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Article

Effect of Light Intensity and Spectra on Inorganic Constituents in Vietnamese Coriander (*Persicaria odorata* (Lour.) Soják)

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Abstract: With the aim of optimizing resources in regional production of nutritive valuable leafy vegetables, this study was conducted to obtain more knowledge regarding the interdependencies between light conditions and accumulation of inorganic constituents. The test plant, *P. odorata*, was cultivated in a climate chamber with fluorescent tubes as the main light source and daylight integrals (DLI) varying between 4.68 and 9.06 mol·m^{-2}·day^{-1}. The average DLI in greenhouse experiments was 41.55 mol·m^{-2}·day^{-1}. Light conditions were modified using additional LEDs (443, 515, and 629 nm) or by covering the plants with photoselective plastic films, leading to a lower DLI and modified light spectrum, especially by reducing the green spectral range. Contents of nitrate, phosphorus, potassium, magnesium, calcium, and iron, biomass accumulation, and water content were analyzed. In terms of particular light modifications, additional green (515 nm) and red (629 nm) LEDs showed reducing effects on nitrate content at both cultivation locations. Other inorganic constituents were affected differently depending on cultivation location. However, the calculation of average partial correlation coefficients enabled a more general statement. Increasing DLI correlated positively with contents of magnesium, nitrate, and potassium but negatively with contents of calcium and iron. Additionally, nitrate content correlated positively with the spectral range of 651–700 nm but negatively with the R:FR ratio. Consequently, a general recommendation related to the light conditions is not possible, as inorganic constituents were affected differently. Nevertheless, as the nitrate content in leafy vegetables is of high concern and was reduced by higher shares of green or red light, this might be one way to regulate nitrate content in leafy vegetables.

Keywords: light intensity; blue, green, and red light spectra; LED; photoselective plastic; minerals; nitrate

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1. Introduction

Consumers' growing interest in sustainable and fresh food with high nutritional quality increases demand for locally produced fruits and vegetables. As latitude increases, lower levels of irradiation limit year-round cultivation, making additional lighting in greenhouses or cultivation in indoor farms necessary. This results, depending on used energy sources, in high energy costs and possibly negative impacts on the environment, requiring an energy-efficient use of lighting systems. Therefore, a better knowledge regarding the impact of light intensity and spectral composition on the accumulation of biomass and nutrients is required to allow a year-round, resource-saving production of fruits and vegetables with high nutritional quality.

Recently, setting the light conditions in greenhouses and indoor farms has mainly focused on provisioning high shares of blue and red spectral ranges [1], as these spectral ranges are seen as most effective for photosynthesis [2]. However, this approach barely considers the impact of light conditions on the nutritive quality of plants, although several studies have shown that secondary metabolites, such as polyphenols [3–5] or flavonoids [4,6,7], are affected by light conditions. On the contrary, the effects of light conditions on the contents of inorganic constituents have only been investigated in a few studies so far. Various minerals are, directly or indirectly, relevant for photosynthetic processes in plants. Among others, potassium is part of several enzymes involved in the synthesis of isoprenoids [8] and porphyrin [9]. Magnesium is the central ion of chlorophyll molecules [10], and iron is involved in photosynthesis, respiration, and chlorophyll synthesis [11]. The results of a few studies describing the impacts of light conditions on the contents of minerals are promising. For example, Samuoliene et al. (2021) [12] showed the positive impacts of green light on several minerals (e.g., potassium, calcium, iron, and magnesium) in *Solanum lycopersicum*. Moreover, the accumulation of several minerals was affected positively by higher ratios of B:R in *Ocimum basilicum* L. [13] and *Lactuca sativa* L. [14].

However, despite the fact that many minerals are essential for humans, e.g., for oxygen transport (iron) [15], intracellular signal transduction (calcium) [16], and the membrane potential of cells and cell excitability (potassium) [17], options to enhance mineral contents in food plants are rarely investigated, especially considering that intake recommendations (e.g., for iron [18] and calcium [19]) are not reached by population groups in Europe and/or Germany.

Results of previous studies and the involvement of various minerals in photosynthetic processes and/or plant growth proposed the idea that their contents might be influenceable by the light conditions. Accordingly, the aim of this study was to investigate the impact of light conditions on contents of inorganic constituents in plants. As a model plant, the Asian herb *Persicaria odorata* (Lour.) Sojak was selected because of its simple cultivation and the short period between planting the cuttings and harvest (3–4 weeks). Additionally, *P. odorata* is known for its particularly high content of polyphenols and antioxidants [20,21], whose response to additional blue (443 nm), green (515 nm), and red light (629 nm) was described previously [22]. Therefore, the present paper focuses on the possible effects of light conditions on selected inorganic substituents in *P. odorata*, cultivated under realistic conditions in greenhouse and set conditions in a climate chamber. As there is little knowledge regarding the effects of light conditions on the contents of inorganic constituents, all light parameters need to be considered. For this purpose, natural sunlight (greenhouse) and the light of fluorescent tubes (climate chamber) were modified using monochromatic LED and photoselective plastic films, leading to changes in the spectral composition of light, including ratios between spectral ranges, as well as the daylight integral. The knowledge obtained in this study might help to understand the effects of light on inorganic constituents in selected herbs to optimize the use of resources in greenhouse and vertical farming for plant production with increased nutritional values.

2. Material and Methods

2.1. Plant Material and Cultivation

Test plant *Persicaria odorata* underwent vegetative propagation, allowing the use of genetically identical plants for the study. Cuttings were obtained from mother plants cultivated in a greenhouse, planted in 35-cell plug trays (44 cm × 28 cm × 5.5 cm), and maintained in a greenhouse. After 10 days, they were potted in 6 L Mitscherlich pots (described by Bergmann, 1957 [23]). Five plants were cultivated in each pot. After planting, all plants were allowed to acclimatize in the greenhouse or climate chamber under control conditions for 1 week. After that, treatment under different light conditions took 3 weeks. As growing substrate, "Gramoflor" was used containing white peat (65%), black peat (20%), and perlite (0.2–6 mm) (15%), produced by the company Gramoflor GmbH and Co. KG (Vechta, Germany). The basic composition of nutrient solution used during the experiment was as follows: N (110 ppm), P (50 ppm), K (225 ppm), Ca (120 ppm), Mg (80 ppm), HCO_3 (90 ppm), SO_4 (60 ppm), and microelements, including Fe (10 ppm). The EC value was equal to 1.5 mS·cm^{-1}, and the pH value was 5.8, adjusted using H_3PO_4 (85%). The HYDROFER computer program compatible with Excel [24] was used to calculate the required amounts of fertilizers, salts, and acids.

2.2. Growth Conditions

Climate parameters in chambers were constant and controlled using a computer. Temperature was set to 24/19 °C (day/night) and relative air humidity was set to 64/56% (day/night), with 16 h day/8 h darkness. As the main light source in climate chambers, 14 fluorescent tubes F58W/827 (Luxline Plus: Feilo Sylvania Germany GmbH, Erlangen, Germany) were used, placed 1 m above the bottom of the chamber. The daylight integral (DLI), provided by fluorescent tubes, was modified in the range of 4.68 to 9.06 mol·m^{-2}·day^{-1}. As the daylight integral was the same for one treatment and the respective control but differed between treatments, absolute values could only be compared between them and not between different treatments. The three-band fluorescent tubes had emission maxima in the blue (435 nm), green (545 nm), and red (611 nm) spectral range (Figure 1 and Table 1; measured using SpectraWiz Spectroradiometer PS-100).

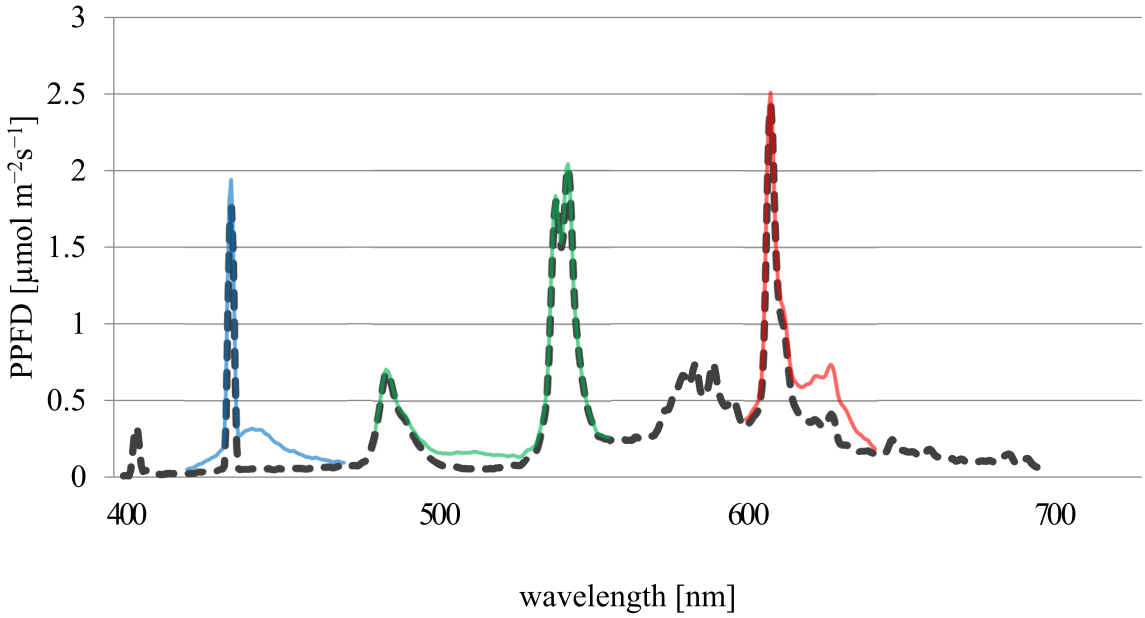

Figure 1. Light spectrum of fluorescent tubes (FTs) (dashed black line), modified using LEDs (blue line: bLED; green line: gLED; red line: rLED) in the climate chamber, measured using an AvantesAvaSpec NIR 256 spectrometer.

Table 1. Daylight integral and spectral light composition of fluorescent tubes (FTb, FTg, FTr = control), modified by LEDs (FT + B: emission maximum at 443 nm, irradiance: 11 µmol·m^{-2}·s^{-1}; FT + G: emission maximum at 515 nm, irradiance: 7 µmol·m^{-2}·s^{-1}; FT + R: emission maximum at 629 nm, irradiance: 12 µmol·m^{-2}·s^{-1}) in a climate chamber, measured using an Avantes-AvaSpec NIR 256 spectrometer.

Treatment	Daylight Integral [mol·m^{-2}·day^{-1}]	Share of Spectral Ranges on Total Radiation (%)					
		401–450 nm	451–500 nm	501–550 nm	551–600 nm	601–650 nm	651–700 nm
FTb	4.68	7.8	10.6	22.8	23.9	27.7	6.8
FT + B	5.07	15.3	13.0	20.1	21.1	24.4	6.1
FTg	6.51	7.8	10.6	22.8	23.9	27.7	6.8
FT + G	6.30	7.4	11.0	26.1	22.7	26.2	6.6
FTr	9.06	7.8	10.6	22.8	23.9	27.7	6.8
FT + R	8.61	7.3	9.9	21.2	22.3	32.8	6.5

Greenhouse experiments were conducted in summer 2013 in the research greenhouse of the Humboldt University of Berlin, Research station Berlin-Dahlem, under natural light. The average daylight integral was 41.55 mol·m^{-2}·day^{-1}. The mean temperature was 30/25 °C (day/night), and the mean relative air humidity was 49%/76% (day/night).

2.3. Light Modification Using LED and Photoselective Plastic Films

With the aim of modifying light conditions in the greenhouse and climate chamber, LED and photoselective plastic films were used. In order to enhance specific light spectra, for each treatment, four LED stripes (l = 120 cm), (Type 25514666; Guangdong Kosoom Lighting, China) were used as additional light sources: blue LED emitted with a maximum of 443 nm (Figure 1, Table 1) (irradiance: 11 µmol·m^{-2}·s^{-1}), matching with the absorption maximum of chlorophylls. To enhance shortwave green light spectra around 500 nm, which was barely paid attention to in previous studies, green light was applied with an emission maximum of 515 nm (irradiance: 7 µmol·m^{-2}·s^{-1}). The emission maximum of the applied red LED (629 nm, irradiance: 12 µmol·m^{-2}·s^{-1}) also belongs to the absorption spectrum of chlorophylls. In the climate chamber, LEDs were placed horizontally 80 cm from the bottom of the chamber. In the greenhouse, LED stripes were fixed on movable wooden frames (80 × 90 cm), with four stripes on each frame. Frames were placed above plants with a distance between frames and plants of 10–15 cm.

In order to modify both spectral composition and light intensity, photoselective plastic films "Half Minus Green" ("H") and "Pale Lavender" ("P") from Lee Filters (UK) were used (Figure 2, Tables 2 and 3). The daylight integral was lowered, depending on cultivation location, by 22% (Half Minus Green) and 46% (Pale Lavender) in the greenhouse and by 28% (Half Minus Green), 43% (Pale Lavender "P1"), and 60% (Pale Lavender "P2") in the climate chamber.

Table 2. Daylight integral and spectral light composition of fluorescent tubes (FTh, FTp1, FTp2 = control), modified by photoselective plastic films (FT + H: covering with "Half Minus Green"; FT + P1: covering with "Pale Lavender", decrease in light intensity by 43%; FT + P2: covering with "Pale Lavender", decrease in light intensity by 60%) in climate chamber, measured using an Avantes-AvaSpec NIR 256 spectrometer.

Treatment	Daylight Integral [mol·m^{-2}·day^{-1}]	Share of Spectral Ranges on Total Radiation (%)					
		401–450 nm	451–500 nm	501–550 nm	551–600 nm	601–650 nm	651–700 nm
FTh	6.51	7.8	10.6	22.8	23.9	27.7	6.8
FT + H	4.69	8.1	11.1	20.7	23.6	30.5	7.7
FTp1	4.68	7.8	10.6	22.8	23.9	27.7	6.8
FT + P1	2.67	9.7	12.4	20.1	20.7	29.5	9.5
FTp2	9.06	7.8	10.6	22.8	23.9	27.7	6.8
FT + P2	3.62	9.7	12.4	20.1	20.7	29.5	9.5

Table 3. Spectral light composition of natural light (NL = control), modified by photoselective plastic films (NL + H: covering with "Half Minus Green"; NL + P: covering with "Pale Lavender", in greenhouse, measured using an Avantes-AvaSpec NIR 256 spectrometer.

Treatment	Transparency (%)	Share of Spectral Ranges on Total Radiation (%)					
		401–450 nm	451–500 nm	501–550 nm	551–600 nm	601–650 nm	651–700 nm
NL	100	1.8	15.6	17.1	18.9	19.0	18.8
NL + H	77.9	11.0	16.3	14.1	15.2	21.6	21.9
NL + P	53.9	13.4	18.2	13.2	10.8	16.7	28.1

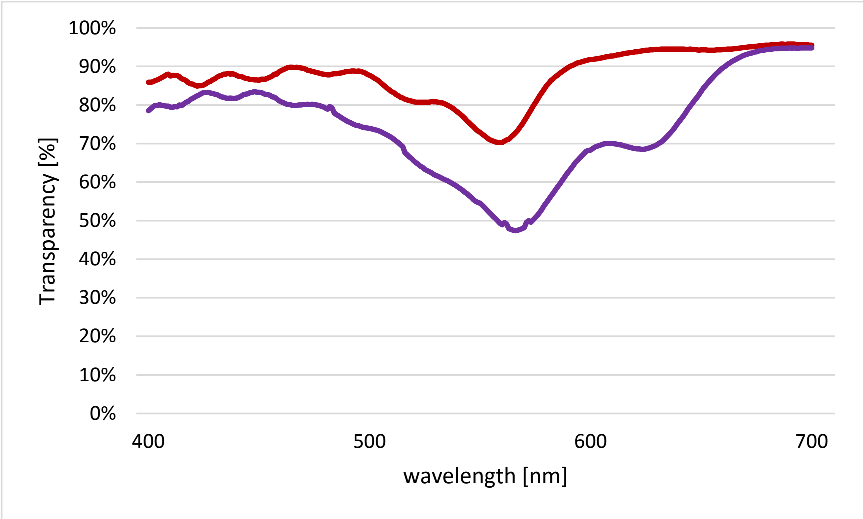

Figure 2. Transparency of photoselective plastic films (red: Half Minus Green ("H"), purple: Pale Lavender ("P")), measured using Unicam UV/Vis Spectrometer UV2.

2.4. Determination of Fresh and Dry Matter, Water Content

Four weeks after placing all plants in the containers, they were harvested. To determine the fresh matter (FM) of *P. odorata*, all leaves were removed from stems and weighed without petioles, as the marketable part of this plant. The leaves were dried at 60 °C to constant weight, expressed as dry matter (DM). Under consideration of fresh and dry matter, water content (%) was calculated.

2.5. Determination of Inorganic Constituents

The content of inorganic constituents (potassium, iron, calcium, magnesium, phosphor, and nitrate) in dried leaves was analyzed at the end of the experiment. After microwave digestion with nitric acid and hydrogen peroxide, potassium, calcium, magnesium, and phosphor were determined using ICP-OES. Analyses of iron were conducted using AAS. Nitrate was extracted with water and quantified using RQflex.

2.6. Data Evaluation

For statistical evaluation of the data, statistical software SAS was applied. Mean values and standard deviations were calculated and analyzed using ANOVA (Tukey test, significance level $p \leq 0.05$). Before analysis of variance, data were tested for normality using the Shapiro–Wilk test. In order to differentiate the effects of different light parameters, partial correlation coefficients were calculated. Depending on the scaling of the data, the Pearson correlation coefficient or Spearman rank correlation was applied. To calculate average correlation coefficients, coefficients were transformed via Fisher-Z transformation, averaged, and then transformed back. To assess the strength of linear relationships between analyzed constituents and fresh matter or water content, Pearson correlation coefficients were calculated (significance level $p \leq 0.05$).

3. Results

Contents of inorganic constituents were affected differently depending on cultivation location and light modification.

3.1. Inorganic Constituents—Cultivation in Greenhouse

In the greenhouse, plants cultivated under natural light with enhanced shares of blue light spectral ranges (NL + B) had significantly higher contents of nitrate and potassium, as well as significantly higher dry and fresh mass and water content compared to plants cultivated under natural light (NL) (Table 4). Higher shares of shortwave green light

(NL + G) significantly decreased nitrate and magnesium contents, as well as dry and fresh matter. Plants cultivated under natural light with enhanced shares of red light spectral ranges (NL + R) contained more phosphorus and potassium and had a higher water content while magnesium content and dry matter were lower.

Table 4. Influence of light conditions on inorganic constituents and growth parameters (fresh and dry matter, water content) in *P. odorata*, cultivated in greenhouse under natural light (NL), modified by additional LEDs (NL + B: emission maximum at 443 nm, irradiance: 11 $\mu mol \cdot m^{-2} \cdot s^{-1}$; NL + G: emission maximum at 515 nm, irradiance: 7 $\mu mol \cdot m^{-2} \cdot s^{-1}$; NL + R: emission maximum at 629 nm, irradiance: 12 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

	NL	**NL + B**	**NL + G**	**NL + R**
Nitrate [$mg \cdot g^{-1}$ DM]	16.72 ^{b}	24.16 ^{a}	11.70 ^{c}	13.30 ^{bc}
P [$mg \cdot g^{-1}$ DM]	7.86 ^{ab}	7.84 ^{ab}	7.56 ^{b}	7.94 ^{a}
K [$mg \cdot g^{-1}$ DM]	38.90 ^{b}	41.66 ^{a}	40.53 ^{ab}	42.55 ^{a}
Mg [$mg \cdot g^{-1}$ DM])	7.84 ^{a}	6.73 ^{ab}	6.50 ^{b}	6.60 ^{b}
Ca [$mg \cdot g^{-1}$ DM]	26.26	23.73	24.63	24.58
Fe [$mg \cdot g^{-1}$ DM]	0.12	0.13	0.14	0.16
Fresh matter [g/plant]	32.18 ^{ab}	33.97 ^{a}	28.79 ^{c}	30.62 ^{bc}
Dry matter [g/plant]	4.38 ^{a}	4.26 ^{a}	3.50 ^{b}	3.48 ^{b}
Water content [%]	86.57 ^{c}	87.96 ^{ab}	87.39 ^{bc}	88.74 ^{a}

The mean values are shown; lowercase letters indicate significant differences between treatments (Tukey test, $p \leq 0.05$).

Simultaneous modification of the spectral composition and light intensity of natural light by covering plants with photoselective plastic films had, overall, less of an effect on inorganic constituents than enhancing specific light spectra by adding LEDs. Both plastic films significantly decreased the contents of nitrate and magnesium, as well as fresh and dry matter, but increased iron content (Table 5).

Table 5. Influence of light conditions on inorganic constituents and growth parameters (fresh and dry matter, water content) in *P. odorata*, cultivated in greenhouse under natural light (NL), modifiedby covering plants with photoselective plastic films (NL + H: covering with "Half Minus Green"; NL + P: covering with "Pale Lavender").

	NL	**NL + H**	**NL + P**
Nitrate [$mg \cdot g^{-1}$ DM]	16.72 ^{a}	10.97 ^{b}	10.14 ^{b}
P [$mg \cdot g^{-1}$ DM]	7.86	7.79	7.41
K [$mg \cdot g^{-1}$ DM]	38.9	39.85	40.1
Mg [$mg \cdot g^{-1}$ DM])	7.48 ^{a}	6.65 ^{b}	6.31 ^{b}
Ca [$mg \cdot g^{-1}$ DM]	26.26	27.54	25.76
Fe [$mg \cdot g^{-1}$ DM]	0.12 ^{b}	0.14 ^{a}	0.15 ^{a}
Fresh matter [g/plant]	32.18 ^{a}	21.68 ^{b}	18.19 ^{c}
Dry matter [g/plant]	4.38 ^{a}	2.83 ^{b}	2.46 ^{b}
Water content [%]	86.57 ^{ab}	87.19 ^{a}	86.43 ^{b}

The mean values are shown; lowercase letters indicate significant differences between treatments (Tukey test, $p \leq 0.05$).

3.2. Inorganic Constituents—Cultivation in Climate Chamber

In the climate chamber, higher shares of blue light (FT + B) increased the content of magnesium, as well as fresh and dry matter (Table 6). Higher shares of green light increased magnesium and calcium but lowered the water content of plants significantly. Increased shares of red spectral ranges (FT + R) lowered the contents of nitrate, phosphorus, and potassium, as well as the fresh matter and water content of the plants.

Table 6. Influence of light conditions on inorganic constituents and growth parameters (fresh and dry matter, water content) in *P. odorata*, cultivated in the climate chamber under fluorescent tubes (FTb, FTg, FTr = control), modified by additional LEDs (FT + B: emission maximum at 443 nm, irradiance: 11 $\mu mol \cdot m^{-2} \cdot s^{-1}$; FT + G: emission maximum at 515 nm, irradiance: 7 $\mu mol \cdot m^{-2} \cdot s^{-1}$; FT + R: emission maximum at 629 nm, irradiance: 12 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

	FTb	FT + B	FTg	FT + G	FTr	FT + R
Daylight integral [$mol \cdot m^{-2} \cdot day^{-1}$]	4.68	5.07	6.51	6.30	9.06	8.61
Nitrate [$mg \cdot g^{-1}$ DM]	21.07	18.52	21.80	18.53	27.10 ^{a}	15.66 ^{b}
P [$mg \cdot g^{-1}$ DM]	7.93	7.90	8.08	7.69	7.41 ^{a}	5.87 ^{b}
K [$mg \cdot g^{-1}$ DM]	37.56	37.59	38.67	37.66	40.90 ^{a}	35.41 ^{b}
Mg [$mg \cdot g^{-1}$ DM])	6.99 ^{b}	7.70 ^{a}	8.46 ^{b}	9.42 ^{a}	7.77	8.47
Ca [$mg \cdot g^{-1}$ DM]	25.09	26.21	25.13 ^{b}	27.48 ^{a}	22.46	24.43
Fe [$mg \cdot g^{-1}$ DM]	0.14	0.15	0.13	0.13	0.13	0.14
Fresh matter [g/plant]	21.29 ^{b}	28.83 ^{a}	32.57	34.51	43.15 ^{a}	37.80 ^{b}
Dry matter [g/plant]	2.78 ^{b}	3.86 ^{a}	4.16	4.87	5.03	5.28
Water content [%]	86.95	86.59	87.24 ^{a}	85.86 ^{b}	88.35 ^{a}	85.95 ^{b}

The mean values are shown; statistical evaluations consider only differences between the treatment and respective control (e.g., FTb and FT + B); lowercase letters indicate significant differences (Tukey test, $p \leq 0.05$).

Lower light intensities and modified spectral compositions by covering the plants with photoselective plastic films had minimal effects on inorganic constituents and growth parameters (Table 7). Decreases in light intensity by 43% and 60% with simultaneous modification of spectral light composition ("P1" and "P2") lowered the fresh and dry matter of the plants. However, only the organic constituents of plants cultivated under lower light intensities (−60%, "P2") were affected significantly. The contents of calcium and iron were increased by the cover, whereas magnesium content decreased.

Table 7. Influence of light conditions on inorganic constituents and growth parameters (fresh and dry matter, water content) in *P. odorata*, cultivated in the climate chamber under fluorescent tubes (FTh, FTp1, FTp2 = control), modified by covering plants with photoselective plastic films (FT + H: covering with "Half Minus Green"; FT + P1: covering with "Pale Lavender", decrease in light intensity by 43%; FT + P2: covering with "Pale Lavender", decrease in light intensity by 60%).

	FTh	FT + H	FTp1	FT + P1	FTp2	FT + P2
Daylight integral [$mol \cdot m^{-2} \cdot day^{-1}$]	6.51	4.69	4.68	2.67	9.06	3.62
Nitrate [$mg \cdot g^{-1}$ DM]	21.80	20.13	21.07	20.40	27.10	30.28
P [$mg \cdot g^{-1}$ DM]	8.08	7.98	7.93	7.99	7.41	7.70
K [$mg \cdot g^{-1}$ DM]	38.67	37.65	37.56	37.38	40.90	41.23
Mg [$mg \cdot g^{-1}$ DM])	8.46	8.44	6.99	7.35	7.77 ^{a}	7.00 ^{b}
Ca [$mg \cdot g^{-1}$ DM]	25.13	25.60	25.09	26.98	22.46 ^{b}	27.84 ^{a}
Fe [$mg \cdot g^{-1}$ DM]	0.13	0.12	0.14	0.15	0.13 ^{b}	0.15 ^{a}
Fresh matter [g/plant]	32.57	30.47	21.29 ^{a}	18.45 ^{b}	43.15 ^{a}	19.40 ^{b}
Dry matter [g/plant]	4.16	3.86	2.78 ^{a}	2.47 ^{b}	5.03 ^{a}	2.10 ^{b}
Water content [%]	87.24	87.29	86.95	86.50	88.35	89.17

The mean values are shown; statistical evaluations consider only differences between the treatment and respective control (e.g., FTp1 and FT + P1); lowercase letters indicate significant differences (Tukey test, $p \leq 0.05$).

3.3. Calculated Interdependencies between Analyzed Parameters and Light Parameters

Adding LEDs to natural light or fluorescent tubes, as well as covering plants with plastic films, affected various light parameters. Accordingly, the results do not allow a statement whether changes can be assigned to modifications of light intensity or spectral composition. To differentiate the effects of different light parameters on the considered constituents, partial correlation coefficients were calculated (Table 8). Taking all test series and light modifications into account, modifications of contents could mainly be assigned to changes in daylight integral. Partial correlation coefficients suggested positive interdependencies between daylight integral and nitrate and magnesium, while there appeared to be a negative interdependence between daylight integral and contents of calcium and iron. Spectral compositions appeared to have less impact on the contents of inorganic constituents. Exceptions were the BR:G ratio for nitrate and phosphorus, R:FR ratio for nitrate and longwave blue light (451–500 nm) and longwave green light (551–600 nm) for iron. Overall, results and partial correlation coefficients demonstrated only few connections between light parameters and contents of inorganic constituents, leaving the question of how to explain significant differences between treatments. Reviewing the data, it is noticeable that plants with high biomass accumulation tended to have lower contents of most analyzed minerals, including iron and calcium. This observation was confirmed by calculating correlation coefficients in accordance with Riedell (2010) [25] between contents of inorganic constituents (mg/g DM) and dry matter (g/plants) (Table 9), indicating negative correlations between the contents of most considered inorganic constituents (phosphorus, potassium, calcium, and iron) and the dry matter of the plants. A positive correlation was only calculated for magnesium. Nitrate did not correlate significantly with dry matter but, like potassium, correlated with the water contents of the plants.

Table 8. Interdependencies (average partial correlation coefficients) between light parameters and contents of inorganic constituents or fresh and dry matter, as well as water content, of *P. odorata*, cultivated in the greenhouse or climate chamber under natural light or fluorescent tubes, modified by additional LEDs or photoselective plastic films.

	Partial Correlation Coefficients											
	DLI	Share of Spectral Ranges						Ratio between Spectral Ranges				
		401–450	451–500	501–550	551–600	601–650	651–700	B:R	BR:G	B:G	R:G	R:FR
Nitrate	0.30	0.18	0.01	−0.20	0.02	0.03	0.39	0.30	0.45	0.45	−0.03	−0.68
P	−0.03	−0.02	0.01	0.08	0.28	−0.10	−0.08	−0.15	−0.48	0.00	0.05	0.34
K	0.21	0.20	0.15	−0.05	0.02	−0.27	0.26	0.16	−0.15	0.08	−0.08	−0.25
Mg	0.36	0.00	−0.02	−0.13	−0.05	0.17	−0.24	−0.14	0.37	0.12	−0.04	−0.07
Ca	−0.39	0.20	−0.09	−0.29	−0.16	−0.10	−0.04	−0.12	0.03	−0.03	0.22	0.16
Fe	−0.31	0.29	0.46	0.14	−0.51	−0.06	−0.30	0.27	−0.13	0.10	0.15	−0.04
FM	0.75	0.37	0.32	0.08	−0.14	−0.34	0.16	0.22	0.45	0.41	−0.27	−0.32
DM	0.64	−0.31	−0.22	0.02	−0.06	0.04	−0.20	−0.15	−0.14	−0.22	−0.12	0.13
Water content	0.14	−0.40	−0.35	−0.09	0.53	0.15	−0.41	−0.31	−0.21	−0.42	−0.22	0.73

Table 9. Interdependencies (Pearson correlation coefficients) between contents of inorganic constituents and dry matter or water content of plants.

	Nitrate	P	K	Mg	Ca	Fe
Dry matter [g/plant]	0.02	**−0.51**	**−0.26**	**0.65**	**−0.37**	**−0.37**
Water content [%]	**0.23**	0.09	**0.49**	0.16	0.04	0.02

Bold values indicate significant correlations ($p \leq 0.05$).

4. Discussion

Although inorganic constituents were affected by light modifications, differences between test series did not allow a clear picture. An exception would appear to be the nitrate content that correlated positively with daylight integral. This finding was surprising. As nitrate functions as a regulator of osmotic pressure [26–28], higher contents at lower light levels were expected, as described by others [28–33]. However, a study with lettuce [34] did not show any clear relationship between nitrate content and daylight integral. The observed positive correlation of nitrate content and water content (Table 9) can be explained and has been described before [35–37]. In contrast to the analyzed minerals, an effect of spectral ranges on nitrate content was observed. Enhancing red and green spectral ranges led to decreased nitrate levels. Related to green spectral range, this result confirms the observations of Gräf et al. (2020) [38], presenting lower nitrate levels in cabbage, pak choi, and rocket using RGB treatment instead of RB treatment. As a possible explanation, results of Bian et al. (2018) indicated a promotion of nitrate reductase and nitrite reductase-related gene expression, as well as higher activities of enzymes involved in nitrate assimilation [39]. With regard to the effects of red light on nitrate content, results are supported by Chen et al. (2021) [40], demonstrating positive impacts of higher shares of red light on nitrate content in lettuce. In the present study, nitrate content additionally correlated negatively with R:FR ratio. This leads to the assumption that somehow phytochromes are involved. This observation could be explained by a positive impact of phytochromes on the expression of nitrate reductase, proven in other studies [41–44].

In addition to nitrate, magnesium correlated positively with daylight integral, confirming the results found in lettuce [45]. However, this finding was not unexpected, as studies previously described a higher demand of magnesium as a reaction to higher light intensities [46–50], to prevent damage to photosynthetic electron transport [47,51]. On the contrary, calcium and iron contents correlated negatively with daylight integral. Regarding calcium, this observation confirms the results of other studies [44–54]. However, a causal connection has not yet been clarified. At the same time, calcium correlated negatively with dry matter. Other have described the nonproportional uptake of nutrients compared to the rate of accumulation of dry matter, known as the dilution effect [55–57], or compared to the higher concentration of minerals, known as the synergy effect [55]. As the accumulation of biomass depends on the availability of light, it might be possible that calcium content was not directly affected by light conditions but by the rate of biomass accumulation and, therefore, indirectly by light intensity. Similarly to calcium, iron correlated negatively with daylight integral. A negative impact of increasing light intensities on iron content has previously been described [54,58]. In addition, iron correlated negatively with dry matter. This might indicate a dilution effect, which was previously described for iron [59]. The growth-related dilution of iron content was explained by McGrath (1985) [57] as due to the low diffusion coefficient. As a result, iron ions move slowly to the roots, and the iron demand of fast-growing plants might not be required.

Although phosphorus and potassium contents differed between treatments, no clear impact of light conditions was calculated under consideration of all test series and treatments. These results were not unexpected, as previous studies did not show clear results. In terms of phosphorus, several studies have obtained contradictory results regarding the impact of light intensity. In some studies, light intensity had no impact on phosphorus content [54,60,61]. Other studies proved higher contents when light intensity decreased [44,62,63]. In *Tagetes patula*, additional lighting with red or blue LEDs had no effect on phosphorus content [64]. Although there was no clear impact of light conditions on phosphorus content, it correlated negatively with dry matter, indicating a dilution effect.

Lower contents of phosphorus at higher rates of biomass accumulation have been described for young leaves of *Larix laricana*, *Picea mariana*, *Betula papyrifera*, and *Almus crispa* [65,66]. Similarly to phosphorus, no clear connection could be described for light conditions and potassium content, confirming the observations of Sams et al. (2016) [64]. However, a clear correlation was calculated for potassium content and water content.

This correlation was previously described by Leigh and Johnston (1983) [67] and can be explained by the function of potassium in the regulation of osmotic pressure [68].

5. Conclusions

Variations of light conditions affected the contents of inorganic constituents in *P. odorata*. In general, contents were affected more by daylight integral than spectral light composition. As an exception, nitrate content was affected negatively by supplemental green (515 nm) or red (629 nm) light and correlated negatively with R:FR ratio. This could be an opportunity to lower the nitrate contents of indoor cultivated leafy vegetables in order to comply with nitrate limits of the European Commission ("EU NO1258/2011").

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