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Variations in pod detachment forces in *Arachis hypogaea* forecast the most suitable conditions for mechanical harvesting

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ABSTRACT

Peanut cultivation is regaining interest in Italy due to its agronomic and nutritional value, but profitable production requires well-defined practices that ensure efficient harvesting. In this context, one of the most affordable approaches for mechanised harvesting involves a two-phase process: first, plants are dug from the soil and left drying naturally, then pods are separated from vines. In this perspective, it remains crucial to investigate whether morphological traits of the plant affect the detachment forces between pods, peduncles, and vines, which influence harvest losses. The study investigated the effects of two planting densities and inoculation with Azotobacter spp. bacteria on yield, maturation, and detachment forces. Relevant morpho-physiological traits were sampled along the maturation phase, and A multivariate analysis of variance was performed to identify the variables most associated with tensile resistance . In addition, the productivity of the harvesting system was assessed, with particular attention to field losses. Results showed that pod moisture and peduncle length were correlated with pod-peduncle detachment forces. The peduncle-vine connection showed greater resistance than the pod peduncle one, indicating strong pod–vine attachment during digging but reduced resistance during separation, which facilitated efficient kernel separation. The application of Azotobacter spp. did not significantly affect yield or detachment forces. Average harvesting efficiency reached 85 %, although losses were greater in high-density traits. These findings contribute to defining harvest timing and crop management strategies suitable for Italian environments where peanut production is being reintroduced.

Science4Impact Statement (S4IS)

This study provides quantitative evidence on the temporal variation of pod detachment forces in *Arachis hypogaea*, demonstrating how moisture content decrease, plant morphology and agronomic management influence tensile resistance. The field measurements were conducted under optimal agronomic conditions and through standardized and scalable protocols, ensuring data robustness for further technology assessment. The results offer operational benchmarks to support manufacturers to develop new experimentation protocols for peanut harvesting and to enhance the working efficiency. At the regional scale, the findings inform decision-making processes for reintroducing peanut cultivation in Italy, fostering a more sustainable and locally integrated supply chain through evidence-based cultivation scale.

1. Introduction

Global peanut (*Arachis hypogaea L.*) production in 2023 reached 54 million t, with China and India as the main producers [1]. The crop is cultivated both for oil extraction and as a protein source [2,3]. Peanuts are rich in beneficial fatty acids—40 g of unsaturated fatty acids per 100 g of product—contributing to their high nutritional value [4]. The peanut productivity is influenced by complex interactions between

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physiological traits, agronomic practises, and the environment, leading to breeding efforts to enhance crop productivity [5]. The cultivation is experiencing the transition towards sustainable cultivation methods, including optimised nitrogen fertilisation in combination with nitrogen-fixing bacteria application [6] and improved water management strategies [7]. In the mechanisation context, machinery efficiency and the application of precision agriculture from sowing to post-harvest are also evaluated [8]. Moreover, as a legume, peanut may be inoculated with *Azotobacter* spp., improving crop yield and reducing fertilizer requirements [9,10].

Peanut imports reached 46 353 t in 2024 in Italy [11]. Here, the cultivation is experiencing renewed interest after decades of decline, since the cultivated area increased from 48 ha in 2020 to 203 ha in 2023 [12]. The most recent research on Italian peanuts cultivation focused on many aspects: firstly, the development of viable techniques for harvesting mechanisation, indicated as the most limiting factor for the expansion of the crop cultivation at the national level [13]. Other key research topics are the reduction of aflatoxin biosynthesis under cultivation environments with simulated climate change conditions [14] and the effect on yield from the interaction between irrigation and biostimulant application [5]. In addition, peanut crop biomass has also been investigated as a novel feed resource for livestock [15]. This is an indication of the potential of peanut cultivation in areas characterised by intensive livestock farming like Campania Region, in Southern Italy [16]. Unlike most angiosperms, peanuts develop their pods underground via a specialised structure called a peg (or gynophore), which carries the fertilised ovary into the soil where pod development occurs [17]. Consequently, the efficiency of the two-phase harvesting is influenced by the tensile forces connecting pods, peduncles and plant vines [18]. In fact, the magnitude of the detachment forces is correlated to field losses during harvesting operations [19]. Despite quantitative data being available for these aspects [20], their temporal variation and the influence of agronomic practices remain poorly understood. In addition, no studies have jointly quantified peduncle moisture content, detachment forces and other plant morphological traits throughout the maturation period of field-grown peanuts, nor assessed their combined implications for mechanised harvesting.

The current study assesses the effectiveness of a two-phase peanut harvesting system under different agronomic condition. Two planting densities and the application of nitrogen-fixing bacteria served as experimental treatments. Their effects on yield and on the forces required to detach pods from peduncles and peduncles from vines were evaluated. These parameters were then analysed considering the physiological and morphological characteristics of the peanut plant. Finally, the work productivity was evaluated in combination with production losses.

2. Materials and methods

2.1. Experimental design

Field trials were conducted at the “Arca 2010″ experimental farm (40°57′59’’N 14°25′44’’E, altitude of 28 m) in the municipality of Acerra, Italy. The local climate is Mediterranean, with average temperatures in the period 2003–2023 of 17.2 °C and average rainfall of 846.8 mm y^{-1} [21]. The Bulgarian variety *Arachis hypogaea* L. *cv. 'Lotus'* was chosen for the current experiment. This *cv.* is suitable for two-phase mechanised harvesting with satisfactory harvesting efficiency [13]. A randomised block design with 4 treatments and 4 replicates was adopted, combining two planting densities (HD – high density, LD – low density) and the application of *Azotobacter* spp. Bacteria (AZ – application, NOAZ – no application). Each block contained six rows. For the HD and LD treatments, planting densities of 19.0 plants m^{-2} and 13.3 plants m^{-2} were adopted, respectively. Soil analysis were performed prior to seedling, resulting in: texture = sandy-loam, pH = 7.5, organic matter = 3.3 %, total Nitrogen = 1.7 g/Kg (0.17 % w/w), P_2O_5 = 201 ppm, K_2O = 1680 ppm. Sowing was carried out manually in the first decade of June at a depth of 2 cm. Two *Azotobacter spp.* applications by foliar application occurred in August and September with a dose of 300 g ha^{-1} of compound in the AZ treatments. Additional field operations were: 1) 3 biostimulant applications between August and September (“Atmo-N”, Agritec srl, Benevento, Italy, dose of 3 l ha^{-1}); 2) Pest control with 2 applications of Deltamethrin in August and September, one application of Azoxystrobin in September and one application of *Bacillus Amyloliquefacens* to prevent crop damage caused by the pest *Rhizoctonia Solani;* 3) 6 sprinkler irrigations with an average volume of water applied of 28.7 m^3 ha^{-1} . Furthermore, both mechanical and hand-held weed management were applied to reduce weed infestation, particularly *Portulaca Oleracea* L. The digging step was performed 130 days after sowing with an Inverter Collector machine (model ‘Miac C200’ Colombo S.A., Sao Paulo, Brazil) on October 17, followed by the peanut pods separation from the plants on October 22 with a Bean Harvest Combine machine (Model ‘Double Master II’, Colombo S.A., Sao Paulo, Brazil).

2.2. Samplings

The sampling methodology followed periodic field measurements. The plant roots were conceptually divided into three vertical sections (A, B, C, Fig. 1), aiming to monitor the variability of the experimental parameters in relation to the morphology of the productive structures. Section A included pods attached to the root from the crown until 7 cm of length, section B and C ranged from 7 to 14 cm and from 14 cm until the root edge, respectively . The effective plant density (P, plants m^{-2}) was assessed. Then, six plants were randomly sampled per plot. The height of the plants (H, cm) was measured using a professional measuring tape. For each plant and root section, the average force required to remove pods from peduncles (F_1, g) and peduncles from roots (F_2, g) was measured on five randomly sampled pods and peduncles. Similarly, the average peduncle length (LP, cm) was recorded with the same professional meter. In addition, the number of pods per plant (NP) and seeds per pod (SP) were determined by collecting all the pods

Fig. 1. Graphic representation of the peanut roots in relation to the subdivision into the three productive sections (A,B,C).

from each plant without damage or quality deterioration. The samples were stored in labelled paper bags and transported to the Agriculture Engineering Laboratory of the Agricultural Sciences Department of the University of Naples Federico II (Portici, Naples, Italy) for further analysis. The average pod weight per plant (PW, g plant^{-1}) was measured with a precision scale (Mettler PC 16, Mettler Toledo, Milan, Italy). Yield (Y, t ha^{-1}) was calculated by multiplying PW by plant density. For each treatment and root section, fresh weights of pods and peduncles were recorded. The samples were dried at 105 °C for 24 h and weighed again to determine the dry weight. Moisture content was then calculated for both pods (MC_1, % w/w) and peduncles (MC_2, % w/w). Finally, an additional field sampling was performed. In any experimental trait, plant samples were collected from subplots 6.5 m^2 wide to separate and weigh all the commercial pods to determine the parcel yield (PY, Kg). For each treatment 4 replicants were executed.

During both harvesting phases, the working time of the machines was recorded using a professional stopwatch ('RSpro', RS Italia, Italy**)**, following the methodology established by the *Commission Internationale de l'Organisation Scientifique du Travail en Agriculture* (CIOSTA), widely adopted in agricultural engineering research [13]. The working time was divided into Effective Time (ET, mm:ss), concerning the operative phase representing active machine operation, and Accessory Time (AT, mm:ss**)**, related to machine movements not involving active operations (e.g., turning between rows). Their sum resulted in the Operative Time (OT mm:ss). In addition, losses during digging (L_1, kg ha^{-1}) were estimated by collecting commercially valuable pods left on the soil surface, while losses during separation (L_2, kg ha^{-1}) were evaluated by collecting pods within the top 15 cm of soil. For each plot, field surfaces of 1.5 m^2 were sampled after machine passage. All collected samples were labelled and weighed at the Agricultural Engineering Laboratory. Total losses (L_{tot}, kg ha^{-1}) were calculated by summing L_1 and L_2. The operative yield (EY, t ha^{-1}) was then determined by subtracting L_{tot} from the gross yield (Y). Harvest efficiency (E, %) was calculated for each experimental plot following Eq. (1). Field capacity was subsequently determined using Eq. (2).

$$E = \frac{Y - Ltot}{Y} \tag{1}$$

$$Fc = \frac{w\cdot}{Es}0.1 \tag{2}$$

Where Fc the field capacity (ha h^{-1}), s the field speed (km h^{-1}), w the implement working width (m), equal to 1.5 m, and E is the field efficiency, decimal.

2.3. Statistical data analysis

To improve the robustness of the statistical analyses, outliers were identified and removed using the Interquartile Range (IQR) criterion. For each variable, values lying either below the first quartile or above the third quartile, applying the 1.5 × IQR threshold, were considered anomalous and excluded. Then, Principal component analysis (PCA) was performed using the free PAST software, version 4.03 [22] to determine the agronomic factors determining variations in the sample and their relative contributions. The raw data set for the PCA includes all sampled numerical variables (MC1, MC2, LP, SP, P, PW, Y, NP, L2, L1, F1, F2,). In the post-processing phase, the PCA results were grouped by choosing three factors (treatments, sampling dates, plant section) to obtain a useful visual representation of the raw data . Subsequently, a 50–50 multivariate analysis of variance (MANOVA) procedure was performed [23,24], a generalised multivariate ANOVA method based on PCA of standardised data, with the same set of variables adopted for PCA analysis. Both analysis were conducted using R software, version 4.5.0 [25]. MANOVA was conducted to detect significant differences between the agronomic aspects and morpho-physiological characteristics of peanut plants, considering further factors: AZ/NOAZ treatment, planting density, F_1, F_2, and their interactions. Corrected P values were obtained using rotation tests based on 99,999 simulated data sets. The contribution of the variables was extracted for each rotation test [26]. Finally, a one-way ANOVA analysis was performed between the most relevant variables with Tukey post-hoc test to assess any significant differences ($p < 0.05$).

3. Results

3.1. Statistical analysis

3.1.1. PCA

A PCA was conducted by filtering the data based on the four treatments (HD, LD, AZ, NOAZ) (Fig. 2a), the sampling date (Fig. 2b), and the plant section (Fig. 2c). PC1 contributed to 35.64 % of the total variance in correlation. Counting the contribution for PC2 (14.32 %) and PC3 (9.47 %), 59.43 % of the variance is explained by the first three PCs. These results suggest that many agronomic factors should be considered when evaluating peanut maturation and its relationship to mechanical harvesting. In Fig. 2a, along the first axis (PC1), observations from low-density (LD) plots are positioned on the right (positive) side of the graph, whereas those from high-density (HD) plots lie on the negative side. Considering the contribution of agronomic and morpho-physiological variables (loadings; vectors in Fig. 2a), the increase in planting density is mainly positively correlated with Y and P and inversely correlated with PW, NP, and losses, highlighting that yield differences discriminate a large part of the variability without any impact from the AZ–NOAZ factor. This evidence suggests that all parameters related to peanut productivity in PC1 are relevant for discriminating variability in the sampled data, highlighting differences in crop yields between treatments.

By plotting PC2-PC3 (Fig. 2b) based on the sampling date, the last sampling date, closest to the harvesting operations, defines an independent cluster and, in relation to the loadings, is positively correlated with losses and negatively correlated with moisture content. It can be predicted that the MC of the plant followed a relevant path during the ripening phase; therefore, it will be carefully considered for the analysis of harvesting performance. In Fig. 2c, where the data were sorted according to the three sections of the peanut root, no relevant clusters were determined, demonstrating that the role of the root section in subsequent analyses is irrelevant. Overall, PCA suggests that yield, moisture content, and maturation time should be considered when studying the mechanical properties of peanut pods in relation to harvesting performance.

3.1.2. MANOVA among the tested variables

The results of the three-way MANOVA are reported in Table 1 and in Table 2, as a function of F_1 and F_2 respectively. The 50–50 MANOVA procedure reported highly significant differences ($P < 0.0001$) considering AZ × PD. The individual factors, including F_1 and F_2, showed highly significant differences ($P < 0.0001$). In particular, the interaction of AZ and PD with F_2 showed highly significant differences ($P < 0.0001$). The AZ × PD time-based rotation test showed highly significant contributions ($P < 0.0001$) to the dependent variables PW, NP, P, Y, L_2, and LP, and relatively significant contributions ($P < 0.01$) to L_1 and MC2. Considering the individual factors, for F_1, the highest significant contributions ($P < 0.0001$) were provided by MC_1, SP, L_1, and L_2. For the AZ × F_2 interaction, the highest significant contribution ($P = 0.00001$) was provided by LP. On the other hand, for the PD × F_2 interaction and the single factor F_2, the rotation test did not report significant contributions.

3.2. Yield

The experimental plots exhibited different productive performances, while no significant differences were found in plant H (with NOAZLD reaching the highest average H).

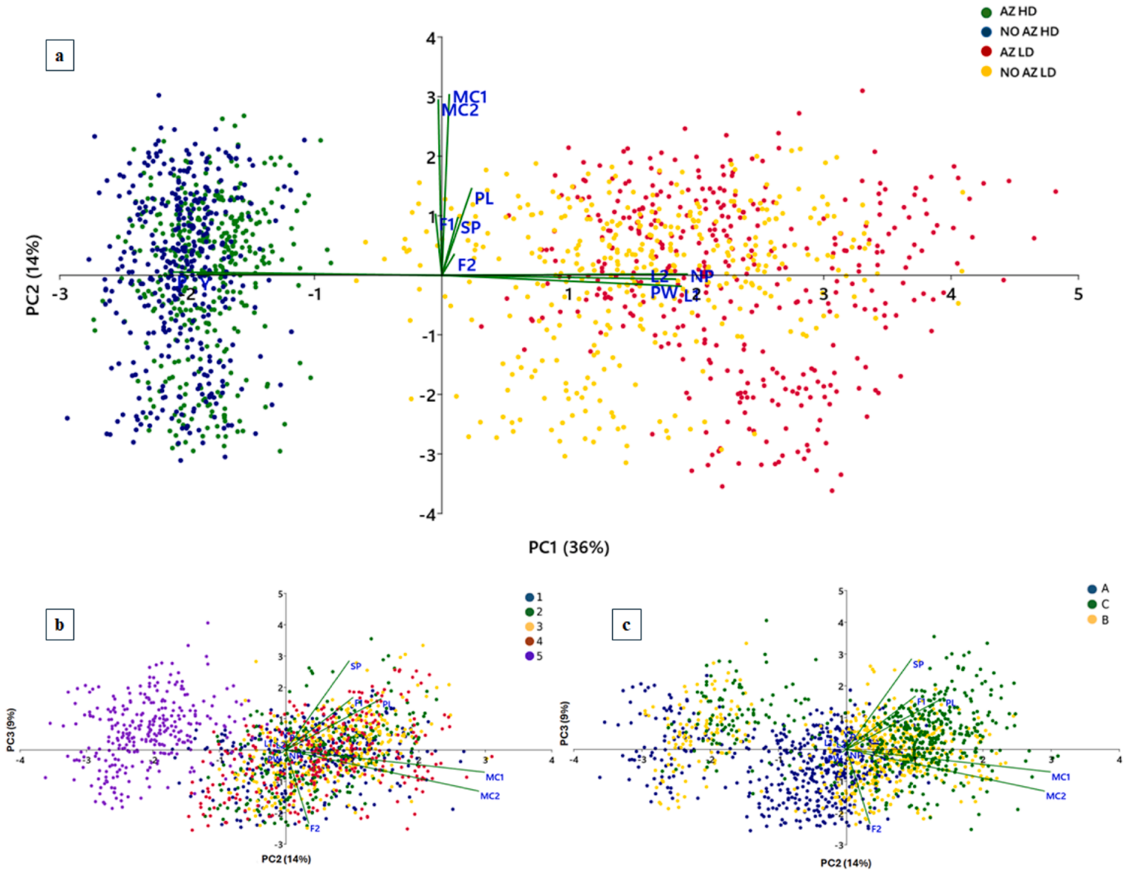

Fig. 2. a) PC1-PC2 biplot as a function of treatments (i.e., nitrogen fixation and planting density); b) PC2-PC3 biplot as a function of sampling date (1 to 5); c) PC1-PC2 biplot in relation to root section (A, B, C).

Table 1
Multivariate analysis of variance (MANOVA) results based on nitrogen-fixing treatment, plant density, and pod-peduncle detachment forces.

SOURCE	DF	exVarSS	nPC	nBu	exVarPC	exVarBU	p-Value
AZ	1	0.010138	9	1	0.99	1	**0**
PD	1	0.29217	7	3	0.946	1	**0**
F_1	1	0.005538	9	1	0.991	1	**0**
AZ×PD	1	0.011825	9	1	0.989	1	**0**
AZ×F_1	1	0.000386	9	1	0.991	1	0.555377
PD×F_1	1	0.001289	9	1	0.991	1	0.0878
F_1×AZ*PD	1	0.00084	9	1	0.99	1	0.24161
Error	1492	0.677789					

DF, degrees of freedom; exVarSS, explained variances based on sums of squares; nPC, number of principal components used for testing; nBu, number of principal components used as buffer components; exVarPC, variance explained by nPC components; exVarBU, variance explained by (nPC + nBU) components; P-value, the result from 50 to 50 MANOVA testing.

Table 2
Multivariate analysis of variance (MANOVA) results based on nitrogen-fixing treatment, plant density, and peduncle-vine detachment forces.

SOURCE	DF	exVarSS	nPC	nBu	exVarPC	exVarBU	p-Value
AZ	1	0.009817	9	1	0.990	1.000	**0**
PD	1	0.288598	7	3	0.946	1.000	**0**
F_2	1	0.001586	9	1	0.991	1.000	**0.000010**
AZ×PD	1	0.011129	9	1	0.989	1.000	**0**
AZ×F_2	1	0.003543	9	1	0.991	1.000	**0**
PD×F_2	1	0.001692	9	1	0.991	1.000	**0.000015**
F_2xAZ*PD	1	0.000983	9	1	0.991	1.000	0.081316
Error	1492	0.678081					

DF, degrees of freedom; exVarSS, explained variances based on sums of squares; nPC, number of principal components used for testing; nBu, number of principal components used as buffer components; exVarPC, variance explained by nPC components; exVarBU, variance explained by (nPC + nBU) components; P-value, the result from 50 to 50 MANOVA testing.

The productive results highlight that the 4 plots reached significantly different PD, with the lowest results in LD traits (Table 3). Consequently, greater Y were reported in the HD plots (with significant differences between NOAZHD and AZHD plots) than the LD plots (without significant differences between AZLD and NOAZLD), with the highest obtained in the NOAZHD plot. At the same time, the development was affected by the different seedling rate, as plants obtained both in AZLD and NOAZLD plots showed higher yield per single plant (higher NP and PW, with significant differences between the two plots). On the other hand, in NOAZHD and AZHD, the higher seedling rate compensated for the low NP and PW values, with no significant differences between AZLD and NOAZLD. The SP parameter was not particularly affected by the experimental traits. Finally, The NOAZHD traits exhibited the highest average PY (the 4 subplot yielded 3.46 ± 0.28a Kg of commercial pods), followed by the AZHD trait (3.20 ± 0.39a Kg,−7 %), the NOAZLD trait (2.19 ± 0.50b Kg, - 37 %) and, finally the AZLD plot (2,16 ± 0.33b Kg, - 37 %). Significant differences were found between the planting densities, while the application of the Azobacter spp did not produce any relevant difference.

3.3. Detachment forces and moisture content pathways

In Table 4, MC values were statistically analysed based on the sampling date. At the digging phase (sampling 4), the MC_1 reached comparable values without significant differences among the 4 plots, while the MC_2 exhibited significant differences. While MC_1 showed a homogeneous trend characterised by a progressive reduction across the peanut maturation phase, MC2 is subject to extensive variations attributable to a pronounced influence of pedoclimatic factors. Both MC parameters decreased after the natural drying during the solar exposition of peanut roots between the digging and separation phase (sampling 5). Specifically, the peduncles retained more MC, with NOAZLD exhibiting a significant higher value than the other plots. On the other hand, MC_1 ranged in comparable values.

According to the preliminary statistical analysis, detachment force values were evaluated by combining plant sections and sampling phases, regardless of the experimental treatments (Table 5).

F_2 reported larger values than F_1 along the maturation phases. Moreover, F_1 followed a homogeneous trend, since the average values for section A were lower than B and C. Interestingly, the parameter showed a decreasing trend along the peanut root from section A to section C in the last two final samplings, close to the harvesting operations. On the other hand, average F2 values showed greater variability; for example, the average value for section B in the last sampling was 15 % higher than that of section C.

By comparing MC_1 and F_1 values grouped by sampling date and root section (Fig. 3), it is shown that F_1 at the digging phase between sections was not affected by statistical differences (17 October), despite higher values for section C (995.9 g) than B (981.3 g) and A (873.3 g). Moreover, section C consists of pods with longer peduncles than B and A. As shown in Fig. 4, where the F_1 values were grouped in 4 different LP ranges, it is shown that longer peduncles (6.9 – 8–7 mm) always registered the highest F_1 values. Peduncles with an intermediate LP expressed slight variability, whereas shorter peduncles obtained the lowest F_1 values. On the other hand, F_2 values clearly showed wider variability and no clear discrimination among the different LP classes.

Table 3
Results of productive performances and pod development among the four tested plots.

PLOT	H (cm)	PD (pt m^{-2})	SP	Y (t ha^{-1})	NP	PW(g)
AZLD	37.42 ± 0.68 ^{a}	4.04 ± 0.25 ^{a}	1.78 ± 0.52 ^{ab}	3.21 ± 0.49 ^{c}	89.11 ± 12.95 ^{a}	161.42 ± 25.83 ^{a}
NOAZLD	38.00 ± 0.62 ^{a}	4.93 ± 0.14 ^{b}	1.70 ± 0.49 ^{b}	3.25 ± 0.75 ^{c}	72.98 ± 15.90 ^{b}	133.40 ± 34.58 ^{b}
AZHD	37.58 ± 0.68 ^{a}	8.78 ± 0.44 ^{c}	1.81 ± 0.45 ^{a}	4.75 ± 0.59 ^{b}	46.28 ± 8.73 ^{c}	78.54 ± 17.16 ^{c}
NOAZHD	37.90 ± 0.80 ^{a}	9.30 ± 1.08 ^{d}	1.81 ± 0.29 ^{a}	5.12 ± 0.42 ^{a}	45.40 ± 5.55 ^{c}	83.40 ± 12.85 ^{c}

a-c: significance letters obtained with the post-Hoc Tukey test.

Table 4
Temporal variation of MC_1 and MC_2 in the 4 treatments.

PLOT	MC_1 (%)				
	Sampling date				
	1	2	3	4	5
NOAZHD	63.31 ± 11.46 ^{ab}	61.01 ± 6.08 ^{abcde}	57.71 ± 6.43 ^{abc}	53.28 ± 17.96 ^{g}	23.46 ± 4.26 ^{h}
NOAZLD	61.62 ± 13.96 ^{abc}	59.80 ± 10.45 ^{bcdef}	61.10 ± 5.74 ^{abcd}	56.06 ± 8.98 ^{defg}	24.38 ± 8.54 ^{h}
AZHD	65.73 ± 13.96 ^{a}	53.24 ± 8.90 ^{g}	55.58 ± 5.57 ^{fg}	53.60 ± 8.52 ^{g}	24.65 ± 13.84 ^{h}
AZLD	62.98 ± 13.87 ^{ab}	57.72 ± 6.43 ^{cdefg}	62.15 ± 7.59 ^{abc}	55.95 ± 5.57 ^{efg}	24.54 ± 6.19 ^{h}
	MC_2 (%)				
NOAZHD	51.48 ± 9.49^{i}	57.22 ± 6.04^{h}	74.41 ± 10.2 ^{bc}	86.10 ± 18.0 ^{a}	34.06 ± 8.54^{kl}
NOAZLD	67.92 ± 8.37^{efg}	63.72 ± 10.4^{fg}	73.52 ± 5.74 ^{bcd}	69.08 ± 8.98 ^{cdef}	43.67 ± 4.26^{j}
AZHD	63.35 ± 10.4^{g}	77.67 ± 8.90 ^{b}	69.62 ± 5.57 ^{cde}	68.09 ± 8.52 ^{efg}	36.74 ± 13.8^{k}
AZLD	68.19 ± 5.80^{defg}	66.28 ± 6.43^{efg}	63.02 ± 7.59 ^{g}	75.72 ± 11.9 ^{b}	28.99 ± 6.19 ^{l}

a-k: significance letters obtained with the post-Hoc Tukey test.

Table 5
Temporal pattern of F_1 and F_2 with statistical differences within the root sections in each sampling date.

SECTION	F_1 (g)				
	Sampling date				
	1	2	3	4	5
A	1061.1 ± 343.7 b	987.3 ± 405,5 b	947.3 ± 379.2 b	873.3 ± 386.8 a	831.0 ± 315.6 b
B	1204.7 ± 120.9 a	1090.3 ± 457. 8 ab	999.3 ± 345.3 ab	981.3 ± 425.9 a	957.10 ± 392.1 ab
C	1193.9 ± 423.0 a	1207.1 ± 495.5 a	1113.3 ± 556.9 a	995.9 ± 539.6 a	1045.0 ± 434.5 a
	F_2 (g)				
	1	2	3	4	5
A	1630.5 ± 344.5 a	1705.7 ± 404.6 a	1326.7 ± 525.2 a	1452.8 ± 428.4 b	1221.0 ± 495.5 c
B	1664.0 ± 304.3 a	1679.5 ± 470.7 a	1434.2 ± 472.7 a	1693.4 ± 392.9 a	1614.1 ± 414.8 a
C	1325.5 ± 403.6 b	1706.45 ± 386.0 a	1370.1 ± 457.0 a	1246 ± 517.8 c	1440.8 ± 563.2 b

a-c: significance letters obtained with the post-Hoc Tukey test.

3.4. Work productivity and harvesting efficiency

Regarding harvesting performances, the higher average L_1 was measured for AZHD plot, followed by NOAZHD.

During the harvesting operations, two product losses occur. The first (L_1) is caused by the detachment of peanut pods from the peduncle during the plant digging, while L_2 are superficial and due to the absence of separation of pods from the plant residues by the machine organs. Statistical differences were obtained in both cases among the 4 treatments. The highest L_1 were registered for AZHD, while the lowest occurred with AZLD treatment (Table 6). The same plot also registered the lowest L_2, followed by NOAZLD (+ 50.1 kg ha^{-1}), AZHD (+ 112.8 kg ha^{-1}) and NOAZLD (+264.5 kg ha^{-1}). Thus, AZHD obtained the highest L_{tot}, followed by NOAZHD (−6 %), NOAZLD (−39 %) and AZLD (−49

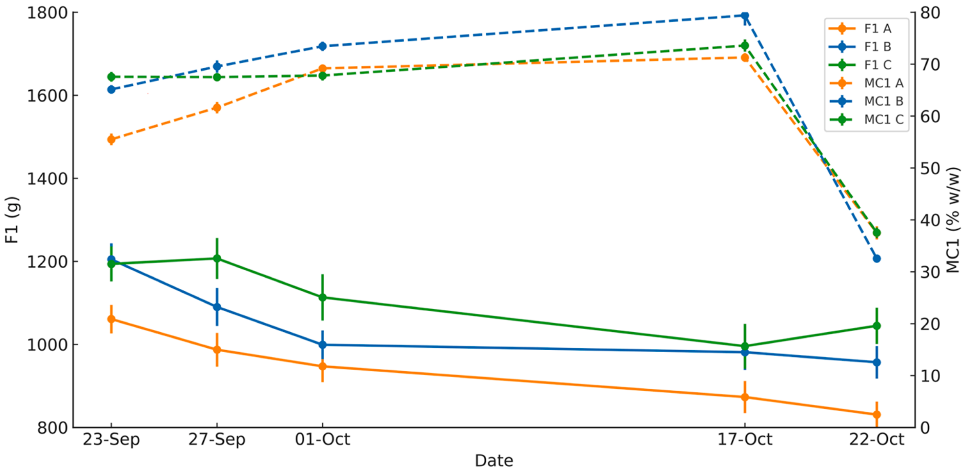

Fig. 3. Temporal variation of F_1 and MC_1 along the peanut root during the maturation phase. Error bars represent the standard error of the mean.

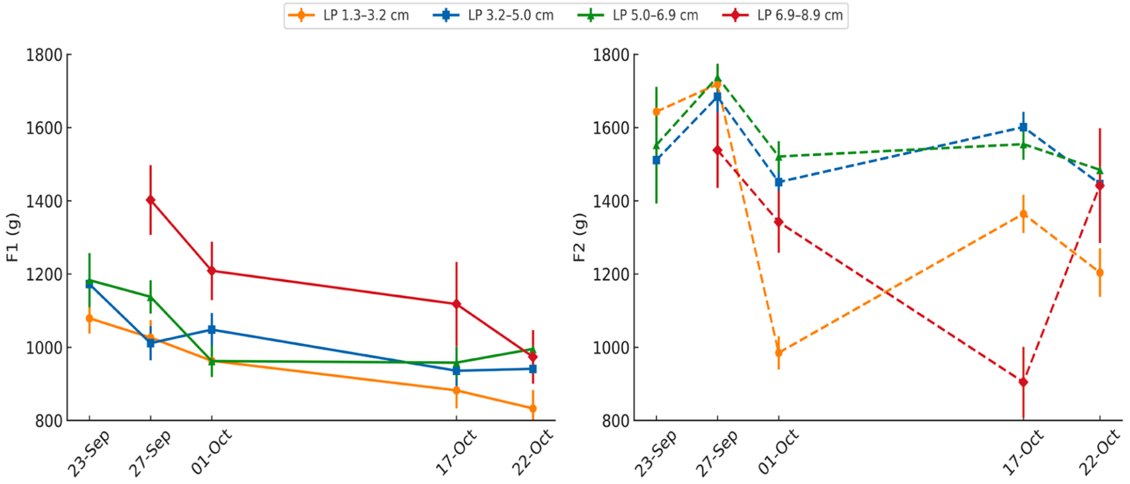

Fig. 4. Temporal trend of F_1 and F_2 in the different LP classes. Error bars represent the standard error of the mean.

Table 6

Productive losses and harvesting efficiency reported for the 4 experimental traits.

PLOT	L_1 (kg ha^{-1})	L_2 (kg ha^{-1})	L_{tot} (kg ha^{-1})	EY (t ha (1)	E (%)
NOAZHD	453.13± 18.91 ^{b}	370.08 ± 16.45 ^{a}	823.22	4.38 ± 0.17 ^{a}	84 %
NOAZLD	401.22 ± 27.61 ^{c}	155.56 ± 25.65 ^{c}	556.78	2.78 ± 0.56 ^{b}	83 %
AZHD	657.70 ± 19.70 ^{a}	218.82 ± 32.78 ^{b}	876.52	4.01 ± 0.27 ^{c}	81 %
AZLD	365.32 ± 28.82 ^{d}	105.44 ± 19.24 ^{d}	470.76	2.73 ± 0.29 ^{b}	85 %

a-d: significance letters obtained with the post-Hoc Tukey test.

%). As a result, both “HD” treatments obtained higher EY than the “LD” treatments, (without a statistical difference between AZLD and NOAZLD). However, the E values were comparable among the four traits, However, the E values were comparable among the four traits ($E = 85$ %) .

The Fc values recorded (Table 7) for digging and separation phase were comparable among the 4 treatments. AZLD recorded the highest Fc for both harvesting phases.

4. Discussions

[27] reported that Y decreases progressively as inter-row density increases, which appears consistent with the trends obtained in the present study. The PW results reported in research on *Lotus* cv. show a

Table 7

Working times and field capacity for the digging and separation phases.

PARAMETER	DIGGING				SEPARATION			
	NOAZHD	NOAZLD	AZHD	AZLD	NOAZHD	NOAZLD	AZHD	AZLD
ET (mm:ss)	01:39	01:39	01:39	01:39	01:52	01:52	01:52	01:52
AT (mm:ss)	00:31	00:31	00:31	00:31	01:51	01:51	01:51	01:51
OT (mm:ss)	02:10	02:10	02:10	02:10	03:43	03:43	03:43	03:43
Operative speed (km h^{-1})	4.69	4.69	4.69	4.69	3.87	3.87	3.87	3.87
E (%)	84 %	83 %	81 %	85 %	84 %	83 %	81 %	85 %
Fc (ha h^{-1})	0.59	0.58	0.57	0.60	0.49	0.48	0.47	0.49

lower value than AZLD treatment (−12 %) and a higher value than the other plots (+7 %, +72 % and +83 % in respect of NOAZLD, AZHD and NOAZHD, respectively). On the other hand, the experimental SPs were lower than the values reported by these authors [12]. The treatment with *Azotobacter spp.* Bacteria did not exhibit significant improvements in peanut Y, in contrast to the available literature [9,10,28]. A possible explanation is that the effective establishment of such strains may be hindered by biological factors, including competition from native soil microorganisms for colonisation of the plant rhizosphere [29]. In addition, the experimental field lays in an area where soils derived from the deposits of Vesuvius eruptions, characterized by high background levels of major nutrients in comparison to typical Italian and European agricultural soils [30]. It has been reported that biological nitrogen fixation is inhibited in soil with high nitrogen levels and that introduced nitrogen-fixing bacteria frequently show poor establishment [31].

It has been widely proposed to adopt MC (% w/w) to monitor pod maturation and determine the most suitable ripening time. Indeed the MC content of the subterranean peanut organ varies at the harvesting stage [18]. Experimentations were performed despite several issues, both agronomic (sowing was performed twice because the first batch of seeds showed low germinability.) and climatic (persistent rainfall during the ripening stage). Thus, MC_1 at digging phase was, 40–50 %, coherently with the range given in literature [32]. Then, the average MC_1 dropped at 25 %, in line with the average range [33] proposed in literature to obtain an optimal product. When dried between the digging and separation step of a two-phase harvesting, the MC_1 content of peanut plants drops at 10–20 % [34]. In the first sampling dates, the furthest from the ripening date, MC_1 and MC_2 were homogeneous. From sampling 4 ongoing, the peduncle retained more moisture than the pod. The fact that MC_2 values were on average higher than MC_1 may be related to physiological processes, as peanut peduncles maintain nutrient transport fluxes towards the kernel even after the digging phase [35]. Throughout the sampling period, F_2 values consistently exceeded F_1 values. This trend indicates that during the digging phase— when pods remain attached to the plant with the detachment force applied upward through the peduncle—a strong mechanical bond persists between the pod and the vine. Such conditions may contribute to lower L_1 levels. Conversely, during the separation phase, pods exhibit lower resistance to the mechanical action of the harvesting equipment, thereby minimising impurity levels and facilitating the efficient removal of a high proportion of kernels from the plant.

MC_1 and F_1 decreased progressively during the maturation phase, supporting the hypothesis that MC influences mechanical behavior of pods and peduncles in combination with morphological factors. The correlation found between LP and the root sections suggests that the shortest peduncles, set mostly in the root region closer to the plant crown, exhibited lower mechanical resistance. The usefulness of pairing morphological and physiological factors has been clarified in other research [18]. These authors either confirm that F_2 values remain higher than F_1 and that the mechanical properties of the peanut changed between the maturation period and the drying phase. Furthermore, it is possible that the central root section (B) is characterised by vast variability in the temporal trend of F_1, reflecting a potential relation with the high heterogeneity of peg maturation in this zone. On the other hand, both the more superficial pegs and the more subterranean may show a less variable response to tensile stress due to superior maturation homogeneity. However, an accurate monitoring of peanut maturation with the application of appropriate methodologies like the Hull-Scrape Method may offer further evidence [36]. For instance, several authors proposed to evaluate the peanut maturation with an index based on the variations of the pod colour carter [37].

Work productivity in peanut harvesting is affected by the proficiency of the rider with regard to the correct alignment of the longitudinal axes of the machine with the cultivated rows [38]. The operative speed in both harvesting phases (3.5 km h^{-1} in the digging phase, 5.0 km h^{-1} in the separation phase) is in line with the values displayed in literature [39,40]. It is reported that product losses may vary between 3.2–47.1 % out of potential yield, depending on the working speed, the moment of execution and the operative parameters of the machines [13,41]. These values were obtained with an Fc of 0.45–0.50 ha h^{-1} in both harvesting phases. Other available Fc values in the literature refer to different harvesting methods. For instance, a pull-type harvester implemented in a one-phase harvesting experiment obtained an Fc value of 0.45 ha h^{-1} [42].The experimental results show that “HD” treatments were affected by higher L_{tot} than “LD”. This aspect vary between the tested peanut *cv*: some authors report that with a seedling density of 20 plants m^2, L_{tot} may vary between 562 kg ha^{-1} and 936 kg ha^{-1} with different peanut genotypes [43]. Everything considered, the NOAZHD treatment exhibited an encouraging compromise between the crop productivity and the harvesting efficiency, leading to the highest EY among the treatments tested.

Finally, it is useful to remind that the present study was conducted at a single site and within a single growing season. For this reason, ongoing experimentation is aimed at extending the observations through a multi-site and multi-year approach.

5. Conclusions

The peanut morphology during the harvesting phase was monitored in relation to different planting densities, in the absence and presence of Nitrogen fixing bacteria. The two-phase harvesting technique reported satisfactory work productivity with the chosen cv. Furthermore, the results indicated that the higher productivity observed in high planting density treatments was associated with increased harvesting losses. However, comparable harvesting efficiency to that of the low-density treatment was achieved. In addition, the application of *Azotobacter spp*. did not produce relevant changes in the evaluated parameters. The detachment forces between peduncle and vine show high heterogeneity with no clear connection to the morphological peanut traits. Conversely, the moisture content of peanut pods is confirmed as an affordable indicator to monitor the detachment force between pod and peduncle. Peduncle length showed a clear positive correlation with tensile strength, indicating quantitative heterogeneity along the peanut root section. On the other hand, the experimental treatments did not influence the overall values of detachment forces. In conclusion, the “NOAZHD” treatment achieved the highest EY among the treatments tested. The study suggests an appropriate peanut cultivation strategy for an underexploited area, providing valuable insights to contribute to an emerging agri-food industry. Further experiments could include the comparison of different peanut cultivars using vegetation indices through proximal sensing to predict the maturation pathway without invasive methods.

Ethical statement

This study did not involve human participants or animals; therefore, ethical approval was not required.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors on request.

CRediT authorship contribution statement

Maura Sannino: Writing – review & editing, Visualization, Methodology. **Guglielmo Maresca:** Writing – original draft, Formal analysis, Data curation. **Alberto Assirelli:** Writing – review & editing, Investigation. **Rossella Manganiello:** Writing – review & editing, Resources, Investigation. **Luis Alcino Conceição:** Writing – review & editing, Validation, Software. **Paola D’Antonio:** Formal analysis, Investigation, Writing – original draft. **Costanza Fiorentino:** Writing – original draft, Investigation, Formal analysis. **Salvatore Faugno:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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