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Determination of feed yield and quality parameters of whole crop durum wheat (*Triticum durum Desf.*) biomass under agrivoltaic system

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Abstract Agrivoltaics represents a key technology for reaching sustainable development goals by reducing the competition between land used for food, for feed, and for electricity. It has been demonstrated that Agrivoltaics can increase land productivity and play a role in the expansion of renewable energy production. This work aimed to study the yield and nutritional characteristics, as well as feeding value for ruminants of Durum wheat biomass grown under agrivoltaic. Two years of controlled experiments revealed that the reduction in light moderately limited wheat yields in the phenological phase of soft dough in standard agrivoltaic trackers (i.e. with a Ground Coverage Ratio (GCR) = 13%), otherwise under extended trackers (i.e. GCR = 41%), the yields was reduced compared to control in whole light. The digestible neutral detergent fiber evaluated after 24 h of in situ rumen incubations increased with shading, resulting in different ratios of acid detergent lignin. More shaded theses also had superior crude and soluble proteins, acid detergent-insoluble protein, acid and neutral detergent fiber than the control. The biomass in the shaded treatments showed a better Ca: P ratio for ruminant nutrition. These characteristics are strategic in forage production, allowing a more flexible harvesting strategy. This additional contribution of the nutritional characteristics of Durum wheat produced on Agrivoltaic Systems could allow a better inclusion of the different types in diets and better management of silage or hay harvesting sites. These results might be helpful in improving biomass production and give valuable information on Durum Wheat under the Agrivoltaic System.

Keywords Agrivoltaics · Hay · NIRS · Feed value · Durum Wheat

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Introduction

Agrivoltaic systems (AS) represent a key technology and a smart solution to support sustainability reducing the conflicts due to the competition for land between food and electricity production. AS presents several advantages over traditional ground-based photovoltaic systems (PS) across three different macro-areas: energy, food, and water (Campana et al. 2021).

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Competition for cropland allocation is not a new issue (Johansson and Azar, 2007; Nonhebel 2005), and the percentage of arable lands dedicated to bioenergy production or other industrial use has significantly increased in the last 20 years (Saleem 2022), especially in the most fertile lands of the planet (Foley et al. 2011). The essence of this conflict stays in the alternative use of land, whether it is used to produce food or energy. In order to reduce Greenhouse gases (GHGs) emission, the European Union has decreed that 40% of energy consumption must come from renewable resources by 2030 (European Commission 2019). Photovoltaic energy is expected to reach 16% of global electricity production in 2050, but in view of climate change it should be 30 to 100 TW before 2050 (Jordan et al. 2021). At the same time agricultural productivity is facing an unprecedent challenge due to the effects of climate change on temperatures, rainfall, and extreme events (Edouard et al. 2023). In Italy many projects are being developed to implement AS and several aspects have been defined related to ì) types, ìì) applications, ììì) classification of AS and finally to define the requirements and setting the best practices (UNI 2023). The better understanding of the behavioral response of the main crops when grown under AS represents a major challenge for research. Plants require light to feed the photosynthetic machinery, but in many areas of the world, the amount of light can be in excess, and this, coupled with water limitations, may drive plant stress with a subsequent decrease in production. Similarly to Agroforestry Systems (AF), in AS, crops are cultivated in a partially shaded environment and light is usually the most limiting factor for understory plant growth. The yield of crops in both AS and AF systems is difficult to predict (Dupraz 2023). Indeed, there is still a lack of systematic assessments on how harvestable yields of different crop types respond to varying levels of shading. According to a recent meta-analysis (Laub et al. 2022), a nonlinear relationship between achieved crop yields and reduction in solar radiation (RSR) for all crop types was found, and most crops tolerate (RSR) up to 15%, showing a less than proportionate yield decline. Forages, leafy vegetables, tubers/root crops, and C3 cereals showed yield loss in moderate shading stress (Laub et al. 2022). Based on potential yield changes caused by shading from agrivoltaics, grown forages, which support the Valley's large markets for milk production in Italy, might be affected. Considered a main forage in the Valley, wheat (Triticum spp.) is one of the world's essential crops for grain production and high-quality forage production for livestock (Torell et al. 1999; Dal Prà et al. 2023a; Borrelli and Pecetti 2019 and Ronga et al. 2020). In many parts of the world, cows and sheep maintain their main source of food from vegetative wheat. The concept of wheat grazing was developed in Southern Australia where wheat genotypes that have long vegetative phases were grown. Grazing was allowed primarily until the beginning of stem elongation and had little impact on grain yield (Virgona et al. 2006). As a result, prolonged silage storage might decrease the dry matter (DM) and neutral detergent fiber (NDF) digestibility values (Weinberg and Chen 2013). However, previous research proved that feeding cows fermented whole crops led to an increased dry matter intake (DMI) and improved rumen fermentation (Randby et al. 2019; Owens et al. 2009; and Keady et al. 2007). Nonetheless, maintaining a high farming efficiency in Italy under full sun, the quality of grown wheat can impact milk production if it is cultivated in agrivoltaics systems. To the best of our knowledge, there is no study that assesses the potential changes of agrivoltaics on the nutritional value of milk production from changes in wheat yields. Thus, there is a growing need and interest to identify those changes especially since there is a potential rise in agrivoltaics on existing agricultural lands due to the higher dual-land productivity from energy and food production (Garuti et al 2022). Therefore, this study aimed to evaluate the yield and quality of forage from Durum wheat grown in agrivoltaics in Italy with different solar array layouts that created different shading coverages by comparing the results with those from a control site under full sun conditions.

Materials and methods

Study areas

The AS was installed in April 2011 in the North of Italy (Borgo Virgilio, Mantova 45°05′40''N – 10°47′30''E) and had a total size of 11.42 ha, of which 13% of the surface is dedicated to solar panels, and with a capacity of 2,150.4 kWp (Fig. 1).

Seven hundred sixty-eight trackers (7,680 solar panels) are installed with bi-axial technology (Poly

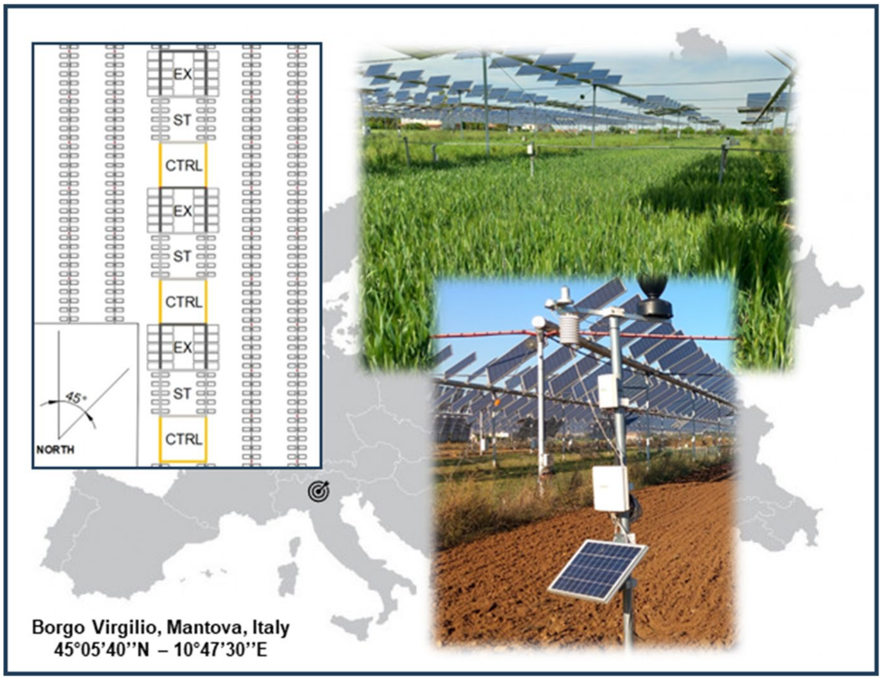

Fig. 1 Location of the Agrivoltaic System and details of the experimental scheme and of the solarimetric and PAR probes

280 WP, Bisol Group, d.o.o. Latkova, Prebold, Slovenia). The height of the poles and panels from the ground was 4.5 m, the angle of inclination (±50°, main axis, ±40°, secondary axis). The total panel modules area (PV) is 1.30 ha, so the Ground Coverage Ratio (GCR) defined as the Area of solar Panels / Area of the land used for the (AS) is 13%. The research was performed from 2022 to 2023 in two consecutive growing seasons. Photosynthetic Active Radiation (PAR) was registered in 1 site for each of the 3 shading treatments and was drawn up as a sum of the monthly averages. PAR and global radiation (have not been processed), monthly averages data have been reported in Online Resource 1. Temperature and rainfall data were collected from a automatic weather station nearby the AS plant. Annual mean temperature was 14.9 °C in 2022 and 13.1 °C in 2023, and total rainfall ~ 114.7 mm (January-May 2022) of and ~ 516 mm (October-May 2022–23) respectively (Fig. 2). The field trials were carried out on a silty sand soil with a pH measured in water of 8.5. The sand, silt, and clay contents were 500, 400, and 100 g kg^{-1} at 0–60 cm depth. The organic C was 1.1%, and the total N was 0.18%. Assimilable P and exchangeable K were 76.4 and 810 mg kg^{-1}, respectively. The previous crop was alfalfa (it was mechanically destroyed by ploughing) in the first year and wheat in the second. Sowing, fertilization, and harvest dates were adapted to climatic conditions or plant development stages each year.

Growth condition

In both field experiments, Durum wheat (*Triticum durum Desf.*) Levante (Syngenta Italia, Milano, Italy) were cultivated; seeds were sown at a density of 300 seeds m^{-2}. The first test was conducted with a short cycle (sowing on February 9, 2022), and the second year was conducted with a long/conventional cycle (sowing on 20 October 2022).

Three replicates were sown under standard (ST) agrivoltaic trackers (GCR = 13%), three replicates under extended (EX) agrivoltaics with a GCR of 41%, and three replicates as control (CTRL). Each of the 9 replicas had a surface of 12 × 12 m the test was conducted in a total area of 1.296 m^2 (Fig. 1). The sampling was performed following the representativeness of plots with respect to the shading factor. Each sampling was conducted along a 12-m (3-m, 6-m, and 9-m) central linear transect of each thesis and replicates (3 thesis × 9 samples × 2 years). The biomass produced was estimated in 54 test areas and samples were moreover sent to the NIRS laboratory for analysis.

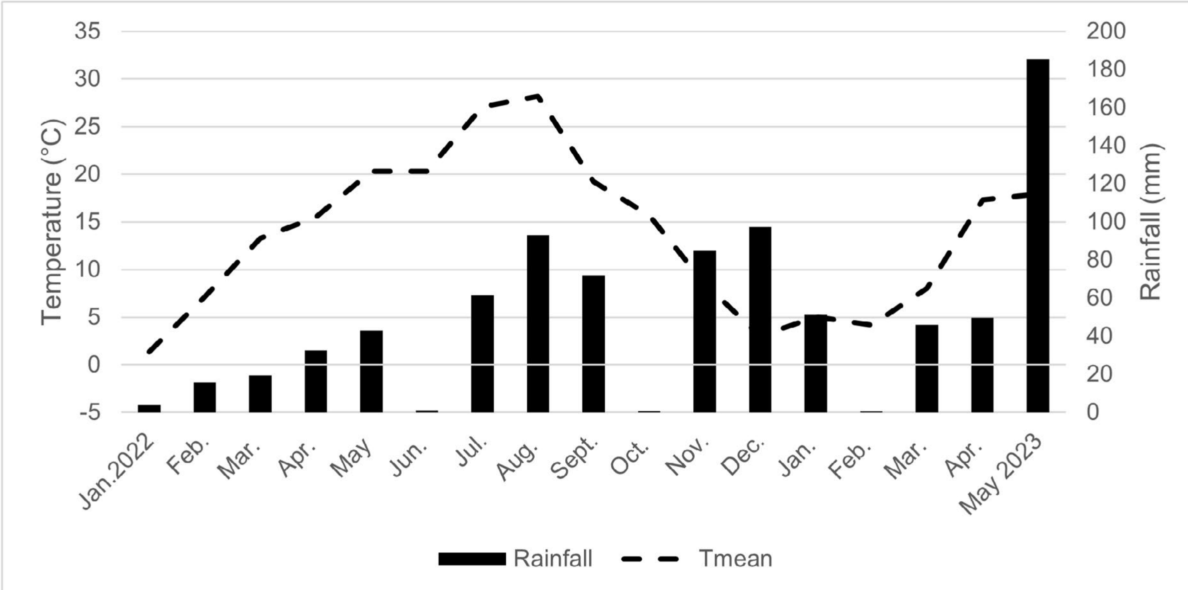

Fig. 2 Monthly mean air temperature and total rainfall recorded over the experimental period (Jan 2022/May 2023)

The harvest has always been made on a single date (27 May 2022 and 19 May 2023); each treatment was harvested according to crop growth stage 8.5 Soft dough Zadoks scale (or on reaching the phenological stage of the first treatment). Biomass samples for the yield and quality measurements were collected with a HEGE (212) forage plot harvester (Hege Equipment Inc., Colwich, KS, USA), biomass was retained above a 5 cm harvest height.

Near-infrared reflectance spectroscopy analysis

A set of 54 biomass samples of about 1 kg (3 thesis × 9 samples × 2 years) has been collected to estimate the dry matter (DM) yield. The batches were then analyzed in the laboratory (using Near-Infrared Reflectance Spectroscopy), and DM was attributed. To estimate the nutritional value, hay samples were ground to 2 mm, and the spectra acquisition was performed using the instrument Foss NIR-System 5000 monochromator (NIR-System, Silver Spring, MD, USA) using the spinning ring cup cell as sample transport module by double scanning each sample in the 1098–2500 nm spectral region. Mathematical treatments of spectral data were processed using WinISI II V1.5 software (Infrasoft International, Port Matilda, PA, USA). NIRS calibration equations were developed for Italian hay's predicted in vitro NDF parameters. Predictions were performed using the equation developed and validated by Brogna et al. 2009; Palmonari et al. 2016; and Dal Prà et al. 2023a, considering a coefficient of determination higher than 0.85 and a standard error ranging from 1.9 and 3.4 in cross-validation. The NIRS curve (.cal editable file) is periodically validated with chemical analyses based on official methods and in vivo NDF parameters. Indeed, the following parameters were recorded: dry matter (%), ash (% of DM), crude protein content (% of DM), neutral detergent-insoluble protein (% of DM), acid detergent-insoluble protein (% of DM), and soluble protein (% of DM) according by Goering and Van Soest 1970; Licitra et al. 1996; neutral detergent fiber with amylase and sodium sulfite method, according to Mertens DR, 2002, (NDF, % of DM), acid detergent fiber (ADF, % of DM), acid detergent lignin (ADL, % of DM), undigested NDF after 240 h (uNDF, % of aNDFom, as reported by Brogna et al. (2009), dNDF digestible NDF evaluated after 24 h of in situ rumen incubations, as reported by Palmonari et al, (2014), fat (% of DM), starch (% of DM), sugar (% of DM), metals and other elements (Ca, P, Mg, and K) as recommended by AOAC 2000, and net energy for lactation (NE_L, kcal kg DM^{-1}).

Statistical analysis

Descriptive statistics of data were elaborated with R software (R Core Team 2013).

A Principal Component Analysis (PCA) was conducted with the R package Factoextra (Kassambara and Mundt 2020) to define not only how agrivoltaic trackers (CTRL, ST, and EX) could cluster, but also to analyze the contributions of each variable to PCs.

A correlation plot was built with the Ggally R package (Schloerke et al. 2023) to calculate and visualize the pairwise correlations separated by agrivoltaic trackers (CTRL, ST, and EX). Only variables that contributed to at least the 2% of explained variability in both PC1 and PC2 were included in the correlation analysis.

Records for each trait of Durum wheat were analyzed under the following linear model, using the R function lm of stats R package (R Core Team 2013):

$$Y_{ijk} = \mu + T_i + P_j + e_{ijk}$$

where Y is, in turn, the observation for Length, Yields, DM, total PAR, Ash, Crude Protein, ADIP, SolP, NDF, ADF, ADL, dNDF, uNDF, Starch, Sugar, Ca, P, Mg, K, and Net Energy for lactation, previously checked for normality; μ = the overall mean; T = fixed effect of the ith tracker (3 levels: control, conventional and extended panels); P = fixed effect of the jth cycle time (2 levels: short and long) and e = random residual. The interaction between fixed effects was tested for each parameter but resulted in a lack of significance and consequently removed from the model. The least-square means (LSM) have been calculated with the R lsmeans package (Lenth 2016), and the significance of comparisons was carried out with the cld function of the multcomp R package (Hothorn et al. 2008).

Results

The first agronomic test was characterized by a period with limited rainfall and temperatures comparable to the average of recent years. The second agronomic test was characterized by a particularly rainy May.

Statistical analysis

The descriptive statistics (mean, standard deviation, maximum, and minimum values) showed that the three agrivoltaic trackers could affect Durum wheat traits (Table 1).

The plants' length was greater in the EX group, reaching 101 cm. In contrast, the maximum value for CTRL was 89 cm. The yields decreased passing from CTRL (8.3 ± 1.6 tons DM ha-1) to EX group (6.4 ± 1.1 tons DM ha-1), the same for total PAR (from 751 ± 38 to 436 ± 26), DM (27 ± 4.4% to 22 ± 3.5%), starch (from 3.6 ± 1.7% to 3.0 ± 1.6%) and NE_L (from 1314 ± 77 to 1262 ± 76 kcal kg DM − 1). Interesting was that Durum wheat in EX and ST treatments showed a low value of undigested NDF after 240 h (uNDF, % of aNDFom), a parameter that worsens the nutritional feed value; the opposite was for dNDF, which increased in EX tracker (46%) compared to CRTL and ST (~ 43%).

The NDF parameter showed a higher mean in the EX group than the other two trackers, while ADF and ADL resulted in very similar values among agrivoltaic trackers. Also, minerals, except for K, which increased in EX (2.2% vs 1.8% in CTRL), presented the same trend in the three groups (Ca = ~ 0.5%, P = 0.3, Mg = 0.2%).

Durum wheat biomass showed the highest value of ash content in the EX group (8.1 ± 0.9% compared to ST group 7.8 ± 0.8%, and 7.6 ± 0.5% of group CTRL), CP (12.0 ± 1.1% compared to ST group 11.0 ± 0.7%, and 10.0 ± 0.7% of group CTRL), ADIP (0.8 ± 0.1% compared to the other 2 less shaded theses), SolP (5.0 ± 1.1% compared to ST group 4.9 ± 0.8%, and 4.6 ± 0.9% of group CTRL), ADF (37.0 ± 2.0% compared to the other 2 less shaded theses).

Conversely durum wheat showed the highest value of ADL content in the CTRL group, namely 4.9 ± 0.5% (4.8 ± 0.5% in the other 2 more shaded theses). Sugar content maintained 11 ± 1.5% in the CTRL and ST groups, while passed to 10.0 ± 1.4% in EX.

The relationship among measured parameters was studied using PCA. The percentage of explained variance of the top 10 parameters that contributed to PC1 and PC2 was reported in Online Resource 2. The major contributions to PCA were given by NE_L, DM, P, and ADF for PC1 and CP, total PAR, SolP, and

Table 1 Descriptive statistics of Durum wheat plants parameters divided by Agrivoltic trackers

	CTRL				ST				EX			
Variable	Mean	Sd	Min	Max	Mean	Sd	Min	Max	Mean	Sd	Min	Max
Length (cm)	79.0	8.9	61.0	89.0	82.0	9.8	58.0	94.0	83.0	11.0	67.0	101.0
Yields, t ha^{-1}	8.3	1.6	6.5	11.0	8.1	2.2	4.4	12.0	6.4	1.1	5.1	8.1
PAR (W / m^{-2})	751	38	668	767	620	30	552	632	436	26	388	449
DM (%)	27.0	4.4	19.0	34.0	25.0	3.7	18.0	30.0	22.0	3.5	17.0	28.0
Ash (% of DM)	7.6	0.5	6.6	8.4	7.8	0.8	6.3	9.4	8.1	0.9	7.1	9.7
CP (% of DM)	10.0	0.7	8.2	11.0	11.0	0.7	10.0	13.0	12.0	1.1	9.7	14.0
Fat (% of DM)	1.9	0.3	1.4	2.5	2.0	0.2	1.0	2.4	2.0	0.2	1.7	2.5
ADIP (% of DM)	0.7	0.1	0.5	1.0	0.7	0.1	0.5	0.9	0.8	0.1	0.5	1.0
SolP (% of DM)	4.6	0.9	3.8	6.3	4.9	0.8	3.8	6.7	5.0	1.1	3.7	6.9
NDF (% of DM)	54.0	4.2	46.0	61.0	55.0	4.1	48.0	60.0	58.0	1.8	54.0	61.0
ADF (% of DM)	36.0	2.3	34.0	41.0	36.0	2.1	34.0	41.0	37.0	2.0	34.0	40.0
ADL (% of DM)	4.9	0.5	4.0	6.0	4.8	0.5	4.1	5.6	4.8	0.5	4.2	5.6
dNDF (% of NDF)	43.0	4.0	36.0	51.0	44.0	2.9	40.0	49.0	46.0	2.2	42.0	51.0
uNDF (% of NDF)	26.0	4.3	21.0	36.0	24.0	3.2	19.0	31.0	24.0	3.9	18.0	31.0
Starch (% of DM)	3.6	1.7	1.6	8.3	3.2	1.3	1.6	5.9	3.0	1.6	1.0	6.3
Sugar (% of DM)	11.0	1.5	9.2	14.0	11.0	1.5	8.3	14.0	10.0	1.4	8.3	13.0
Ca (% of DM)	0.5	0.2	0.2	0.7	0.6	0.1	0.4	0.7	0.6	0.1	0.3	0.7
P (% of DM)	0.3	0.0	0.3	0.4	0.3	0.0	0.3	0.4	0.4	0.0	0.3	0.4
Mg (% of DM)	0.2	0.0	0.1	0.2	0.2	0.0	0.1	0.3	0.2	0.1	0.2	0.3
K (% of DM)	1.8	0.3	1.4	2.5	2.0	0.4	1.6	2.8	2.2	0.5	1.5	2.9
NE_L (kcal kg DM^{-1})	1314	77	1164	1411	1305	81	1161	1412	1262	76	1164	1394

Standard Agrivoltaics (ST; GCR = 13%), Extended Agrivoltaics (EX; GCR = 41%), and control (CTRL) trackers. Length of plants at the phenological stage of harvesting; PAR, the sum of the monthly averages; DM, dry matter; CP, crude protein content; ADIP, acid detergent-insoluble protein; SolP, soluble protein; NDF, neutral detergent fiber with α-amylase, sodium sulfite, and correcting for ash contamination; ADF, acid detergent fiber; ADL, acid detergent lignin; dNDF, digestible NDF evaluated after 24 h of in situ rumen incubations; uNDF, undigested NDF after 240 h of in situ rumen incubations; NE_L, net energy for lactation

yields for PC2. The result of PCA analysis is visualized in the biplot in Fig. 3A; the sum of the contributions of the two first principal components accounted for 57.70% of the total data variability. PC1 revealed 39.80% of the total variability and differentiated EX from CTRL and ST, which were partially intersected. PC2 instead explained 19.90% of the total variability, and it is able to differentiate mainly CTRL from EX. Finally, it could be concluded that PCA revealed three groups, where CTRL and EX were at the extremes, while ST was in an intermediate position (Fig. 4).

The most robust negative correlations were observed between yields and NDF, i.e., -0.7, (CTRL -0.7, ST -0.7, while EX resulted not correlated); total PAR with CP, i.e. -0.7 (CTRL -0.7, ST -0.1, and EX -0.8). DM with ADF, i.e. -0.7 (CTRL -0.7, ST -0.8, and EX -0.8), with dNDF, i.e. -0.8 (CTRL -0.9, ST -0.6, and EX -0.6) and for what concerns minerals with Sugar, i.e. 0.7 (CTRL 0.7, ST 0.6, and EX 0.6), Ca = 0.7 (CTRL 0.7, ST 0.9, and EX 0.8), P = -0.8 (CTRL -0.8, ST -0.8, and EX -0.7), K -0.7 (CTRL -0.9, ST -0.5, and EX -0.4), and also with NE_L 0.8 (CTRL 0.8, ST 0.9, and EX 0.8). Ash also showed a strong positive correlation with ADF (= 0.7) (CTRL 0.5, ST 0.7, and EX 0.8), Sugar -0.7 (CTRL -0.8, ST -0.7, and EX -0.6), K 0.8 (CTRL 0.8, ST 0.7, and EX 0.7) and NE_L -0.7 (CTRL -0.4, ST -0.8, and EX -0.8). As expected, CP and the respective soluble fraction (SolP) had a significant positive correlation of 0.8 (CTRL 0.8, ST 0.9, and EX 0.9). NDF showed a high negative correlation with NE_L, -0.7 (CTRL -0.8, ST -0.7, and EX -0.5). ADF showed a strong positive correlation with ADL, 0.7 (CTRL 0.6, ST 0.7, and EX 0.9), Starch,—0.7 (CTRL -0.8, ST -0.5, and EX -0.7), P, 0.7 (CTRL 0.9, ST 0.7, and EX 0.8), K, 0.7 (CTRL 0.7, ST 0.8, and EX 0.8), and

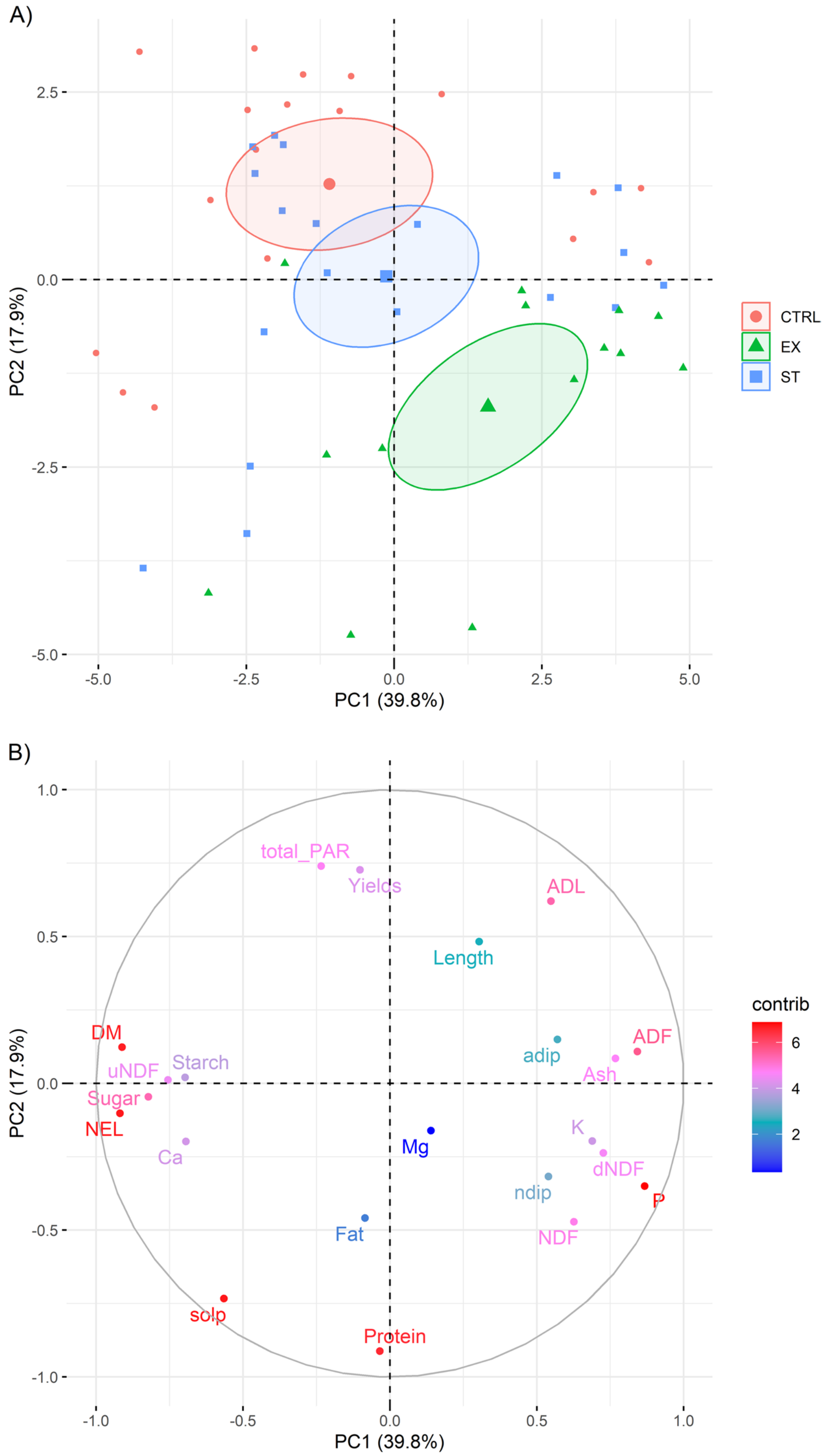

Fig. 3 Principal Component Analysis (PCA): **A**) of samples and **B**) of parameters included in the analysis. (i.e. Total PAR, the sum of the monthly averages; DM, dry matter; Protein, crude protein content; ADIP, acid detergent-insoluble protein; SolP, soluble protein; NDF, neutral detergent fiber with α-amylase, sodium sulfite, and correcting for ash contamination; ADF, acid detergent fiber; ADL, acid detergent lignin; dNDF, digestible NDF evaluated after 24 h of in situ rumen incubations; uNDF, undigested NDF after 240 h of *in situ* rumen incubations; NE_L, net energy for lactation). **B** Shows the PCA by variables, i.e., PAR, length of plants, and all the nutritional parameters analyzed. Crude protein, SolP, NE_L, DM, and P explained the highest percentages of variability (more than 6% each). ADL, ADF, and sugar showed great values, followed by total PAR, NDF, ash, dNDF, and uNDF. Mg, fat, ADIP, NDIP, and plant length scarcely contributed to PCs. The parameters' coordinates found in PCA allow us to establish which variable mainly weights by separating the three clusters: P, NDF, dNDF, and K distinguished EX trackers from ST and CTRL. Total PAR and yields represent the parameters that have characterized the CTRL and ST groups. Some relations can also be highlighted between the evaluated parameters and the increased stress from shading

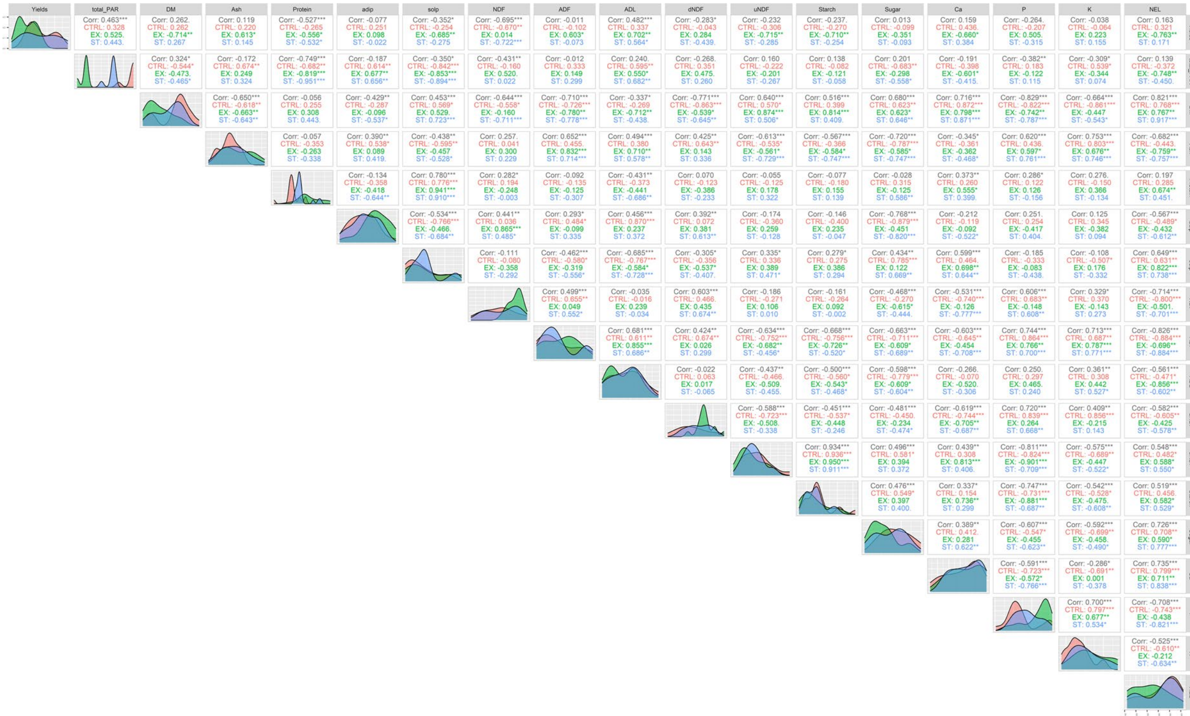

Fig. 4 Correlogram among variables which explained more than the 2% of variability both in PC1 and PC2, where "***" *p*-value < 0.001, "**" *p*-value < 0.01, "*" *p*-value < 0.05, "." *p*-value < 0.10

NE_L -0.8 (CTRL -0.9, ST -0.9, and EX -0.7). dNDF showed strong correlations with P (0.7 and -0,8, respectively), with a positive first one and a negative one for uNDF, representing the complementary indigestible fraction of the dNDF. Sugar and Ca showed a high positive correlation with NE_L (0.7). Finally, P showed a high positive correlation with K, 0.7 (CTRL 0.8, ST 0.5, and EX 0.7) and a negative correlation with NE_L -0.7 (CTRL -0.7, ST -0.8, and EX -0.4). However, there were many observations in which the different theses showed different correlation trends. Yields and NDF showed the same negative correlation in CTRL and ST. However, no correlation was observed in EX. The correlation between Dry matter and dNDF was -0.9 in CTRL, then decreased with increasing shading. A negative correlation between ADL and NE_L was observed (-0.5) in CTRL and then increased to -0.9 in EX.

Table 2 reports the least square means for each parameter analyzed for each statistically significant fixed effect included in the model. The tracker effect didn't affect ADF. It is striking that plant yield was higher in CTRL and ST (~ 7 tons DM ha-1) than EX (5.92 tons DM ha-1). As expected, differences concerning yield were reported between short and long cycles, 6 and ~ 8 tons DM ha^{-1}, respectively, and for the plant length parameter, which was highly reduced in the short cycle. DM ranged from 28.45% in CTRL to 23.35% in EX, making the tracker effect statistically significant for the DM parameter. The difference was slight but significant for ash content, i.e., 7.95 and 7.23% in long and short cycles, respectively. The protein content resulted distinct for each tracker, ranging from 12.06% in EX to 10.54% in CTRL. The short cycle presented higher protein content than the long one (12.16 vs 10.48%). For ADIP and NDIP, the EX tracker showed higher values than the other two groups. SolP resulted in 6.5% in the short and 4.5% in the long cycle. NDF reached 58.1% in the EX group; lower values were observed in ST and CTRL (54.74 and 53.64%, respectively). ADL was significantly higher in long cycles, while the tracker effect was not significant. The short cycle showed greater values for fat and sugar than the long one. The sugar content estimated in CTRL was 12.14%,

Table 2 Least square means (LSM) and standard error (SE) for parameters analyzed divided for tracker effect levels (CTRL = control; ST = standard; EX = extended panels) and cycle time effect levels (long and short)

Parameters	Effect levels	LSM	SE	group
Yield (t ha^{-1})	CTRL	7.66	0.43	a
	ST	7.45	0.43	a
	EX	5.92	0.47	b
	long	7.91	0.25	a
	short	6.11	0.54	b
Length (cm)	long	84.50	1.12	a
	short	66.88	2.40	b
PAR (W / m^{-2})	CTRL	723.73	1.63	a
	ST	592.00	1.60	b
	EX	412.76	1.76	c
	long	612.62	0.95	a
	short	535.72	2.04	b
DM (%)	CTRL	28.45	0.91	a
	ST	26.52	0.90	a
	EX	23.35	0.99	b
	long	23.64	0.53	b
	short	28.57	1.14	a
Ash (% of DM)	long	7.95	0.11	a
	short	7.23	0.23	b
Crude Protein (% of DM)	CTRL	10.54	0.13	c
	ST	11.37	0.13	b
	EX	12.06	0.14	a
	long	10.48	0.07	b
	short	12.16	0.16	a
Ndip (% of DM)	CTRL	1.98	0.17	b
	ST	2.06	0.17	ab
	EX	2.59	0.19	a
Adip (% of DM)	CTRL	0.62	0.03	b
	ST	0.63	0.03	b
	EX	0.74	0.03	a
	long	0.77	0.02	a
	short	0.56	0.03	b
SolP (% of DM)	long	4.49	0.07	b
	short	6.50	0.16	a
NDF (% of DM)	CTRL	53.64	0.98	b
	ST	54.74	0.97	b
	EX	58.10	1.06	a
ADL (% of DM)	long	4.96	0.06	a
	short	4.18	0.13	b
Fat (% of DM)	long	1.91	0.03	b
	short	2.36	0.06	a

Table 2 (continued)

Parameters	Effect levels	LSM	SE	group
Sugar (% of DM)	CTRL	12.14	0.33	a
	ST	11.57	0.33	ab
	EX	10.76	0.36	b
	long	10.52	0.19	b
	short	12.47	0.42	a
Ca (% of DM)	long	12.47	0.42	a
	short	10.52	0.19	b
P (% of DM)	CTRL	0.32	0.01	b
	ST	0.34	0.01	ab
	EX	0.36	0.01	a
Mg (% of DM)	CTRL	0.14	0.01	b
	ST	0.16	0.01	ab
	EX	0.19	0.01	a
	long	0.18	0.01	a
	short	0.14	0.01	b
K (% of DM)	CTRL	1.81	0.10	b
	ST	2.02	0.10	ab
	EX	2.17	0.11	a
dNDF (% of NDF)	CTRL	42.07	0.81	b
	ST	43.37	0.80	ab
	EX	45.21	0.87	a
	long	44.91	0.47	a
	short	42.19	1.01	b
NE_L (kcal kg DM^{-1})	long	7.23	0.02	a
	short	7.15	0.01	b

Total PAR, sum of the monthly averages; DM, dry matter; ADIP, acid detergent-insoluble protein; SolP, soluble protein; NDF, neutral detergent fiber with α-amylase, sodium sulfite, and correcting for ash contamination; ADL, acid detergent lignin; dNDF, digestible NDF evaluated after 24 h of in situ rumen incubations; uNDF, undigested NDF after 240 h of in situ rumen incubations; NE_L, net energy for lactation

while the lower value was found in EX (10.76%). The trend for minerals (P, Mg, and K) was similar: greater values in the EX group and slightly lower in CTRL, with ST tracker even with intermediate estimates. Ca and Mg resulted significant for cycle effect, showing higher values in the long cycle. dNDF ranged from 45% in EX to 42% in CTRL. NE_L was slightly higher in the long cycle than the short one (7.23 vs 7.15).

Discussion

Suitable light intensity is important for photosynthesis, as well as for attaining large biomass and the yield of valuable organs (Sun et al. 2011). The optimal light intensity for growth and development varies with the plant ecotype: total exposure to the sun is favorable for the biomass of sun plants (Ding et al. 2010), while a certain degree of shading can increase the biomass of shade plants. However, the relationship between reduction in solar radiation and crop yield is not simply proportional. Hence, a simple classification such as shade benefiting or susceptibility (Beck et al. 2012) is less meaningful than a detailed analysis of yield response curves, which helps optimize the shade level in AS (Laub et al. 2022). Reduced light substantially modifies the plant's characteristics and inhibits metabolic processes, including photosynthesis and antioxidant capacity (Guenni et al. 2018). Prolonged shade exposure elicits a group of growth responses collectively termed the Shade Avoidance Syndrome (SAS) (Ballaré and Pierik 2017). SAS responses consist of a range of morphological adjustments at the expense of leaf and storage organ expansion to avoid shade, including reduced branching, accelerated flowering time, and reduced growth cycle (Ballaré and Pierik 2017; Casal 2012; Wollenberg et al. 2008). To increase dairy cattle feed efficiency, and a better inclusion in diets, a better strategy should be adopted; to do this, a rapid assessment of the nutritional composition of the forage should be available for farmers (Ronga et al. 2020; Dal Prà et al. 2023b). The production of forages is a crucial element in the production areas of Parmigiano Reggiano PDO, and Grana Padano DOP cheese in Italy, where regulations require at least 50% of the dry matter (DM) of the ration coming from fodder and at least 75% from local crops. In this perspective, the development of AV technology can make a contribution but there is no information on the feed value produced under AV conditions. Yields, as dry matter values, measured during the two years have shown a difference between the three theses in the study (CTRL, ST, and EX) which is substantially proportional to the intensity of the shading. The result is not surprising considering that the accumulation of Carbon in wheat is basically a function of the amount of radiation absorbed. The feeling, however, that the overall effects are to be considered also in the light of possible thermal effects (average temperature of the canopy in the various theses) as recently demonstrated (Williams et al. 2023). Reher et al, (2024) carried out a study on the production of common wheat grain (2022 and 2023) and showed a significantly reduced yield of 33% (2.9 $t.ha^{-1}$ and 3.1$t.ha^{-1}$) compared to the control (4.6 $t.ha^{-1}$) in 2022. For the 2023 season, overall wheat yield under AV (vertical bifacial) decrease on average by 46% (1.1 $t.ha^{-1}$ and 2.2$t.ha^{-1}$). According to Prakash et al., (2023) shading treatments (and different density of agrivoltaic systems) showed that biological and grain yield was decreased with an increase in shading intensity. There is no bibliography on the feed biomass quality produced in AS. The Italian hays are often of low quality and reduced nutrient value due to climatic conditions (Palmonari et al. 2016); therefore, studies of forage biomass produced in AS are desirable. The nutritive value of whole wheat is determined by phenological state and environmental factors such as soil, weather conditions, grazing, and cutting management.

The yield of biomass in Durum wheat in AS is moreover challenging to predict, this parameter despite being as important as the quality of the feed samples. Italy has included a limit for Ground Coverage Ratios in AS, which is at 40% (Dupraz 2023); we have included in our experimental design a treatment (EX) that approaches this regulatory constraint intending to evaluate the results of production and quality of biomass of whole wheat plant durum. In our study, yields showed low correlations with PAR (0.463). Forages show adaptation mechanisms to RSR, which resulted in no effect on DM yield at 30% RSR (Mercier et al. 2020) and 45% RSR or, depending on the crop species, even a slight increase of DM yield at 45% RSR (Pang et al. 2019). In our study, yield losses were limited in ST and became significant in EX; according to (Laub et al. 2022), losses can become disproportionately large starting at 10% RSR for C3 cereals; at around 50% of shading, all crops show susceptibility. However, there are no studies related to shadow stress in AS where transmitted radiation varies with panel (type, size, density, and placement design), latitude, climate, and time of day. Moreover, the bibliography that correlates the nutritional value of the fodder and the factors listed above is very limited and incomplete, and very useful contributions were provided by (Campana et al. 2021 and Dupraz 2023). The present study showed that fodder produced in AS may be of interest for ruminant nutrition, mainly in the Total Mixed Ratio (TMR) of lactating and heifer cows. Results regarding the fiber fraction are reported in Table 1. In our study the value of neutral fiber detergent with α-amylase, sodium sulfite (NDF) was higher in EX, no difference was observed by Edouard et al., (2023) on alfalfa under similar shading conditions. In the same study however, alfalfa biomass increased by 10% in average in the shade of the AS, for shading between 29 and 44% (Edouard et al. 2023). In our study, differences were observed for dNDF, which in CTRL recorded 43.0 (% of NDF), 44.0% in ST, and 46.0% in EX, with a trend that, unlike other studies, cannot be attributed to the different phenological stages of wheat (Ronga et al. 2020). Crude protein content (expressed as % of DM) differed between CTRL (10.0 ± 0.7%) and ST or EX (11.0 ± 0.7 and 12.0 ± 1.1%, respectively). The ADIP and soluble protein concentrations also were different between CTRL (0.7 ± 0.1%, and 4.6 ± 0.9%) and ST or EX (0.7 ± 0.1%, 4.9 ± 0.8% and 0.8 ± 0.1%, 5.0 ± 1.1%, respectively). Limited differences were instead observed for acid detergent fiber (ADF), and acid detergent lignin (ADL), suggesting that different levels of shading had little effect on these fractions. Starch decreased with the increasing shadow, these findings are related to advancing of the plant growth cycle and to the storage of less efficient photosynthates in the grain. Biomass was collected at the same phenological stage on all levels of shading, however in the EX thesis a lower sugar level was observed. This reduction to the increase of the shading area has also been observed for net energy for lactation (NE_L) predicted, representing the energy needed for all important functions of a cow. Of the macromineral requirements of dairy cattle, calcium, and phosphorus are most often considered due to their roles in skeletal structure, metabolism, and milk (NRC 2001). Calcium requirements of lactating are higher than nonlactating because of the high Ca concentration in milk; in our study, a higher Ca content was observed in EX. According to (Kienzle et al. 2008), mineral contents of forages were low for Ca with a negative correlation with dNDF and aNDFom parameters. Also, P content increased in the most shaded thesis EX; these observations make the fodder biomass different and should be used differently between lactating and heifers. The biomass in the shaded treatments showed a better Ca: P ratio for ruminant nutrition. By contrast, the higher content of K in EX could interfere with calcium homeostasis.

Conclusion

We investigated the impact of limitations of light on Durum wheat yield and quality on the whole plant, also creating an extreme stress treatment compared to the standard condition of Agrivoltaic systems. Two years of controlled experiments revealed that the reduction in light moderately limited wheat yields in the phenological phase of soft dough in standard agrivoltaic tracker (i.e. GCR = 13%); the reduction was 29.6% in extended panels (GCR = 41%). In this study, we tested a long and shorter cycle with sowing carried out in February. The reduced light substantially changed the length of the plants; this affected the quality of the fodder biomass of the whole durum wheat plant. Shading influences the protein and fiber fractions in wheat biomass but greatly affects digestibility. The digestible NDF evaluated after 24 h of in situ rumen incubations increasing with shading, resulting in different ratios of acid detergent lignin. This effect must be considered and implemented into the modern calculating software to formulate an optimal diet with forage wheat inclusion. The biomass in the shaded theses showed a better Ca: P ratio for ruminant nutrition. This new contribution to the knowledge of the nutritional characteristics of Durum wheat produced on AS will allow a better inclusion of the different types in diets and a better management of silage or hay harvesting sites.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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