the alternation between drought and heavy rain, has made hazelnut cultivation more challenging in different areas of Europe.

In the Piemonte Region, hazelnut cultivation is mainly based on 'Tonda Gentile Trilobata' (TGT, synonymous with 'Tonda Gentile delle Langhe'), which is one of the most important cultivars among the major commercial hazelnut cultivars grown in Italy, and it is known worldwide for its excellent nut and kernel characteristics and its high suitability for processing [20]. 'TGT' has been indicated as a variety very susceptible to ECD [21,22]; however, the rate of ECD shows wide differences depending on the year and on the area of cultivation. The harsh climate conditions that occurred in the Piemonte region in recent years have worsened this situation, since the traditional area of cultivation of 'TGT' is often located in marginal areas such as hills at medium-high elevation, with less fertile soil and no water availability for irrigation.

During a three-year period (2022–2024), this study aimed to (i) estimate the extent of early nut drop (END) and yield in four orchards of cv. 'TGT' with different soil and climate conditions, (ii) analyze dropped nuts, (iii) evaluate nut characteristics after harvest, and (iv) investigate candidate factors affecting END and yield.

2. Materials and Methods

The trial was carried out during a three-year period (2022–2024) in four hazelnut orchards located at different sites of the Piedmont Region, Northwest Italy. The hazelnut orchards of the 'TGT' cultivar were chosen to be representative of different areas of hazelnut cultivation in Piedmont: Lu Monferrato (hereafter named as AL; 45°01′05″ N, 8°29′36″ E); Cossombrato (named as AT; 44°59′47″ N, 8°08′03″ E); Manta (named as CN1; 44°36′31″ N, 7°30′21″ E); Cravanzana (named as CN2; 44°33′39″ N, 8°06′02″ E). Characteristics of sites and orchards are reported in Table 1.

Table 1. Characteristics of hazelnut orchards used for the trial.

Site Code	Municipality	Elevation	Soil Position	Year of Planting	Plant Density
AL	Lu Monferrato	165 m asl *	Flat terrain in a hilly area	2012	5 × 5 m 400 plants/ha
AT	Cossombrato	275 m asl	Light slope in hilly area	2011	5 × 5 m 400 plants/ha
CN1	Manta	395 m asl	Flat alluvial plain	2013	5 × 4 m 500 plants/ha
CN2	Cravanzana	500 m asl	Light slope in hilly area	2010	5.5 × 4.5 m 404 plants/ha

* asl = above sea level.

Plants were 9–12 years old at the beginning of the trial, non-irrigated and managed following the regional guidelines for fertilization and crop protection [23]. For each site, the measurements were performed individually on four plants selected for the trial in the central part of the orchard (each plant therefore constitutes a repetition). The same four plants were used for the three-year study.

2.1. Early Nut Drop Estimation

In late May, a mulch cloth was placed under the canopy projection of the four plants in each orchard to collect the material dropped from the plants throughout the season (including nuts at maturity) from early June to mid-September. The material was collected manually every 15 days for laboratory analysis.

During June and July, when early dropped nuts fall in clusters, the nuts from each tree were counted individually at every sampling date to estimate the percentage of early nut drop before maturity. As the nuts approached maturity or reached maturity (from early August to early September), they were classified into two categories: (i) ripe nuts, those that had fallen free from the husk, and (ii) nuts that remained attached to the husk, exhibiting characteristics similar to those that had fallen prematurely. The ripe nuts were counted and weighed to determine the plant's marketable yield, while nuts that fell in clusters, considered equivalent to those that fell prematurely, as they share the same characteristics as those dropped during July, were counted and examined in the laboratory to determine whether or not a developed kernel was present. These nuts, which lacked a developed kernel, were included, along with those that dropped during June and July, in the calculation of END.

The estimation of the percentage of early nut drop (hereafter referred to as %END) was obtained by relating the number of early dropped nuts, from June to early September, to the total number of nuts produced by the plant (early dropped and marketable).

2.2. Analysis of Early Dropped Nuts

The analyses of early dropped nuts were carried out only for the sites AL and AT. When the early dropped nuts reached an average diameter of approximately 10 mm, a representative set of 30 fruits was sampled randomly from each plant and manually cracked to verify the presence or absence of seeds. We analyzed at least one fruit per cluster. When the quantity of collected material was insufficient to provide 30 fruits, at least 20 nuts were sampled. A total of 470 nuts in 2022, 350 nuts in 2023, and 480 nuts in 2024 were analyzed.

Nuts were classified into four classes (Figure 1):

1. Absence of seed (blank).
2. Aborted seed (seed at the early beginning of development).
3. Seed not completely developed (shriveled).
4. Fully developed seed but with defects (corked, moldy, or rotten).

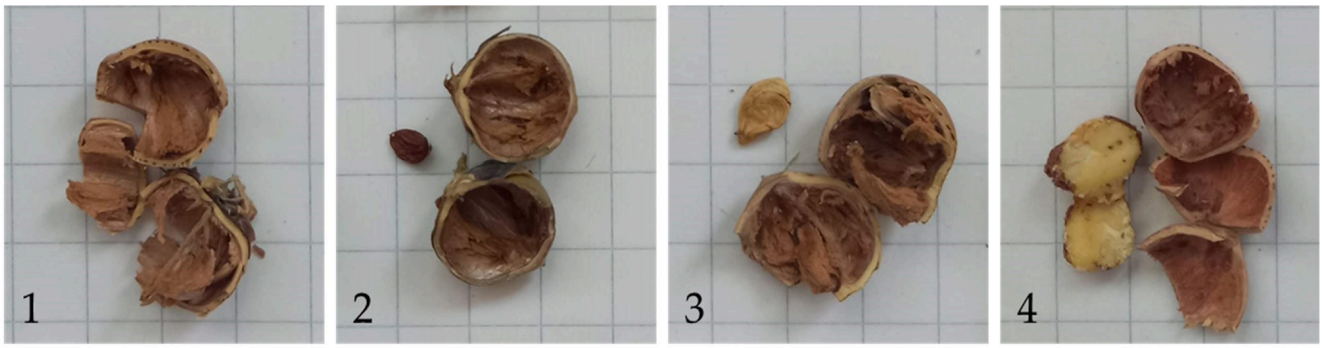


Figure 1. Early dropped nuts classification: 1 = absence of seed; 2 = aborted seed; 3 = seed not completely developed; 4 = fully developed seed but with defects.

2.3. Analysis of Marketable Nuts

Samples of ripe nuts (100 nuts per plant) were analyzed for carpological traits. The following characteristics were assessed: nut and kernel weight (g) were measured using a digital scale; nut and kernel caliber (mm) were measured using a sieve with holes between 10 and 30 mm in diameter; the percentage of kernels with caliber >12 mm, considered the optimal caliber for processing [20], was determined; and shell thickness was measured in the intermediate zone between basal and apical scars of the nut [24] using a digital caliper. In addition, the percentage of good kernels (sound kernels without defects) and the kernel percentage, obtained by the formula 'kernel weight × 100/nut weight', were calculated on samples of 500 g.

2.4. Nutritional Status Assessment

During the three vegetative seasons, the nutritional status of plants and soil parameters were monitored through leaf and soil analyses carried out in an external laboratory.

Leaf Analysis: Leaf samples were collected in early June of every year to detect macronutrient (N, P, K) and micronutrient contents (Fe, Zn, Cu, Mn, and B) through foliar analyses. Foliar sampling was performed by taking 80 leaves for each plant (mature leaves in the central area of the shoot) at eye level and all around the plant, for a total of four samples per site.

All analytical values were expressed on a dry matter (DM) basis, accounting for residual moisture content determined after drying the samples at 90 °C. Total nitrogen (N, %) content was quantified via automated combustion using an elemental analyzer (Thermo Scientific FlashEA 1112, Waltham MA, USA). The concentration of phosphorus (P, %), potassium (K, %), iron (Fe, mg/kg), copper (Cu, mg/kg), zinc (Zn, mg/kg), boron (B, mg/kg), and manganese (Mn, mg/kg) was determined through an initial calcination, followed by acid mineralization with hydrochloric acid (HCl). The resulting solutions were analyzed using inductively coupled plasma (ICP) spectrometry (Varian Liberty RL, Palo Alto CA, USA) to quantify individual element concentrations.

Soil Analysis: Every year, soil parameters were assessed on samples taken approximately 20–40 cm deep near the four plants used for the trial (one sample per site obtained by mixing three soil cores taken across the soil under the four plants). Soil analyses were performed to detect particle size (soil texture), pH, percentage of active limestone (%), C/N ratio, percentage of organic matter (SOM, %), cation exchange capacity (CEC, meq/100 g), total nitrogen (N, g/kg), available phosphorus (P, ppm), exchangeable potassium (K, ppm), exchangeable magnesium and calcium (Mg and Ca, ppm), available manganese, zinc, copper, and iron (Mn, Zn, Cu and Fe, ppm), and soluble boron (B, ppm) contents. The soil analyses were done following the Italian official methods [25].

2.5. Climatic Conditions

The Piedmont (Piemonte) Region in northwest Italy is characterized by a temperate, sub-continental climate in its plains (Po Valley) and hills (Langhe and Monferrato). The region receives an annual average precipitation of 1000 to 1110 mm, highly variable across years and districts. The rainfall distribution follows a bimodal sub-Mediterranean regime, with rainfall peaks registered in spring (April–May) and autumn (October–November). Summers and winters are generally the driest periods.

The regional annual mean temperature across Piedmont fluctuates from around 10.5 °C to 11.4 °C, depending heavily on the specific year. Recent years have broken historic records, with a significant warming up to +1.5 °C above historic 20th-century norms [26].

To evaluate the effect of climatic factors on the early nut drop, a detector for temperature and relative humidity (T °C and RH%) was placed in each of the four hazelnut orchards.

The instrumentation used (HOBO® MX2301A Data Logger) was set to detect the two parameters on an hourly basis and was placed in the canopy of one of the central plants of the plot at each site, about 1.5 m from the ground. Precipitation data were recorded on an hourly basis using data from the RAM weather stations [27] closest to the orchard sites.

2.6. Investigation on Candidate Factors Involved in Early Nut Drop

A principal component analysis (PCA) was performed using the following data recorded in the four orchards: mean and maximum mean temperature, number of critical days (1 h > 35 °C), precipitation and number of wet days (>1 mm), mean relative humidity in the May–July period, used as climate variables; percentages of clay, silt and sand, pH, CEC, SOM, C/N, active limestone percentage, macronutrient (N, P, K, Ca, Mg) and micronutrient content (Fe, Mn, B, Cu, and Zn), used as soil variables; macronutrient (N, P, K) and micronutrient content (Fe, Mn, Zn, Cu, and B) in leaves sampled in June, used as plant nutritional status variables. The factor scores were extracted using an orthogonal rotation (Varimax), with all variance inflation factors (VIFs) equal to 1.0.

A multiple linear regression analysis was performed using the extracted PCA factor scores to identify the relationship between the variables under investigation and early nut drop (%END) and yield (Y).

2.7. Statistical Analysis

Data obtained for early nut drop estimation, early dropped nuts analysis, fruit traits of marketable nuts, and leaf analysis were processed with one-way ANOVA within a single year and with two-way ANOVA considering the following as factors: year, site, and their interaction. Data from soil analysis were analyzed with one-way ANOVA. Data that showed significance by ANOVA were further analyzed using Tukey's (HSD) test at the $p \leq 0.05$ level. All data were statistically analyzed using IBM SPSS Statistics v29.0 software (IBM SPSS v30 software, Armonk, NY, USA).

3. Results

3.1. Early Nut Drop Estimation and Yield

To estimate the percentage of nut loss, the total number of nuts produced by the plant (early dropped and mature) was counted. During the year 2022, plants of the AL orchard produced the highest number of nuts (Table 2), while the lowest was counted for plants of the CN2 orchard, which did not differ significantly from that of CN1. The mean percentage of early nut drop in the four orchards in 2022 was 14.15%, with CN1, which differed significantly from the other sites, having the lowest value of 3.2%. The marketable yield ranged from 7201 to 4107 g per plant.

Also, in 2023, AL showed both the highest number of total nuts and mature nuts, with no significant differences from the CN1 orchard. AT had the highest significant number of nut loss (1058.5 nuts) and the highest %END (64.9%). Again, CN1 differed significantly and had the lowest %END (6.4%), while for AL and CN2 the %END values were similar to those registered in 2022. Concerning the marketable yield, CN1 showed the highest value, followed by AL and CN2, while that of AT was significantly reduced (1259 g/plant).

The highest mean %END for the four orchards was registered in 2024, with an average value of 36.4%. The highest values were registered for AT (58.1%) and CN2 (49.8%); AT had the highest number of early dropped nuts (1441.3), while the CN2 orchard also showed a significantly reduced number of nuts produced by the plants (only 840 per plant).

The two-way ANOVA revealed significant effects of year and orchard site, as well as a highly significant year × site interaction (Table 3). The average %END increased over the three years, from 14.2% to 36.4%, reaching the highest value in the AT orchard (46.7%) and

the lowest in the CN1 orchard (8.45%). The AL and CN1 orchards were the most productive (>5.5 kg plant^{-1}), whereas the AT and CN2 orchards showed the lowest productivity.

Table 2. Number of nuts (marketable, early dropped, total), percentage of early nut drop (%END), and marketable yield (g/plant) for the four orchards in the three years of observations (Mean ± SE; four replicates per site).

Year/Site	Number of Marketable Nuts	Number of Early Dropped Nuts	Total Number of Nuts	Percentage of Early Nut Drop (%END)	Marketable Yield (g/Plant)
Year 2022					
AL	4264.3 ± 594.6 ^{a}	1181.4 ± 176.6 ^{a}	5445.7 ± 756.6 ^{a}	21.7 ± 1.1 ^{a}	7201.0 ± 905.5 ^{a}
AT	3542.9 ± 430.0 ^{ab}	713.3 ± 49.7 ^{b}	4256.2 ± 457.9 ^{ab}	17.1 ± 1.4 ^{a}	5688.3 ± 444.5 ^{ab}
CN1	2542.5 ± 185.1 ^{bc}	87.3 ± 21.3 ^{c}	2629.8 ± 204.4 ^{bc}	3.2 ± 0.5 ^{b}	5775.0 ± 416.1 ^{ab}
CN2	1899.0 ± 194.0 ^{c}	324.8 ± 76.6 ^{bc}	2223.8 ± 202.8 ^{c}	14.6 ± 3.8 ^{a}	4107.5 ± 363.3 ^{b}
stat	**	***	***	***	*
Year 2023					
AL	2216.3 ± 134.3 ^{a}	551.5 ± 43.0 ^{b}	2767.8 ± 151.1 ^{a}	20.0 ± 1.3 ^{b}	4642.3 ± 275.3 ^{b}
AT	572.5 ± 82.7 ^{c}	1058.5 ± 99.8 ^{a}	1631.0 ± 92.0 ^{b}	64.9 ± 5.0 ^{a}	1259.3 ± 189.6 ^{c}
CN1	2139.0 ± 135.7 ^{a}	147.8 ± 17.3 ^{c}	2286.8 ± 146.7 ^{ab}	6.4 ± 0.6 ^{c}	6460.0 ± 391.7 ^{a}
CN2	1573.5 ± 181.1 ^{b}	395.8 ± 67.3 ^{bc}	1969.3 ± 231.6 ^{b}	19.9 ± 1.9 ^{b}	3370.3 ± 391.7 ^{b}
stat	***	***	**	***	***
Year 2024					
AL	3308.8 ± 167.5 ^{a}	930.0 ± 59.0 ^{b}	4238.8 ± 213.9 ^{a}	21.9 ± 0.8 ^{b}	7082.5 ± 329.0 ^{a}
AT	1075.3 ± 93.4 ^{b}	1441.3 ± 54.3 ^{a}	2487.8 ± 48.7 ^{b}	58.1 ± 3.2 ^{a}	2442.8 ± 218.6 ^{c}
CN1	1595.8 ± 162.4 ^{b}	336.5 ± 99.2 ^{c}	2034.5 ± 258.3 ^{b}	15.7 ± 2.8 ^{b}	4845.0 ± 423.4 ^{b}
CN2	401.0 ± 32.7 ^{c}	432.8 ± 97.4 ^{c}	840.0 ± 110.1 ^{c}	49.8 ± 6.2 ^{a}	976.8 ± 118.4 ^{d}
stat	***	***	***	***	***

Results from ANOVA analysis for each year are expressed by the symbols: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p < 0.001$. Mean values followed by the same letter in the column for the same year did not differ at $p \leq 0.05$ according to Tukey's HSD test.

Table 3. Two-way ANOVA for number of nuts (marketable, early dropped, total), percentage of nut drop (%END), and marketable yield (Mean ± SE; 16 replicates per year and 12 per site).

Year/Site	Number of Marketable Nuts	Number of Early Dropped Nuts	Total Number of Nuts	Percentage of Early Nut Drop (%END)	Marketable Yield (g/Plant)
Year					
2022	3062.18 ^{a}	576.66 ^{b}	3638.84 ^{a}	14.16 ^{c}	5692.96 ^{a}
2023	1625.31 ^{b}	538.38 ^{b}	2163.69 ^{b}	27.79 ^{b}	3932.94 ^{b}
2024	1595.19 ^{b}	785.13 ^{a}	2400.25 ^{b}	36.38 ^{a}	3836.75 ^{b}
Site					
AL	3263.09 ^{a}	887.63 ^{b}	4150.72 ^{a}	21.20 ^{c}	6308.58 ^{a}
AT	1730.23 ^{bc}	1071.00 ^{a}	2791.65 ^{b}	46.69 ^{a}	3130.11 ^{b}
CN1	2092.42 ^{b}	190.50 ^{d}	2317.00 ^{bc}	8.45 ^{d}	5693.33 ^{a}
CN2	1291.17 ^{c}	384.42 ^{c}	1677.67 ^{c}	28.11 ^{b}	2818.17 ^{b}
Year	***	***	***	***	***
Site	***	***	***	***	***
Year × Site	***	***	***	***	***

Results from ANOVA analysis are expressed by the symbols: *** $p < 0.001$. Different letters in each column for year and site represent significant differences at $p \leq 0.05$ according to Tukey's HSD test.

3.2. Analysis of Early Dropped Nuts

To investigate the causes of nut loss, early dropped nuts from two orchards (AL and AT) were analyzed and separated into four classes: absence of seed (1), aborted seed (2), seed not completely developed (3), fully developed seed with defects (4); results are presented in Table 4 as the relative percentage of nuts in each class. In 2022, analyses showed that there were no significant differences between classes 1, 2 and 3 for both orchards. On the contrary, in 2023 and 2024, most of the early dropped nuts belonged to class 1, followed by class 2, whilst no significant differences were observed between the nuts classified in classes 3 and 4. The difference between years may be explained by the climate conditions of 2022, which were particularly dry and led to a high percentage of poorly developed seeds (class 3). The two-way ANOVA underlined the effect of the year in determining the presence of nuts with no seed (class 1) and nuts with a partially developed seed (class 3), while the site only influenced the presence of fully developed nuts (class 4).

Table 4. Results of analysis of early dropped nuts in AL and AT sites for three years: percentages of nuts in four different classes: 1 = absence of seed; 2 = aborted seed; 3 = seed not completely developed; 4 = fully developed seed with defects (mean ± SE; four replicates per site; *N* = 470 nuts in 2022, 350 nuts in 2023, and 480 nuts in 2024).

Type of Nuts	1 %	2 %	3 %	4 %	One-Way ANOVA
AL	34.4 ± 1.8 ^{a}	24.8 ± 2.6 ^{ab}	25.3 ± 2.4 ^{ab}	15.4 ± 3.3 ^{b}	**
AT	34.9 ± 4.4 ^{a}	29.0 ± 7.3 ^{ab}	27.0 ± 3.3 ^{ab}	9.0 ± 3.9 ^{b}	*
AL	52.0 ± 1.5 ^{a}	25.1 ± 5.1 ^{b}	9.1 ± 2.5 ^{c}	13.8 ± 4.8 ^{bc}	***
AT	60.0 ± 3.0 ^{a}	32.0 ± 5.1 ^{b}	5.4 ± 1.6 ^{c}	2.5 ± 1.2 ^{c}	***
AL	56.0 ± 3.5 ^{a}	29.4 ± 2.9 ^{b}	6.0 ± 0.3 ^{c}	8.6 ± 1.1 ^{c}	***
AT	48.1 ± 2.9 ^{a}	35.5 ± 3.4 ^{b}	12.4 ± 2.0 ^{c}	4.0 ± 0.8 ^{c}	***
Year	***	ns	***	ns	
Site	ns	ns	ns	**	
Year × Site	ns	ns	ns	ns	

Results from ANOVA analysis are expressed by the symbols: ^{ns} $p > 0.05$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Different letters in each line represent significant differences at $p \leq 0.05$ according to Tukey's HSD test.

3.3. Analysis of Marketable Nuts

Samples of marketable nuts were analyzed to evaluate the quality of fruits in terms of technological parameters to assess suitability for industrial processing. Nuts produced by the CN1 orchard had the highest nut weight for the three years, but also the highest value of shell thickness (Table 5). The percentage of kernel was higher than 45%, except for AT and CN1 in 2022. In this year, the quality of the kernel was optimal only in the CN2 orchard, with 99.5% of kernels having a caliber suitable for industry (kernel caliber > 12 mm), while for the other orchards the percentage of kernels lower than 12 mm (kernels discarded from quality check) ranged from 55.8% in AT to 31.4% in CN2. No significant differences were found for the percentage of doubles, which is known to be a genetic trait, while the percentage of good kernels (sound kernels without defects) was particularly low in 2024 due to the high presence of defective kernels. Carpological parameters were highly influenced by year and site and their interaction (Table 6), except for the percentage of doubles.

Table 5. Carpological traits of nuts from four sites in Piemonte in the three years of the trial (Mean ± SE; four replicates per site).

Year/Site	Nut Weight g	Kernel Weight g	Percent Kernel %	Shell Thickness mm	Nut Caliber mm	Kernel Caliber mm	Kernel Caliber > 12 mm %	Doubles %	Good Kernels %
Year 2022									
AL	2.01 ± 0.05 ^{b}	0.93 ± 0.04 ^{ab}	46.3 ± 1.58 ^{a}	1.16 ± 0.02 ^{ab}	16.7 ± 0.04 ^{c}	11.8 ± 0.35 ^{ab}	65.7 ± 13.41 ^{ab}	0.0 ± 0.00	97.0 ± 1.15 ^{a}
AT	1.82 ± 0.13 ^{b}	0.82 ± 0.08 ^{b}	43.2 ± 2.14 ^{ab}	1.04 ± 0.05 ^{b}	16.8 ± 0.18 ^{c}	11.1 ± 0.54 ^{b}	44.2 ± 15.71 ^{b}	0.0 ± 0.00	97.3 ± 0.85 ^{a}
CN1	2.82 ± 0.17 ^{a}	1.06 ± 0.03 ^{a}	39.7 ± 0.32 ^{b}	1.30 ± 0.05 ^{a}	18.8 ± 0.08 ^{a}	12.1 ± 0.19 ^{ab}	68.6 ± 6.34 ^{ab}	0.5 ± 0.29	92.0 ± 1.08 ^{ab}
CN2	2.33 ± 0.12 ^{ab}	1.00 ± 0.03 ^{ab}	47.7 ± 0.62 ^{a}	1.24 ± 0.02 ^{a}	17.8 ± 0.13 ^{b}	13.3 ± 0.06 ^{a}	99.5 ± 0.30 ^{a}	0.5 ± 0.29	90.3 ± 2.39 ^{b}
Stat	***	*	**	**	***	**	*	ns	*
Year 2023									
AL	2.47 ± 0.03 ^{b}	1.20 ± 0.01 ^{b}	48.2 ± 0.14 ^{a}	1.01 ± 0.00 ^{b}	17.9 ± 0.05 ^{c}	13.9 ± 0.08 ^{b}	99.5 ± 0.51 ^{a}	0.1 ± 0.10	93.6 ± 1.23 ^{a}
AT	2.54 ± 0.01 ^{b}	1.22 ± 0.01 ^{b}	46.1 ± 0.25 ^{b}	1.03 ± 0.01 ^{b}	18.5 ± 0.09 ^{b}	13.8 ± 0.11 ^{b}	93.8 ± 1.63 ^{b}	0.4 ± 0.31	84.5 ± 1.68 ^{b}
CN1	2.81 ± 0.02 ^{a}	1.34 ± 0.01 ^{a}	47.8 ± 0.57 ^{a}	1.09 ± 0.02 ^{a}	18.9 ± 0.07 ^{a}	14.6 ± 0.04 ^{a}	99.0 ± 0.58 ^{a}	1.0 ± 0.58	94.0 ± 0.82 ^{a}
CN2	2.34 ± 0.02 ^{c}	1.14 ± 0.02 ^{c}	48.9 ± 0.35 ^{a}	1.03 ± 0.01 ^{b}	17.6 ± 0.17 ^{c}	13.6 ± 0.11 ^{b}	98.0 ± 0.83 ^{a}	0.0 ± 0.00	95.0 ± 1.00 ^{a}
Stat	***	***	***	**	***	***	**	ns	***
Year 2024									
AL	2.36 ± 0.04 ^{bc}	1.15 ± 0.02 ^{b}	48.7 ± 0.31 ^{a}	0.90 ± 0.04 ^{b}	18.3 ± 0.12	14.2 ± 0.05 ^{b}	99.5 ± 0.32	0.0 ± 0.00	84.1 ± 1.79 ^{a}
AT	2.43 ± 0.01 ^{b}	1.21 ± 0.01 ^{ab}	49.7 ± 0.49 ^{a}	1.01 ± 0.01 ^{a}	18.3 ± 0.11	14.3 ± 0.14 ^{ab}	99.2 ± 0.80	0.2 ± 0.11	75.0 ± 1.84 ^{ab}
CN1	2.74 ± 0.06 ^{a}	1.28 ± 0.02 ^{a}	46.7 ± 0.60 ^{b}	1.00 ± 0.01 ^{a}	18.8 ± 0.15	14.7 ± 0.07 ^{a}	100.0 ± 0.00	2.0 ± 2.00	76.8 ± 4.15 ^{ab}
CN2	2.23 ± 0.04 ^{c}	1.01 ± 0.02 ^{c}	46.7 ± 0.36 ^{b}	0.96 ± 0.01 ^{ab}	18.3 ± 0.13	14.0 ± 0.11 ^{b}	98.6 ± 1.40	1.1 ± 1.12	63.7 ± 4.75 ^{b}
Stat	***	***	***	**	ns	**	ns	ns	**

Results from ANOVA analysis for each year are expressed by the symbols: ^{ns} $p > 0.05$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p < 0.001$. Mean values followed by the same letter in the column for the same year did not differ at $p \leq 0.05$ according to Tukey's HSD test.

Table 6. Two-way ANOVA for carpological traits (Mean ± SE; 16 replicates per year and 12 per site).

Year/Site	Nut Weight g	Kernel Weight g	Percent Kernel %	Shell Thickness mm	Nut Caliber mm	Kernel Caliber mm	Kernel Caliber > 12 mm %	Doubles %	Good Kernels %
Year									
2022	2.24 ^{b}	0.95 ^{c}	44.21 ^{b}	1.18 ^{a}	17.53 ^{c}	12.11 ^{b}	69.50 ^{b}	0.25	94.13 ^{a}
2023	2.44 ^{a}	1.22 ^{a}	47.73 ^{a}	1.04 ^{b}	18.22 ^{b}	14.0 ^{a}	97.58 ^{a}	0.38	91.76 ^{a}
2024	2.54 ^{a}	1.16 ^{b}	47.92 ^{a}	0.97 ^{c}	18.43 ^{a}	14.31 ^{a}	99.31 ^{a}	0.83	74.88 ^{b}
Site									
AL	2.28 ^{b}	1.10 ^{b}	47.69 ^{a}	1.02 ^{b}	17.65 ^{c}	13.32 ^{bc}	88.21 ^{ab}	0.03	91.55 ^{a}
AT	2.26 ^{b}	1.08 ^{b}	46.32 ^{ab}	1.03 ^{b}	17.86 ^{bc}	13.11 ^{c}	79.09 ^{b}	0.21	85.58 ^{b}
CN1	2.79 ^{a}	1.23 ^{a}	44.72 ^{c}	1.13 ^{a}	18.81 ^{a}	13.81 ^{a}	89.21 ^{ab}	1.17	87.58 ^{ab}
CN2	2.30 ^{b}	1.05 ^{b}	47.75 ^{a}	1.08 ^{ab}	17.92 ^{b}	13.66 ^{ab}	98.68 ^{a}	0.54	82.98 ^{b}
Year	***	***	***	***	***	***	***	ns	***
Site	***	***	***	***	***	***	**	ns	***
Year × Site	***	***	***	***	***	***	**	ns	***

Results from ANOVA analysis are expressed by the symbols: ^{ns} $p > 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Different letters in each column for year and site represent significant differences at $p \leq 0.05$ according to Tukey's HSD test.

3.4. Nutritional Status Assessment

The nutritional status of the plants was assessed annually (in 2022, 2023, and 2024) by foliar analysis. Leaves were sampled in mid-June, at the onset of cluster drop. Foliar analysis consistently revealed highly significant differences among orchard sites in nitrogen (N), phosphorus (P), and potassium (K) concentrations (Table S1). Across the three years, the lowest average nitrogen concentration was recorded in the AT orchard (2.21%), which also showed the lowest average potassium concentration (0.98%). In contrast, the CN2 orchard exhibited the highest average potassium concentration (1.49%). The highest phosphorus concentration was observed in the CN2 and CN1 orchards (Table 7). No significant year × site interaction was detected for nitrogen concentration, whereas phosphorus and potassium concentrations were significantly affected by both year and orchard site.

Table 7. Results of foliar analysis performed in mid-June at four sites: mean data per year and site. All analytical values were expressed on a dry matter (DM) basis (Mean ± SE; 16 replicates per year and 12 per site).

Year/Site	N %	P %	K %	Fe mg/kg	Cu mg/kg	Zn mg/kg	B mg/kg	Mn mg/kg
Year								
2022	2.69	0.17 ^{b}	1.21 ^{a}	140.21 ^{a}	70.50 ^{b}	21.39 ^{b}	33.13 ^{b}	128.33 ^{a}
2023	2.70	0.17 ^{b}	1.10 ^{b}	109.23 ^{b}	78.32 ^{a}	29.10 ^{a}	33.88 ^{b}	109.18 ^{b}
2024	2.79	0.20 ^{a}	1.24 ^{a}	123.70 ^{ab}	40.21 ^{c}	29.94 ^{a}	50.48 ^{a}	112.90 ^{ab}
SITE								
AL	2.93 ^{a}	0.15 ^{b}	1.13 ^{b}	121.98	38.35 ^{c}	24.31 ^{b}	76.50 ^{a}	66.66 ^{b}
AT	2.21 ^{b}	0.16 ^{b}	0.98 ^{c}	137.89	115.37 ^{a}	25.33 ^{b}	22.62 ^{c}	29.39 ^{c}
CN1	2.93 ^{a}	0.20 ^{a}	1.13 ^{b}	132.61	11.56 ^{d}	31.47 ^{a}	31.20 ^{b}	354.07 ^{a}
CN2	2.84 ^{a}	0.20 ^{a}	1.49 ^{a}	105.06	86.76 ^{b}	26.13 ^{b}	30.32 ^{bc}	17.10 ^{c}
Year	ns	***	***	*	***	***	***	*
Site	***	***	***	ns	***	***	***	***
Year × Site	***	***	***	*	***	***	*	***

Results from ANOVA analysis are expressed by the symbols: ^{ns} $p > 0.05$, * $p \leq 0.05$, *** $p \leq 0.001$. Different letters in each column for year and site represent significant differences at $p \leq 0.05$ according to Tukey's HSD test.

Micronutrient concentrations showed significant differences among sites over the three years, except for Fe and Zn in 2022 and for Fe in 2023 (Table S1). Two-way ANOVA revealed

no significant effect of orchard site on iron concentration, while highly significant site effects were detected for the other micronutrients. The CN1 orchard showed the highest average concentrations of manganese (354.1 ppm) and zinc (31.5 ppm), the AT orchard had the highest copper concentration (115.4 ppm), and the AL orchard had the highest boron concentration (76.5 ppm; Table 7).

The four orchards showed relevant differences in soil texture (Table 8). AL showed the highest percentage of clay (29.6%) and was classified as silty clay loam soil [28]; CN2 had the highest percentage of sand (66.4%; sandy loam soil), while AT had the highest percentage of silt (63.1%; silt loam soil). CN1 is also classified as silt loam soil but showed a more balanced soil texture. The AL, AT, and CN2 orchards had moderately alkaline soil, while CN1 had neutral soil (Table 9). The highest percentage of active limestone (5.8%) was found in AT, while CN1 had almost no presence of active limestone. The organic matter content was particularly low in CN2 soil (percentage lower than 0.5%), as was the value of the cation exchange capacity (CEC), which was lower than 10 meq/100 g. The soil of the AL orchard was the most fertile, having the highest organic matter content and CEC, as well as a good content of macronutrients (nitrogen, phosphorus, and potassium). The micronutrient content of the four soils is shown in Table S2.

Table 8. Soil Texture classification (WRB FAO system) and percentage of clay, silt, and sand (Mean ± SE of 2022–2023–2024).

Site	Clay (%)	Silt (%)	Sand (%)	Soil Texture Classification
AL	29.58 ± 1.09 ^{a}	56.66 ± 1.03 ^{ab}	13.76 ± 0.32 ^{c}	Silty clay loam
AT	16.93 ± 0.95 ^{b}	63.11 ± 1.89 ^{a}	19.96 ± 1.60 ^{c}	Silt loam
CN1	10.70 ± 1.48 ^{c}	53.01 ± 0.84 ^{b}	36.29 ± 2.30 ^{b}	Silt loam
CN2	8.30 ± 1.07 ^{c}	25.27 ± 2.48 ^{c}	66.43 ± 3.46 ^{a}	Sandy loam
Stat	***	***	***	

Results from ANOVA analysis are expressed by the symbols: *** $p \leq 0.001$. Mean values followed by the same letter in the column did not differ at $p \leq 0.05$ according to Tukey's HSD test.

Table 9. Soil characteristics and main nutrient concentrations of the four investigated orchards (Mean ± SE of 2022–2023–2024).

Site	pH	Active Lime (%)	Organic Matter (%)	CEC (meq/100 g)	C/N	N Total (g/kg)	P Avail. (ppm)	K Exch. (ppm)
AL	7.93 ± 0.06 ^{a}	3.41 ± 0.21 ^{b}	2.09 ± 0.19 ^{a}	24.15 ± 0.84 ^{a}	9.11 ± 0.39	0.13 ± 0.01 ^{a}	9.19 ± 0.32 ^{a}	263.96 ± 28.81 ^{a}
AT	8.22 ± 0.09 ^{a}	5.83 ± 0.06 ^{a}	0.85 ± 0.06 ^{b}	11.69 ± 0.10 ^{b}	8.13 ± 0.84	0.08 ± 0.01 ^{b}	3.51 ± 0.81 ^{b}	128.96 ± 8.01 ^{b}
CN1	6.65 ± 0.34 ^{b}	0.43 ± 0.26 ^{c}	1.66 ± 0.09 ^{a}	12.02 ± 0.49 ^{b}	8.23 ± 0.50	0.12 ± 0.01 ^{ab}	9.02 ± 0.38 ^{a}	102.08 ± 13.96 ^{b}
CN2	8.34 ± 0.05 ^{a}	2.91 ± 0.09 ^{b}	0.32 ± 0.05 ^{c}	7.00 ± 0.93 ^{c}	7.90 ± 2.11	0.02 ± 0.00 ^{c}	3.17 ± 0.29 ^{b}	76.46 ± 13.31 ^{b}
Stat	***	***	***	***	ns	***	***	***

Results from ANOVA analysis are expressed by the symbols: ^{ns} $p > 0.05$, *** $p \leq 0.001$. Mean values followed by the same letter in the column did not differ at $p \leq 0.05$ according to Tukey's HSD test.

3.5. Climatic Data

The main climatic parameters were registered across the three years of the trial. The year 2022 was a very dry year with only 412 mm of precipitation as the average of the four sites (Table 10). AL was the driest site with 333 mm per year and 41 days with rainfall > 1 mm (only 14 in the May–July period). AT was the hottest site, with a yearly mean max temperature of 22.2 °C (36.5 °C during July, with 22 days with temperatures exceeding 35 °C for at least 1 h; Table S3), together with the lowest maximum relative humidity (84.5%), especially during July (80.2%, Table S3). On the contrary, CN1 was the wettest site with 522 mm (224 mm during May–July with 20 wet days), and the coolest,

with the mean maximum temperature during the May–July period and only 3 days with temperatures > 35 °C.

Table 10. Climatic parameters registered in the four investigated orchards during the three years of the trial: sum of rainfall, wet days (>1 mm) and critical days (1 h > 35 °C), and averages of temperature and relative humidity for each year and for the May–July period of every year.

Period of Time	Site	Rainfall mm	Wet Days No.	T Min Mean °C	T Mean °C	T Max Mean °C	Critical Days No.	RH Min Mean %	RH Mean %	RH Max Mean %
Year 2022	AL	332.6	41	9.0	14.5	21.0	19	53.2	73.1	91.5
	AT	389.0	51	10.0	15.3	22.2	35	48.2	68.5	84.5
	CN1	522.0	60	7.7	13.4	20.3	4	29.2	53.8	97.0
	CN2	402.6	50	7.1	13.0	20.6	15	29.1	76.8	94.5
	Mean/Sum	**411.6**	**50.5**	**8.5**	**14.1**	**21.0**	**18.3**	**39.9**	**68.0**	**91.9**
May–July 2022	AL	104.4	14	16.6	23.1	30.1	13	42.7	66.8	89.8
	AT	177.0	18	17.3	23.9	31.9	26	39.0	61.7	81.6
	CN1	224.0	20	15.7	22.3	29.4	3	22.6	44.7	95.1
	CN2	170.6	17	14.5	21.1	29.7	11	21.0	72.9	92.3
	Mean/Sum	**169.0**	**17.3**	**16.0**	**22.6**	**30.3**	**13.3**	**31.3**	**61.5**	**89.7**
Year 2023	AL	417.4	57	8.8	14.3	21.0	21	54.7	76.8	92.6
	AT	527.2	62	9.7	14.6	21.2	20	51.0	71.8	87.3
	CN1	972.6	75	7.6	13.2	20.2	4	51.5	77.4	95.6
	CN2	643.2	62	7.1	12.9	20.4	13	53.6	78.7	95.0
	Mean/Sum	**640.1**	**64.0**	**8.3**	**13.7**	**20.7**	**14.5**	**52.7**	**76.2**	**92.6**
May–July 2023	AL	173.6	24	15.9	21.8	28.5	10	50.9	73.3	92.2
	AT	231.8	26	16.1	21.6	28.3	9	51.1	71.7	88.0
	CN1	553.4	33	14.4	20.1	26.7	0	56.0	79.0	94.7
	CN2	354.4	26	13.4	19.2	26.4	1	59.7	80.3	93.7
	Mean/Sum	**328.3**	**27.3**	**15.0**	**20.7**	**27.5**	**5.0**	**54.4**	**76.1**	**92.1**
Year 2024	AL	994.6	83	9.3	13.9	19.9	0	58.1	77.7	90.9
	AT	990.2	86	9.9	14.3	20.2	8	53.9	74.2	88.7
	CN1	1119.2	90	7.9	13.0	19.5	0	58.2	81.7	97.1
	CN2	1024.6	74	7.6	12.7	20.1	11	56.4	83.3	97.6
	Mean/Sum	**1032.2**	**83.3**	**8.7**	**13.5**	**19.9**	**4.8**	**56.7**	**79.2**	**93.6**
May–July 2024	AL	234.6	25	15.7	20.7	26.5	0	54.1	72.8	87.7
	AT	187.0	23	15.7	20.4	26.1	2	55.0	74.1	88.6
	CN1	335.2	28	14.2	19.9	26.3	0	55.6	80.6	98.9
	CN2	182.0	15	13.2	18.7	26.8	3	57.0	84.4	98.6
	Mean/Sum	**234.7**	**22.8**	**14.7**	**19.9**	**26.4**	**1.3**	**55.4**	**78.0**	**93.5**

The year 2023 was also less rainy than usual, except for the CN1 site (973 mm). AL was the driest site (417 mm) and AT the hottest (T mean max temperature of 21.2 °C) like in 2022. Rainfall was abundant in May at all the sites, with 130 mm of rainfall recorded in June for the two orchards in CN province (CN1 and CN2, Table S3). July was the hottest month, with mean maximum temperature > 30 °C at all sites, although days with temperature > 35 °C for at least 1 h were registered only in the AL and AT orchards (8 days in both of them).

Rainfall was higher in 2024 than in the previous years (1032.3 mm and 83 days with rain), with lower mean temperatures (ranging from 12.7 to 14.3 °C as the annual average). Rainfall was abundant in May (>100 mm of precipitation) and still present in the period June–July (nut development), with the lowest number of wet days in the CN2 orchard (15 days). The months from May to July were cooler than in 2022 and 2023, since maximum mean temperatures exceeded 30 °C only in July (Table S3), with a few days with temperatures > 35 °C (2 days in AL and 3 days in the CN2 orchards).

3.6. Investigation on Candidate Factors Involved in Early Nut Drop

A PCA analysis was performed as an exploratory investigation aimed at identifying environmental and nutritional conditions associated with variability in hazelnut %END and yield. Data recorded to characterize the four orchards for climate conditions (temperature, precipitation, relative humidity), soil parameters (texture, macro- and micronutrient content, pH, active lime%, CEC, SOM, C/N), and plant nutritional status (macro- and micronutrient content from leaf analysis) were used in the PCA. The PCA extracted five principal components with eigenvalues > 1, cumulatively explaining 88.1% of the total variance. The first two components accounted for 54.4% of the variance (PC1 = 28.0% and PC2 = 26.4%), while PC3 captured an additional 16.2%, followed by PC4 (12.8%) and PC5 (4.8%). A multiple linear regression analysis was performed using the five extracted PCA factor scores as independent predictors to estimate the percentage of early nut drop (%END) and yield (Y).

The regression model for %END was statistically significant (F (5, 42) = 10.61, $p < 0.001$), accounting for 55.8% of the total variance (Adjusted R^2 = 0.505, Table 11). Among the five predictors, REGR Factor score 2, representing mainly soil characteristics, exerted a strong and significant negative effect on the response variable (β = −0.63, t = −6.18, $p < 0.001$). On the contrary, REGR Factor score 3, associated with climate variables, showed a significant positive contribution (β = 0.32, t = 3.09, $p = 0.004$). REGR Factors 1, 4, and 5 did not show any statistically significant influence ($p > 0.05$).

Table 11. Multiple linear regression results using PCA factor scores to predict early nut drop percentage (%END).

	β	Std. Error	Stand. β	t-Value	*p*-Value
Constant	26.112	2.04		12.799	<0.001
REGR Factor score 1	−0.907	2.062	−0.045	−0.44	0.662
REGR Factor score 2	−12.732	2.062	−0.633	−6.176	<0.001
REGR Factor score 3	6.373	2.062	0.317	3.091	0.004
REGR Factor score 4	3.899	2.062	0.194	1.891	0.066
REGR Factor score 5	2.594	2.062	0.129	1.258	0.215

Model diagnostics: R^2 = 0.558; adjusted R^2 = 0.505; F = 10.61; $p < 0.001$.

The regression model for yield was statistically significant (Table 12). REGR Factor scores 1 and 2, both explaining soil characteristics, exerted a significant positive effect (β = 0.45 and 0.5, respectively), while REGR Factor score 3 showed a negative contribution (β = −0.30, t = −3, $p = 0.007$). Again, REGR Factor scores 4 and 5 did not show any statistically significant influence ($p > 0.05$).

Table 12. Multiple linear regression results using PCA factor scores to predict yield.

	β	Std. Error	Stand. β	t-Value	*p*-Value
Constant	4488	224.163		20	<0.001
REGR Factor score 1	987.018	227	0.453	4357	<0.001
REGR Factor score 2	1096	227	0.503	5	<0.001
REGR Factor score 3	−638	227	−0.293	−3	0.007
REGR Factor score 4	112	227	0.052	0	0.623
REGR Factor score 5	−25	227	−0.012	0	0.912

Model diagnostics: R^2 = 0.546; adjusted R^2 = 0.492; F = 10.12; $p < 0.001$.

PC1 and PC2 mainly explain soil characteristics and nutritional parameters (Figure 2 and Table 13). PC1 showed high positive loadings for cation exchange capacity (CEC, r = 0.98), percentage of clay (r = 0.94), soil organic matter (SOM, r = 0.79), available

potassium (K_SOIL), calcium (Ca_SOIL) and boron (B_SOIL) content had the highest effects (r = 0.92, 0.94 and 0.95, respectively), as well as for the boron content in leaves (B_LEAF, r = 0.86). Regarding soil texture, the presence of clay had a positive effect (r = 0.94) and sand a negative effect (r = −0.71). On PC2, soil pH (r = −0.92) and active lime (ACT_LIME, r = −0.83) exhibited strong negative loadings, as well as the copper content in leaves (Cu_LEAF, r = −0.64). On the contrary, phosphorus (P_LEAF, r = 0.74), iron, manganese, and zinc content (r > 0.88) loaded in the positive direction, as well as Mn_LEAF (r = 0.96). Among climate variables, the amount of rainfall showed a positive loading (r = 0.57).

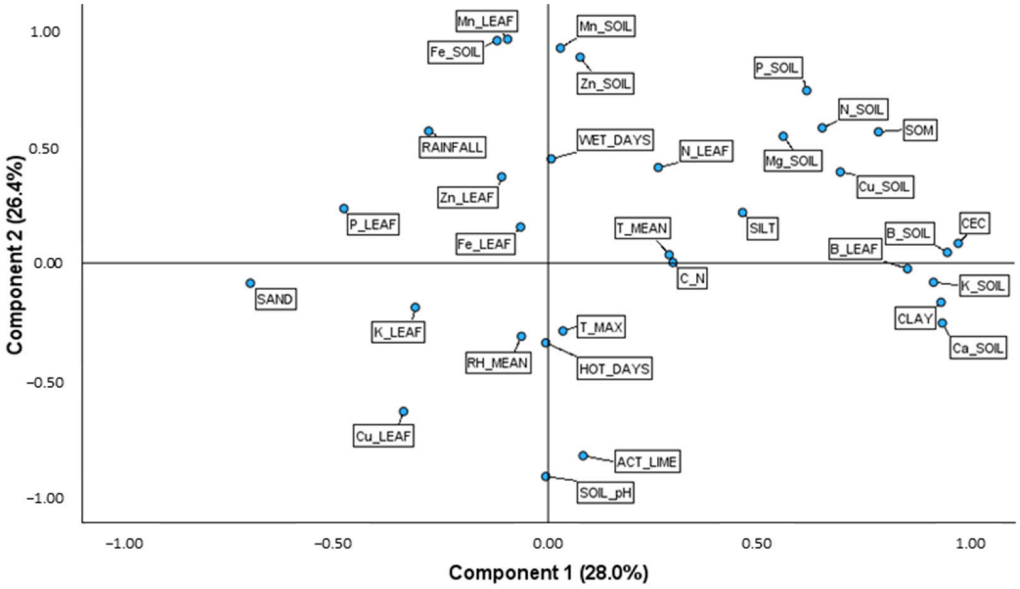


Figure 2. Loading plot for PC1 and PC2 (climate, soil, and plant variables).

Table 13. Rotated component matrix (varimax with Kaiser normalization) from PCA (components 1, 2 and 3). Climatic variables refer to the May–July period. Loadings >0.50 are reported in bold.

Code	Variable	Component 1	Component 2	Component 3
RAINFALL	Rainfall	−0.285	**0.566**	**0.608**
WET_DAYS	Number of Wet Days (>1 mm)	0.007	0.447	**0.678**
T_MEAN	Average Mean Temperature	0.288	0.036	**−0.841**
T_MAX	Average Maximum Temperature	0.035	−0.291	**−0.919**
HOT_DAYS	Number of Critical Days (T > 35 °C)	−0.006	−0.342	**−0.741**
RH_MEAN	Average Mean Relative Humidity	−0.064	−0.314	**0.782**
CLAY	Soil Percentage of Clay	**0.936**	−0.168	−0.099
SILT	Soil Percentage of Silt	0.463	0.217	−0.142
SAND	Soil Percentage of Sand	**−0.710**	−0.086	0.141
SOIL_pH	Soil pH	−0.006	**−0.915**	−0.202
CEC	Soil Cation Exchange Capacity	**0.977**	0.085	−0.056
SOM	Soil Organic Matter Percentage	**0.787**	**0.563**	−0.097
C_N	Soil Carbon/Nitrogen Ratio	0.297	0.003	0.013
ACT_LIME	Soil Active Limestone Percentage	0.083	**−0.826**	−0.224
N_SOIL	Soil Nitrogen	**0.653**	**0.580**	−0.273
P_SOIL	Soil Phosphorus	**0.616**	**0.740**	−0.17
K_SOIL	Soil Potassium	**0.918**	−0.082	−0.122
Ca_SOIL	Soil Calcium Exchangeable	**0.939**	−0.257	−0.07

Table 13. *Cont.*

Code	Variable	Component 1	Component 2	Component 3
Mg_SOIL	Soil Magnesium Exchangeable	**0.560**	**0.544**	0.269
Fe_SOIL	Soil Iron Assimilable	−0.122	**0.954**	0.184
Mn_SOIL	Soil Manganese Assimilable	0.029	**0.922**	0.158
B_SOIL	Soil Boron Soluble	**0.951**	0.046	−0.196
Cu_SOIL	Soil Copper Assimilable	**0.696**	0.391	−0.043
Zn_SOIL	Soil Zinc Assimilable	0.076	**0.883**	0.361
N_LEAF	Leaf Nitrogen	0.262	0.41	0.129
P_LEAF	Leaf Phosphorus	−0.487	0.234	0.471
K_LEAF	Leaf Potassium	−0.317	−0.190	0.078
Fe_LEAF	Leaf Iron	−0.066	0.155	−0.348
Mn_LEAF	Leaf Manganese	−0.097	**0.960**	−0.01
Zn_LEAF	Leaf Zinc	−0.111	0.37	**0.802**
Cu_LEAF	Leaf Copper	−0.345	**−0.636**	−0.18
B_LEAF	Leaf Boron	**0.856**	−0.024	0.135

PC3 is mainly related to the climate variables measured in the May–July period (Figure 3 and Table 13): it showed high positive loadings for rainfall (r = 0.61), wet days (r = 0.68) and relative humidity (RH_MEAN, r = 0.78), and negative loadings for mean temperature (T_MEAN, r = −0.84), maximum mean temperature (T_MAX, r = −0.92) and number of days with temperatures higher than 35 °C (HOT_DAYS, r = −0.74). The only nutritional parameter related to PC3 was Zn_LEAF (r = 0.80) with a positive loading.

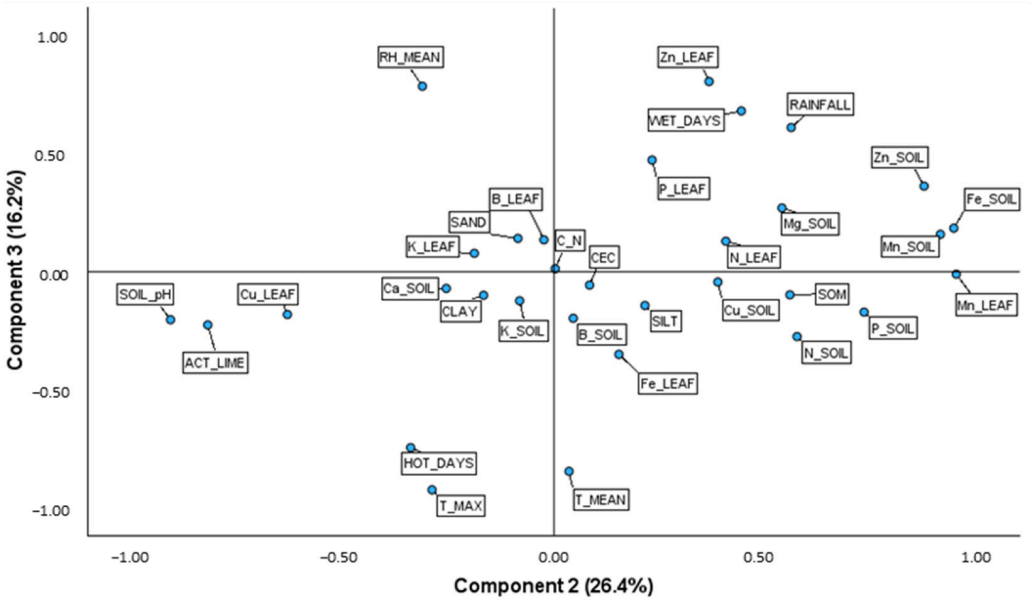


Figure 3. Loading plot for PC2 and PC3 (climate, soil and plant variables).

4. Discussion

The four orchards of 'TGT' investigated in Piedmont showed substantial variation in nut loss among sites and years. Early nut drop was observed from June onwards, consistent with previous studies [6,7]. However, in our study, %END also includes nuts without a developed kernel that fell during harvest. The index therefore combines premature abscission with a later component of seed development failure. Furthermore, %END expresses loss by nut number; thus, comparison with published loss estimates requires caution since the literature presents data on other cultivars and evaluates cluster drop rather than %END. In Turkish hazelnuts, cluster drop values ranged from 14 to 19% between early

June and early August [6], while cluster drop was classified as slight (<10%), intermediate (10–20%), or severe (>20%) in Italian and Slovenian cultivars [7]. However, cluster-based percentages cannot be equated with our individual-nut index, which was nut-based and includes late-falling nuts without developed kernels.

In our study, prolonged drought and high June–July temperatures observed in 2022 coincided with %END of 3.2–21.7% and higher average marketable yield than in the following years (Tables 2 and 3). Nevertheless, the proportion of kernels exceeding 12 mm was lower than in 2023–2024 in AL and CN1 but, above all, in AT, where it dropped to 44%; CN2 retained a high proportion throughout (Table 5). In dropped-nut samples from AL and AT, partially developed kernels represented approximately one quarter of the nuts examined in 2022 and were less frequent subsequently. This is probably the result of the heat and drought stress of the year. Nuts without a seed or with an aborted seed together accounted for approximately 77–92% of these samples in 2023–2024 (Table 4). The higher rainfall and generally milder May–July temperatures in 2023–2024 coincided with higher average %END, indicating that contemporaneous heat and drought alone cannot explain the temporal pattern.

In 2023–2024, the incidence of early nut drop increased, in particular in the AT orchard (64.9 and 58.1%, respectively, in 2023 and 2024), where productivity also remained consistently low (Table 2), whereas the marked increase in CN2 occurred mainly in 2024. Although both occupy gently sloping hilly terrain, they differ in elevation, soil texture, percentage of active limestone, nutritional status, and climatic exposure (Tables 1 and 7–10). AT had higher active limestone and lower averages of N, P, K, and B in leaves; CN2 had a much sandier soil, lower SOM, and lower CEC. CN2 also produced fewer total nuts. AT had the lowest proportion of good kernels in 2023, whereas CN2 had the lowest value in 2024 (63.7%; Table 5). The site × year interaction reinforces the need to consider these distinct trajectories.

The PCA and regression analyses summarize these patterns through combinations of variables potentially associated with %END. Among the five retained components that accounted for 88.1% of predictor variance, PC2 had the largest absolute standardized coefficient for %END ($\beta = -0.633$), followed by PC3 ($\beta = 0.317$), while PC1, PC4, and PC5 were not statistically significant in the reported model (Table 11). According to PC2, %END was negatively associated with leaf Mn and higher soil availability of Fe, Mn, and Zn, but positively correlated with higher soil pH, active limestone, and leaf Cu (Table 13). PC1, associated mainly with CEC, clay, SOM, and several soil nutrients, was positively associated with yield but not significantly associated with %END (Tables 11–13). PC3 combined higher rainfall, more wet days, and higher relative humidity with lower temperatures during the May–July period. Its positive coefficient for %END therefore indicates an association with wetter, cooler conditions. These component-level associations do not establish independent effects of individual nutrients or climatic factors.

The 2022 observations are compatible with limitations during kernel filling, which normally occurs in June and July in 'TGT' [22]. The sensitivity of 'TGT' stomata and carbon assimilation to atmospheric vapor pressure deficit provides a physiological basis for this hypothesis [14]. Seasonal resource allocation may also connect reproductive performance with current assimilation and stored reserves. Preliminary hazelnut observations show declines and recovery in shoot non-structural carbohydrates (NSCs), including a decline during nut growth [13]. Together with the literature on alternate bearing [29,30], this suggests a possible contribution of previous crop demand. However, reserve depletion following 2022 or a carry-over effect of that year's stress can therefore be assumed but not demonstrated without physiological measurements, and three seasons are not enough to establish an alternate-bearing cycle.

The predominance of blanks and aborted seeds in the AL and AT samples in 2023–2024 warrants consideration of earlier reproductive processes, without implying that every blank resulted from embryo abortion. Hazelnut winter pollination is followed by delayed ovule development, fertilization, and kernel growth. While pollination is necessary to initiate ovary development, fertilization is necessary for the formation of normal nuts with embryos. Full-size nuts that are empty at maturity result from pollination without fertilization, or embryo abortion [31]. In *C. heterophylla*, studies linked blank formation to embryo abortion [4], while genomic and anatomical observations in blank-nut mutants identified candidate changes involving embryo development and starch accumulation [32]. These findings connect reproductive development with carbohydrate metabolism, but their transfer to field-grown *C. avellana* requires caution.

Nutritional differences offer further candidate explanations. PC2 associates lower %END with greater soil Fe, Mn, and Zn availability and higher leaf Mn, while leaf Cu lies at the opposite end of this component. Leaf Zn loads mainly on PC3, positively associated with %END, and cannot therefore be described as reducing drop. Previous work found differences in leaf nutrient status among cluster-drop categories [7], but cultivars, soils and sampling dates differ. Lower average leaf B in AT and the association of the B-rich PC1 with yield suggest a possible nutritional contribution without demonstrating a B-specific response.

The soil contrasts also need to be interpreted jointly. AL combined higher SOM and CEC with high productivity, whereas CN2 had the lowest SOM, CEC, and three-year mean yield (Tables 3 and 10). CN1 maintained the lowest %END despite a CEC similar to AT; its lower pH, active limestone, and higher availability of several micronutrients correspond to PC2. These associations are consistent with a contribution of soil and nutritional conditions to reproductive performance, but no single soil property explains the orchard ranking.

Climate may act differently across reproductive stages. Silva et al. [8] associated higher blank-fruit incidence with higher May rainfall and relative humidity in 'Butler', showing that wetter conditions need not coincide with improved reproductive success. Our regression model indicates that rainfall may exert both beneficial effects on yield and detrimental effects on %END, depending on its distribution. Well-distributed rainfall during kernel development promotes yield, whereas rainfall concentrated during the fertilization period and associated with low temperatures may promote brown stain, a physiological disorder associated with blank nut formation [8,33,34]. Brown stain was not quantified here and cannot explain the 2024 increase on the available evidence. Conversely, limitations to kernel filling remain plausible in 2022.

Overall, the three-year comparison characterizes spatial and temporal variation in nut losses in 'TGT' and brings together soil, nutritional and climatic information within a common analytical framework. The multivariate patterns highlight combinations of orchard conditions associated with %END and help explain why individual environmental indicators alone do not capture the observed variability. Within this observational comparison of four orchards, these relationships provide a basis for developing and prioritizing physiological hypotheses. Further replicated studies linking orchard conditions with carbohydrate dynamics, water status, and reproductive development would help clarify the mechanisms involved and evaluate management options for improving reproductive performance.

5. Conclusions

This three-year study documents substantial variation in nut losses in *Corylus avellana* cv. 'TGT' among four non-irrigated orchards and across seasons. Integrating field observations with soil, leaf, and climatic measurements identified potentially relevant associations with %END. A component characterized by higher soil pH and active limestone and lower

availability of several micronutrients was associated with higher %END; a component representing wetter and cooler May–July conditions was also positively associated with %END in the reported model.

These findings highlight the value of considering soil and nutritional status together with the timing of climatic conditions when interpreting reproductive performance. The contrasting seasonal patterns of nut loss and kernel filling also point to the importance of distinguishing developmental stages and of examining carbohydrate allocation and reproductive processes in future investigations.

The associations identified here provide a basis for selecting management practices for evaluation in replicated trials, alongside canopy management and physiological monitoring, to develop strategies for stabilizing 'TGT' productivity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae12111436/s1, Table S1: Results of foliar analysis performed in mid-June at four different sites for the years 2022–2023–2024; Table S2: Soil micronutrient concentrations of the four investigated orchards in 2022–2023–2024; Table S3: Climatic parameters detected during May to July in the years 2022–2023–2024.

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