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Impact of Slope of Growing Trays on Productivity of Wheat Green Fodder by a Nutrient Film Technique System

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Abstract: Application of hydroponic systems in feed production has not been extensively studied. Therefore, there is insufficient data on the effect of the slope of hydroponic growing trays used in the nutrient film technique on wheat fodder yield and its qualitative parameters. The slope of the trays has only been studied for food crops. This study conducted experimental research using a nutrient film technique hydroponic fodder growing device to evaluate the impact of growing tray slope angle on hydroponic wheat fodder production. The slope angle of the growing trays was changed from 2.0% (1.15°) to 8.0% (4.57°) with increments of 1.5% (0.86°). This research used two different light sources for wheat sprout illumination: indoor lighting (fluorescent lamps) and light-emitting diode illumination. In addition, two nutrient solutions were used for sprout irrigation: tap water and a solution enriched with macro- and microelements. Experimental studies confirmed the hypothesis that the slope angle of growing trays significantly affects the yield of wheat fodder grown for seven days. Analyzing the results, we found that the highest yield of wheat fodder after seven days of cultivation was achieved with growing trays sloped by 6.5% and using indoor lighting. In addition, we achieved the highest wheat fodder dry matter content using a 6.5% slope angle. Experimental studies also confirmed the hypothesis that using macro- and micronutrients in the nutrient solution does not significantly affect the yield of wheat fodder grown hydroponically for seven days.

Keywords: hydroponics; growing tray; slope angle; nutrient solution; nutrient film technique; wheat fodder

1. Introduction

Globally, declining resources caused by climate change and a growing population have challenged traditional agricultural systems [1]. The human population will grow to an estimated 8 billion people by 2025 and 9 billion by 2050, and it is widely recognized that global agricultural productivity must increase to feed the world's population [2]. Consequently, raw materials for food production must also be increased. However, as the climate changes, it will become increasingly difficult to do so. Therefore, scientists are forced to look for alternatives to address these challenges. Globally, cattle meat and milk production have more than doubled between 1961 and 2014, increasing from 28 to 68 million tons per year for meat products and 344 to 792 million tons for milk products [3]. According to Alexandratos and Bruinsma [4], by 2050, the demand for food will grow by 60% between 2010 and 2050. The production of animal proteins will grow by around 1.7% per year, with meat production and dairy projected to rise by nearly 70% and 55%, respectively. This demand marks a growth factor of almost two. However, if we were to extrapolate the growth rates of the last 40 years forward to 2050, this would, in theory, quadruple the needs. In animal production farms, feed is considered as the most fundamental and expensive element [5].

Most of the feed in the world is produced using conventional agriculture, such as growing plants in arable land [6]. Soil is usually the most available growing medium for plants as it provides anchorage, nutrients, air, and water for successful plant growth. However, soils also pose serious limitations for plant growth. The presence of disease-causing organisms and nematodes, unsuitable soil reaction, unfavorable soil compaction, poor drainage, and degradation because of erosion are some of them [7,8]. Hence, there is a need for feed production using hydroponic technology (HT). In agriculture, hydroponics is an advanced technology. Hydroponic production guarantees a constant production of high-quantity green forage throughout the year for livestock feed at suitable prices [9]. Saha et al. [1] stated that alternative agricultural practices, such as hydroponics, could generate high yield per unit area using limited land, water, and no soil.

HT offers many advantages, such as improved quality of crops, higher rates of production, a reduction of labor requirements, increased productivity [10], uniform plant production, a significant reduction in the area required for production, cultivation at any time of the year, rapid economic return [11], and high-quality products [12].

By using HT, various commercial and specialty crops can be grown, including cereal grains, lettuce, tomatoes, cucumbers, peppers, and eggplant [13,14]. Sprouting is the practice of soaking and leaving seeds until they germinate and start to sprout [15]. This practice is associated with improvements in the nutritive value of seeds [16]. At the same time, there are indications that germination is effective in reducing phytic acid [17] and other antinutrition factors. Germination reduces dry matter and starch content and improves amino acid composition. Increased grain germination duration increases vitamin C and beta-carotene as well as other antioxidants [18].

Consuming sprouted grains is beneficial for human health. Positive consumer perceptions about sprouted cereals have resulted in new food and beverage product launches [19]. Sprouted seeds with higher enzymes have good prospects of being used in future food and feed production [20].

Hydroponic fodder production is an effective alternative technology for sustainable livestock production [9]. The hydroponic forage production requires only about 3–5% water to produce the same amount of forage produced under field conditions [21]. HT can produce different types of fodder crops, such as barley [5,10], oats, wheat [22,23], sorghum, alfalfa, cowpea [21], and maize [24].

Hydroponic cereal green fodder are grown for 6–9 days [5,11,25–27]. The choice of which hydroponic fodder to produce depends on the geographical and agroclimatic conditions and easy availability of seeds. Wheat (*Triticum aestivum* L.) can also be an economically effective choice for the production of hydroponic fodder [23,28]. Wheat is by far the most widely grown crop in the Baltic region in Europe. For this reason, as well as the price/quality ratio, this crop should be used for hydroponic germination.

Depending on the method of feeding the nutrition solution, there are six hydroponic systems (HS) available for growing plants using HT, namely, ebb and flow HS, nutrient film technique (NFT), aeroponics, deep water culture HS, wick HS, and drip-irrigation HS. All of these have some common components (pump, frame, and piping), regardless of the method used to feed the plants. Because of the development of suitable pumps, time clocks, plastic plumbing, solenoid valves, and other equipment, the entire hydroponic system can now be automated, reducing both capital and operational costs [29]. Usually, this cultivation using HS is valued in feed production because of the excellent usage volume of the growing room [30]. The germination process of various seeds, however, must still be optimized by considering the conditions and equipment of germination [31].

Depending on the method of feeding the nutrient solution, all HS systems could be applied to grow plants for food production [7], and applying the NFT technology to irrigate the roots of the plants is most promising for forage cultivation [21,32].

Applying the NFT system in feed production has not been extensively studied. Only the effectiveness of using water for irrigation has been studied [21]. Rajesh et al. [33] investigated the suitability of different cereal grains for hydroponic feed production. Other scientists [25,26] have investigated the effect of seed density in growing trays on yield. Regarding hydroponically produced feed, most scientific studies have been conducted on hydroponically produced feed itself and its influence on animal feeding and not on different growing parameters (structural or technological). Scientific literature holds insufficient data on the effect of slope of NFT hydroponic growing trays on wheat fodder yield and qualitative parameter changes. The slope of the trays has only been studied for food crops. Crops with a large root system that are grown for a long duration, such as 18-month tomato crops, will need a higher slope than a lettuce crop, which has a smaller root system and is grown for a short duration [34].

Experiments with NFT have indicated that a growing tray with a width of 80 mm, depth of 40 mm, length of 3.1 m, and slope of 1.5% with a flow rate of 0.2 L min^{-1} is ideal for the production of lettuce [35]. In some scientific studies, plants were grown on NFTs on trays sloped at an angle of 1% [14]. López-Pozos et al. [36] reported that the slope of the growing tray influenced the oxygenation of the NS at 4% slopes, resulting in higher dissolved oxygen compared with the 2% slope. Using a steeper slope of the NFT channel could significantly improve tomato productivity [36]. The authors stated that a proper slope must be maintained in trays for the free flow of the nutrient solution to avoid stagnation of water in trays. Oxygen deficiencies resulted in root damage in some types of hydroponic systems unless air was bubbled constantly into the nutrient solution [37].

Researchers have reported that nutrient solutions used to water hydroponically germinated seeds determine plant growth, appearance, and nutritional value [38,39].

The present study aimed to investigate the influence of technological and structural parameters of the NFT hydroponic device on changes in wheat fodder yield in seven days. The following scientific hypotheses were tested: (1) the slope angle of the hydroponic growing tray significantly influences the yield of wheat fodder that is grown for seven days and (2) using macro- and micronutrients in the nutrient solution does not significantly affect the yield of hydroponically grown wheat fodder.

2. Materials and Methods

Experimental research was conducted in 2018–2019 using a hydroponic growing device at the Agricultural Machines Technological Process Research Laboratory, Vytautas Magnus University, Agriculture Academy, Lithuania (Figure 1). The device was made to evaluate the slope angle of the growing trays for NFT plant cultivation equipment.

The hydroponic device (stand) (Figure 1) consisted of a frame (labeled No. 6 in Figure 1) that was made of aluminum profile (40 × 40 × 2 mm). Its construction was divided into two different growing floors. Each floor was equipped with four growing trays (1000 mm long, 225 mm wide, and 75 mm high, labeled No. 11 in Figure 1) made of polyvinyl chloride (PVC) plastic. The growing area of a single tray was 0.225 m^2, and the total growing area in the device was 1.8 m^2. One end of each growing tray was open so that the nutrient solution would moisturize the roots of the cultivated grass by passing through them. The slope angle of the growing trays was changed from 2.0% (1.15°) to 8.0% (4.57°) with increments of 1.5% (0.86°) (Figure 1).

The slope angle was measured with a Bosch DNM 60 L electronic spirit level. An on-site irrigation system consisting of a pump (NOVA UP 300MAE, capacity 166 L min^{-1}, labeled No. 9 in Figure 1), a PVC piping (labeled No. 15 in Figure 1), flow control valves (labeled No. 8 and 12 in Figure 1), and an irrigation tank (labeled No. 10 in Figure 1) supplied the plants with water and nutrients.

The tests were conducted at the following parameters critical for cultivation: temperature (21.4 ± 0.2 °C), relative humidity (31.06 ± 2.9%), nutrient solution flow rate (3.3 L min^{-1}), light-emitting diode (LED) for lighting (wavelengths blue for 449–459 nm and red for 617–627 nm), and indoor luminescent lamps (6500 K). Table 1 shows the measurement limits and accuracy for equipment and instruments used in the study.

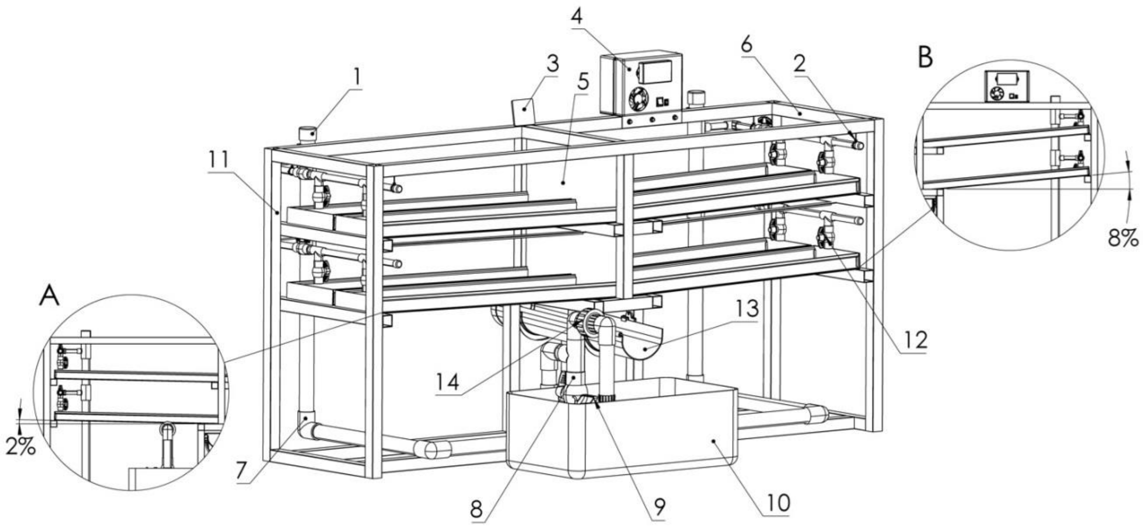

Figure 1. Hydroponic fodder growing stand scheme: (**A**) trays sloped at 2.0% and (**B**) trays sloped at 8.0%; 1—blind, 2—pipe holder, 3—temperature and humidity meter, 4—light-emitting diode (LED) controller, 5—organic glass, 6—aluminum profile frame, 7— polyvinyl chloride (PVC) elbow, 8—total flow adjustment valve, 9—irrigation pump, 10—irrigation tank, 11—growth tray, 12—feed solution flow control valve, 13—collection pipe, 14—disassemble coupling, 15—PVC piping.

Table 1. Equipment and measuring instruments used in the research.

Name, Type, and Number of Measuring Instrument and Equipment	Range of Measurement	Measurement Accuracy
Thermometer—Sencor SWS 1500 RD	0–50 °C	±1 °C (from 0 °C to 40 °C)
Room humidity meter—Sencor SWS 1500 RD	20–95%	±5% (from 40% to 80%)
Light flux meter—LX1010B	0–50.000 Lx	±5% (from 0 °C to 50 °C)
Digital spirit level—Bosch DNM 60L	0–90°	±0.05°
Drying and heating chamber—Binder FP400	5–300 °C	±2.5 °C (at 150 °C)
Electrical conductivity detector—ADWA AD-204	0–19.99 mS cm^{-1}	<1%
Electronic weighing scales—METTLER TOLEDO SB 16001	0–16 kg	±0.1 g
Spectrophotometer—LABOMED UVD-3200	190–1100 nm	±0.3 nm
Lighting flow controller—TC420	0–24 V	—

2.1. *Upper Floor Lighting for Growing Trays*

The plants were illuminated with artificial indoor lights because there was no lighting mounted on the top floor of the growing device. Considering that the fluorescent lamps used for illumination had a color temperature of 6500 K, they produced an average luminous flux of 235.91 ± 10.6 Lx per growing tray, which corresponds to 4.01 ± 0.18 (μmol m^{-2}) s^{-1}.

2.2. *Lower Floor Lighting for Growing Trays*

The lower floor lighting was equipped with LED lighting consisting of two strips of wavelengths (blue and red) powered by a 24 V amplifier. Each LED strip was 1 m long. One strip of red and blue was attached above each growing tray at a distance of 0.21 m. The TC420 controller was used to control the illumination flow. Researchers Son and Oh [40] recommend a 4:1 ratio of red to blue illumination, which corresponds to 80% red and 20% blue. This ratio was maintained by selecting 449–459 nm blue LED strips and 617–627 nm red LED strips. Thus, the blue LED strip at 449–459 nm produced an average illumination flux of 197.4 ± 23.1 (μmol m^{-2}) s^{-1}, while the 617–627 nm red produced 47.4 ± 2.1 (μmol m^{-2}) s^{-1}. The total luminous flux of the LED was 244.7 ± 24.1 (μmol m^{-2}) s^{-1}.

A typical 12-hour lighting cycle [41] illuminated the lower floor trays. At 8:00 a.m., the light was turned on, and at 8:00 p.m., it was switched off.

2.3. Preparation of Seeds before Germination and Cultivation of Wheat Fodder

This study used winter wheat (*Triticum aestivum* L.) seeds of the *Arcadia* variety. Wheat for this research was grown in the fields at Vytautas Magnus University, Agriculture Academy (Lithuania). The seeds were cleaned of debris and other foreign matter. Before testing, seed germination was determined using the moistened tissue method [42], and it was 97.0 ± 4.4%.

Scientists recommend germinating 4.5–8.0 kg m^{-2} seeds [25,26,43], and therefore we decided to use 1.3 kg of cleaned dry wheat seeds per growing tray (equivalent to 5.8 kg m^{-2}). The seeds to be sprouted on the growing trays of the hydroponic unit must first be soaked. Researchers suggest germinating seeds for 12–72 h in water [44]. In this study, a soaking time of 12 h was chosen to shorten the time of production, thereby significantly reducing the cost of feed. The seeds were soaked at room temperature (21.4 ± 0.2 °C) in tap water. After soaking, the weight of the seeds increased by about 30%, on average or 0.60 ± 0.06 kg. The trays, PVC pipes, and the irrigation tank were sterilized with sodium hypochlorite solution before each cycle of fodder growth. After sterilizing these components, the entire system was thoroughly rinsed with clean water to avoid the residual disinfectant solution.

2.4. Seed Spreading on Growing Trays and Watering

The soaked seeds were spread on the trays, without any substrate, of the growing stand. Each tray was filled with 1.90 ± 0.06 kg of soaked seeds for germination. Seeds were spread on the trays in a uniform layer of 3.5 cm, and each tray was watered four times daily (at 9:00 a.m., 3:00 p.m., 9:00 p.m., and 3:00 a.m.) with the irrigation pump automatically switching on. Water was applied at a flow rate of 3.3 L min^{-1} for two minutes. The nutrient solution was collected in an irrigation tank for reuse.

2.5. Nutrient Solution

The nutrient solution consisted of tap water and fertilizers used for hydroponic plant cultivation. Two concentrated nutrient solutions were produced to hydroponically germinate the seeds, namely, A (20 L of water dissolved in 1.8 kg calcium nitrate) and B (20 L of water dissolved in 0.5 kg magnesium sulfate, 2.7 kg Universol violet complex fertilizer, and 0.5 kg potassium nitrate). The concentrated solutions should not be prepared in one container because the chemical reactions result in insoluble calcium phosphates and calcium sulfates, which react with each other to precipitate and could clog the irrigation system.

Electrochemical assay methods were used to measure the concentration of nutrients in the solution by measuring the electrical conductivity (EC) of the solution. All electrochemical measurements were performed with the ADWA AD-204 handheld electrical conductivity sensor with a measurement range of 0–19.99 mS cm^{-1} and an accuracy of less than 1%.

After the production of concentrated nutrient solutions A and B, equal parts of concentrated solutions A and B were added to the irrigation tank during the preparation of the first solution until the EC of the nutrient solution reached 1.8 mS cm^{-1}. The concentration of ions in the nutrient solution might change over time, leading to an increase in nutrient imbalance. To prevent this, the nutrient solution was drained and reconstituted daily.

The first solution used for irrigation contained the following concentrations of substances: total nitrogen (N)—223.83 ppm; phosphorus (P)—47.17 ppm; potassium (K)—396.67 ppm; calcium (Ca)—227.67 ppm; magnesium (Mg)—32.23 ppm; sulfur (S)—43.00 ppm; and trace elements of boron (B)—0.21 ppm, copper (Cu)—0.21 ppm, iron (Fe)—0.90 ppm, manganese (Mn)—0.45 ppm, molybdenum (Mo)—0.02 ppm, and zinc (Zn)—0.21 ppm. These concentrations were selected taking into account the mixtures used in five existing hydroponic farms in Lithuania (located in Biržai, Marijampolė, Šilutė, Kaunas, and Panevėžys) that are growing hydroponic fodder for animal feed.

Concentrated nutrient solutions A and B in the second nutrient solution (tap water) were not used for watering the seeds. To study the influence of structural parameters on fodder yield, plain tap water with an EC of 0.2 mS cm^{-1} was used as a nutrient solution.

2.6. Criteria for the Evaluation of Hydroponic Fodder

Aside from basic nutritional and qualitative feed parameters, it is critical to consider mass yield, dry matter, chlorophyll *a* and *b*, and carotenoids.

2.7. Fodder Yield

Each cycle of green fodder cultivation with different growing tray slope angle lasted for seven days. During the growing cycle, the weight of each growing tray was measured twice daily (at 8:00 a.m. and 8:00 p.m.). The weight of each empty tray was measured, and the yield and mass changes were calculated for each growing day.

2.8. Determination of Dry Matter

Clean, dry, empty dishes and their lids were dried in an oven (Binder FP400) at 105 °C for one hour. The lids were placed next to the dishes so that all surfaces dry uniformly. The dishes with lids were removed from the cupboard and placed in a desiccator. The cooled dishes were covered with lids and weighed by Mettler Toledo SB 16001 electronic scales (measurement accuracy of ± 1 mg).

The prepared dishes were uncovered, and 100–130 g of the sample was placed on the bottom as quickly as possible. The dishes were covered and weighed (W_1) (weighing accuracy of ± 1 mg). If more than one dish was weighed, the covered dishes were placed in a desiccator until all the samples were weighed and ready to be placed in an oven. Three prepared dishes containing samples of the product were analyzed.

The dishes and their lids were placed separately in the oven, dried at 105 °C, and weighed periodically until the sample mass became constant (± 2 mg). The drying time depends on the moisture of the sample and can last from 2–3 to 12 h and longer.

After drying, the dishes were removed from the oven, covered, and placed in a desiccator, which was cooled to room temperature. After cooling, the dishes with contents were weighed (W_2) (weighing accuracy of ± 1 mg). Further dry matter content of the sample was calculated as follows (LST ISO 712:2010):

$$DM = 100 - \left(\frac{W_1 - W_2}{W_1}\right) \times 100 \quad (1)$$

DM is the dry matter content, %;
W_1 is the mass of the test sample before drying, g; and
W_2 is the mass of the test sample after drying, g.
The arithmetic mean was calculated from the results of three samples.

2.9. Determination of Chlorophyll a and b and Carotenoids

Chlorophyll is naturally present in plants as a photosynthetic pigment that gives them their specific coloration [45]. It is one of the most critical physiological parameters that is closely related to plant photosynthesis and growth [46]. Carotenoids are natural pigments that are found in plants, algae, fungi, birds, and fish flesh cuticles of crustaceans or insects. They are referred to as pigment because of their characteristic colors that range from the yellow to the red spectrum [47].

The essence of the method to determine pigments (chlorophyll and carotenoids) relates to determining the optical density of pigment extracts. Representative samples of 0.208 ± 0.024 g were selected for pigment determination, removed, and placed in a porcelain dish with a small amount of sea sand. The triturated material was filled with 50 mL of acetone, and the volume was filtered. The filtered extract was measured with a LABOMED UVD-3200 spectrophotometer (Table 1). Concentrations and the amount of pigments were calculated based on the values obtained, namely, the spectrophotometric method for chlorophyll *a* and *b* content (LST ISO 10519:2001) and the spectrophotometric method for the carotenoid content (LST ISO 6558-2: 2001).

2.10. Electricity Costs and Water Consumption

Two single-phase electricity meters (Taxxo ER 80-1) were used to measure the electricity and heating costs per growing cycle (7 days). The data started recording from seed soaking to harvesting. To calculate the electricity costs for heating, it was assumed that 100 m^2 is required to grow 1000 kg of feed.

The dn20 130 mm 4 m^3/h R100 meter was used to estimate the cold water consumption throughout the growing cycle (7 days).

2.11. Economic Evaluation

The cost of feed was calculated by considering the costs used to purchase seeds, fertilizers, electricity, and water. The feed cost was calculated as follows:

$$HF_c = C_g + C_h + C_e + C_w + C_{ft} \quad (2)$$

HF_c—cost of 1000 kg of hydroponic fodder, EUR 1000 kg^{-1};

Cs—cost of purchase of cereal seed, EUR 1000 kg^{-1}, assuming that 1000 kg of seed costs 180 EUR. The seed yield potential, which, in this case, produces 6 kg of hydroponic feed from 1 kg of seeds, was also evaluated;

C_h—heating bill payment, EUR 1000 kg^{-1}, considering that the electricity price is 0.15 EUR kWh^{-1}, including value added tax (VAT);

C_e—cost of paying the electricity bill, EUR 1000 kg^{-1}, considering that the electricity price is 0.15 EUR kWh^{-1}, including VAT;

C_w—cost of paying the water bill, EUR 1000 kg^{-1}, considering that the price of cold water is 2.5 EUR cub.m^{-1}, including VAT; and

C_{ft}—cost of purchasing fertilizer, EUR 1000 kg^{-1}, considering the market price of the following fertilizers:

Calcium nitrate—1.5 EUR kg^{-1}, including VAT;
Magnesium sulfate—1.7 EUR kg^{-1}, including VAT;
Potassium nitrate—2.20 EUR kg^{-1}, including VAT;
Universol violet complex fertilizer—3.2 EUR kg^{-1}, including VAT.

2.12. Statistical Analysis

In this study, the true experimental research design was applied. All experiments were repeated in triplicate or more. Differences among means were compared by the one-way analysis of variance module with the statistical software Statistica 10.0 and using the Tukey's honestly significant difference (HSD) test. A probability level of 0.05 was used as the criterion for tests of significance throughout the data analysis [48]. In this paper, any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

3. Results

3.1. Slope of Growing Trays

In our comparative studies of growing HP wheat fodder, the influence of five different growing tray slope angles (2.0%, 3.5%, 5.0%, 6.5%, and 8.0%) was analyzed. Experimental research confirmed the hypothesis that the slope angle of the tray for cultivation significantly affects the yield of wheat fodder grown hydroponically for seven days. Analyzing the results of the research, the highest yield (31.36 ± 0.97 kg m^{-2}) of wheat fodder after seven days of cultivation was in the 6.5% sloped growing trays and for cultivation using indoor lighting (Figure 2). No significant differences for growth were observed among the slope angles of 5.0%, 6.5%, and 8.0% under LED lighting.

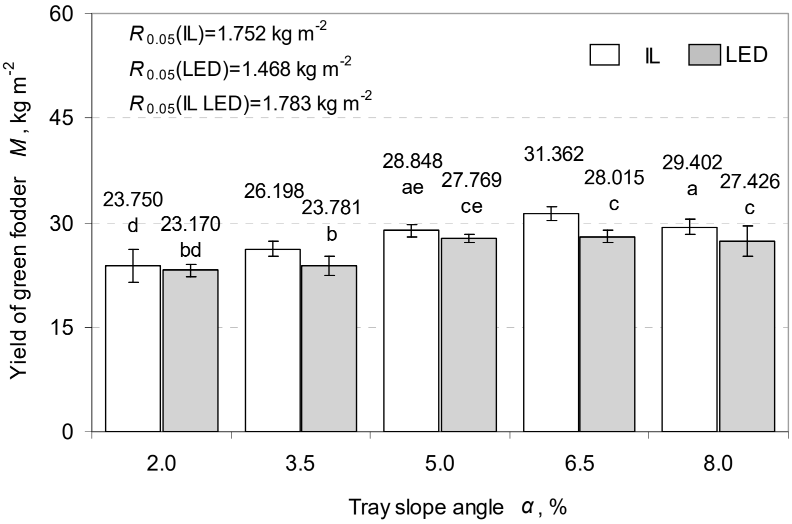

Figure 2. The yield of green fodder (M) after seven days of cultivation using different growing tray slope angles (α) and illuminations (indoor lighting (IL) or LED). Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

In this study, at the 2.0% slope angle, the average mass gain was 1.29 ± 0.14 kg m^{-2} with illumination using indoor lighting, while it was 1.25 ± 0.10 kg m^{-2} with LED (Figure 3).

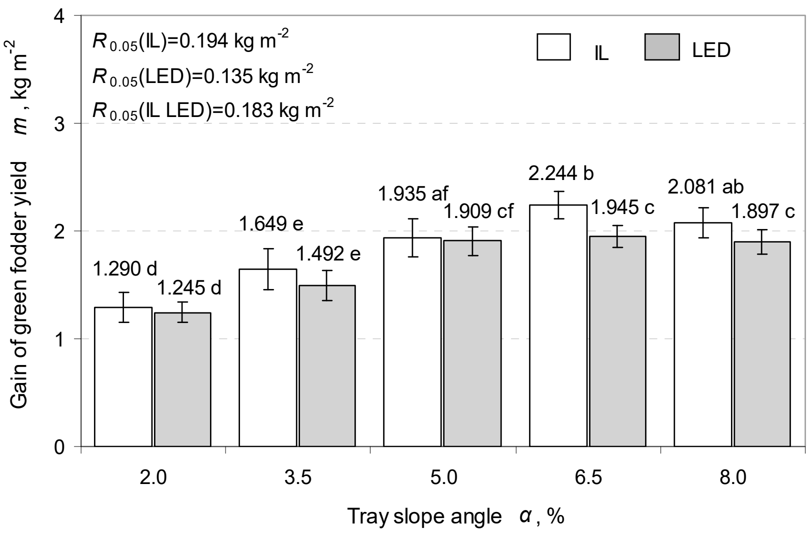

Figure 3. Average yield gain of green fodder (m) using different tray angles (α) and illuminations (IL or LED). Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

By increasing the slope angle of the trays from 2.0% to 5.0%, there was an increase in fodder yield. A 6.5% slope angle of the trays significantly affected the yield of the wheat fodder. The average mass gain at a slope angle of 6.5% was 2.24 ± 0.13 kg m^{-2} using indoor lighting and 1.95 ± 0.10 kg m^{-2} using LED. Notably, by increasing the slope angle of the growing trays to more than 6.5%, the quality of fodder started to decrease because the nutrient solution did not sufficiently nourish and moisten the seeds. With an 8.0% slope angle, the average daily weight gain was 2.08 ± 0.14 kg m^{-2} with indoor lighting and 1.90 ± 0.12 kg m^{-2} with LED. The highest growth productivity (average mass gain) was observed between 84 and 132 h of cultivation, with all five slope angles (2.0%, 3.5%, 5.0%, 6.5%, and 8.0%). However, the greater the slope angle, the longer it took to reach maximum growth productivity.

The effect of the slope angle of the trays on growing wheat fodder for seven days and the effect of the illumination used for cultivation on the dry matter content of grass were also evaluated (Figure 4).

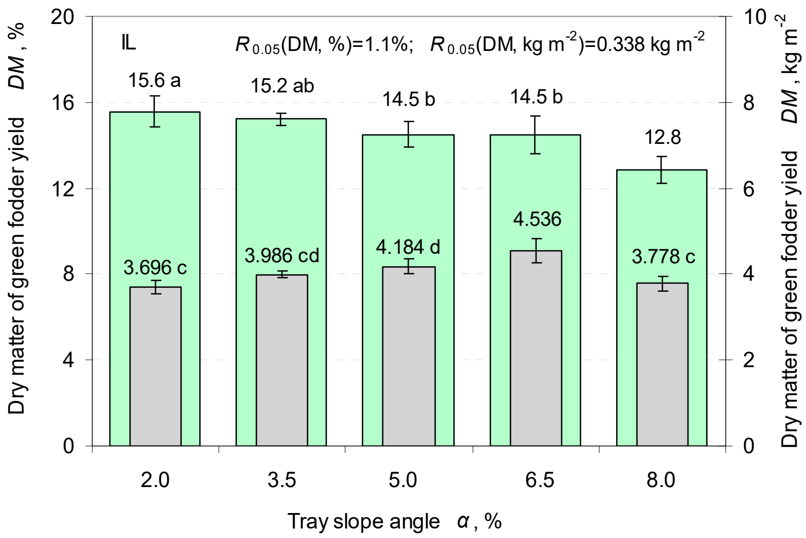

Figure 4. Influence of the slope angle of the growing tray (α) on fodder dry matter (DM) after seven days of cultivation using indoor lighting. Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

Our research showed that the slope angle reduced the dry matter percentage. However, the dry matter per unit area of the tray reached the highest value when using a 6.5% slope angle.

It is appropriate to determine the optimum value of the tray slope angle by considering the dry matter per unit area of the tray. Although the highest percentage (dry matter, %) was found using the slope angles of 2.0% and 3.5%, it was compared to the dry matter content and the total mass of the grown fodder after seven days of cultivation, which showed the highest dry matter content was achieved with a 6.5% slope angle (4.54 ± 0.28 kg m^{-2}) and using indoor lighting.

The results of research on changes in the yield of wheat fodder under different tray angles and illumination for cultivation indicated that increasing the slope angle increased the production of wheat fodder (Figure 2). However, in the estimation of dry matter (%) in wheat fodder grown for seven days, it was observed that increasing the slope angle decreased the dry matter percentage (Figures 4 and 5). After seven days of cultivation, fodder grown in trays sloped at 2.0% and 3.5% angles showed the highest percentage of dry matter. The dry matter content was 15.6 ± 0.7% and 15.2 ± 0.3% using indoor lighting (Figure 4) and 16.7 ± 0.9% and 16.2 ± 0.8% (Figure 5) using LED, respectively.

The lowest percentage of dry matter was recorded in fodder grown in trays sloped at an 8.0% angle at 12.8 ± 0.6% using indoor lighting and 12.7 ± 0.6% using LED. However, it is appropriate to determine the optimum value of the tray slope angle by considering the dry matter per unit area of the tray. Although the highest percentage (dry matter, %) was found using the slope angles of 2.0% and 3.5%, it was compared to the dry matter content and the total mass of the grown fodder after seven days of cultivation, which showed the highest dry matter content when using a 6.5% slope angle (4.54 ± 0.28 kg m^{-2}) with indoor lighting (Figure 4). With LED lighting, the maximum dry matter content was obtained using a 5.0% and 6.5% growing tray slope (4.14 ± 0.18 kg m^{-2} and 4.13 ± 0.18 kg m^{-2}, respectively) (Figure 5).

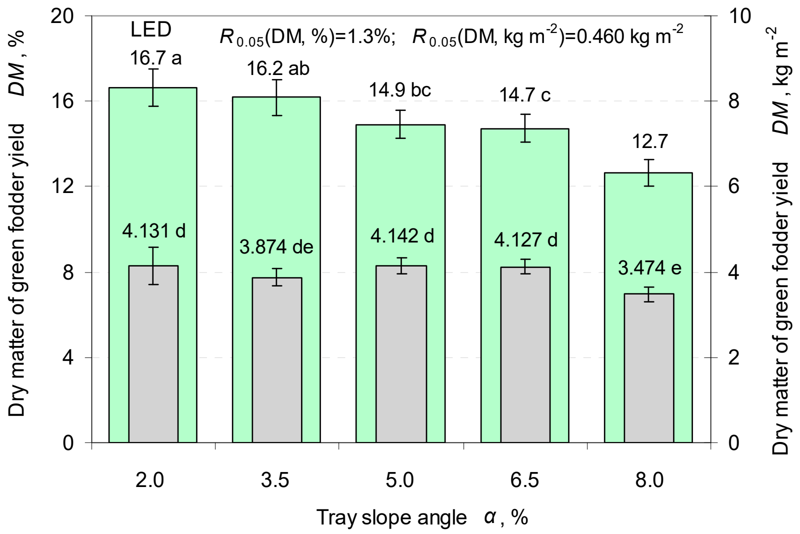

Figure 5. Influence of the slope angle of the growing tray (α) on the fodder dry matter after seven days of cultivation using LED lighting. Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

3.2. Nutrient Solution

During the entire period of seed germination, the yield after seven days for irrigation using tap water (EC = 0.2 mS cm^{-1}) and cultivation with indoor and LED lighting was 31.30 ± 1.56 kg m^{-2} and 28.13 ± 1.32 kg m^{-2}, respectively. For irrigation using a macro- and micronutrient-enriched solution, the yield was 31.23 ± 1.73 kg m^{-2} and 28.79 ± 3.03 kg m^{-2}, respectively (Figure 6). The least significant difference for irrigation using tap water and macro- and micronutrient-enriched solutions using indoor lighting was 1.51 kg m^{-2}, while it was 2.13 kg m^{-2} for LED. Therefore, there was no significant difference between the compared numerical values.

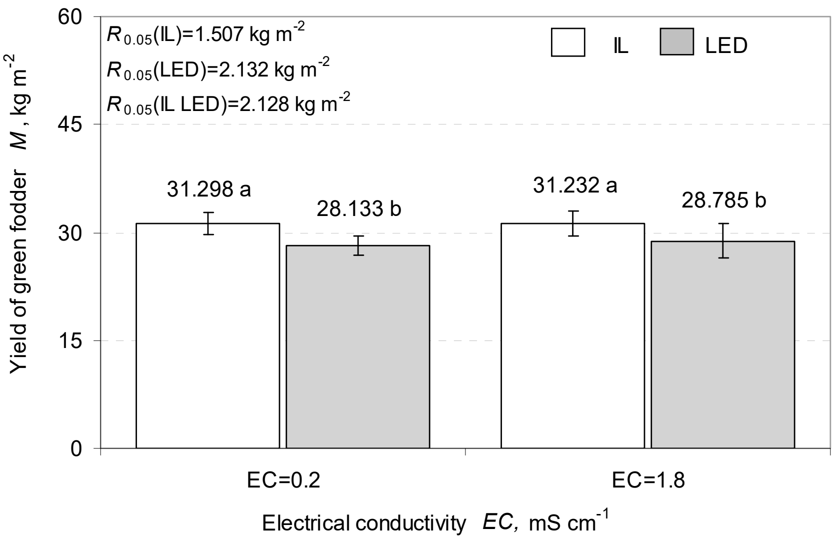

Figure 6. Influence of macro- and micronutrients on fodder yield with indoor lighting or LED and a tray slope angle of 6.5%. Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

An estimation of the average weight gain of wheat fodder over the whole growing cycle also showed that there was no significant difference between the tap water used for irrigation and the macro- and micronutrient-enriched solution using indoor lighting ($R_{0.05}$ = 0.14 kg m^{-2}) or LED ($R_{0.05}$ = 0.24 kg m^{-2}) (Figure 7).

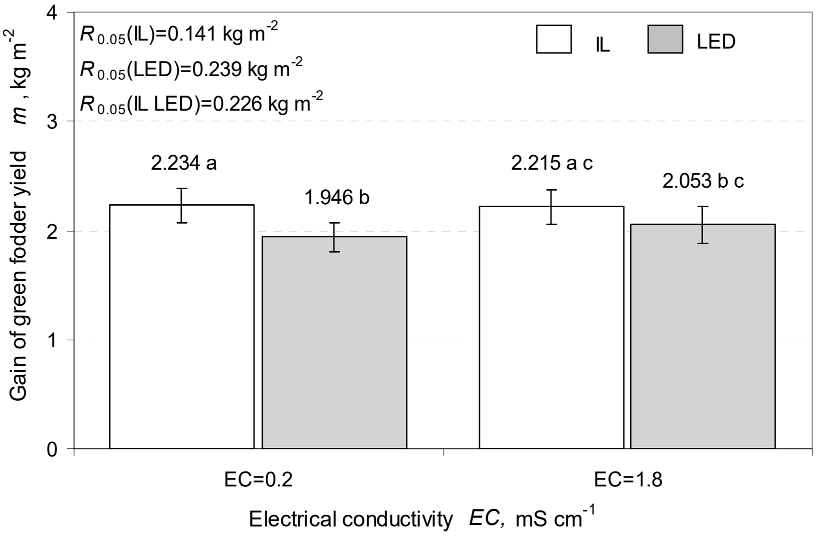

Figure 7. Influence of macro- and micronutrients on the growth of wheat fodder weight with indoor lighting or LED and a growing tray slope angle of 6.5%. Each *vertical bar* is *95% confidence interval*. Any two samples with a common letter are not significantly different ($p < 0.05$), as assessed using the least significant difference.

Analysis of the weight gain (measured twice daily) showed that the influence of macro- and micronutrients in the nutrient solution on the yield of wheat fodder started to develop only after 132 h of cultivation, i.e., from the sixth day (Figures 8 and 9). This could be because of decreasing fat and starch reserves, which are critical in providing energy for the germination process.

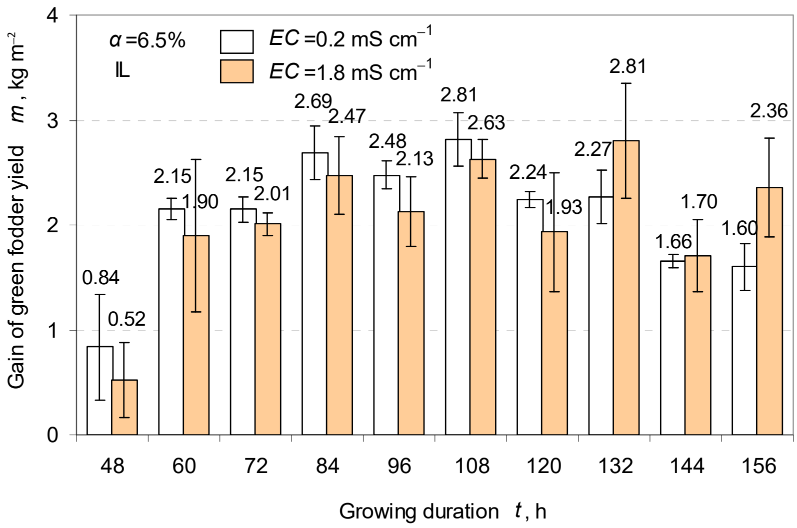

Figure 8. Variation in mass gain of fodder during growing period using indoor lighting. Each *vertical bar* is *95% confidence interval*.

By evaluating the influence of macro- and micronutrients in the nutrient solution (EC = 1.8 mS cm^{-1}), it was found that the amount of chlorophyll *a* and *b* increased by about 20% in wheat fodder grown for seven days compared to using tap water (EC = 0.2 mS cm^{-1}) as the nutrition solution (Figure 10).

3.3. Economic Evaluation

In the case of hydroponic wheat fodder cultivation for feed without a nutrient solution reuse system, the results showed that fertilizer to produce a feed solution constituted about 40% of the feed cost (Table 2).

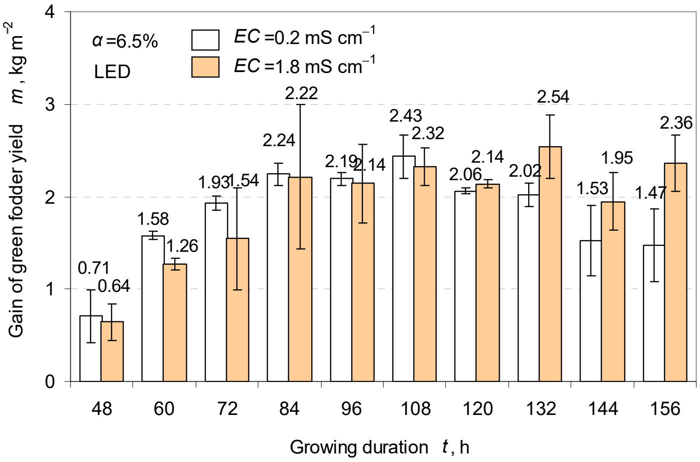

Figure 9. Variation in mass gain of fodder during growing period using LED lighting. Each *vertical bar* is *95% confidence interval*.

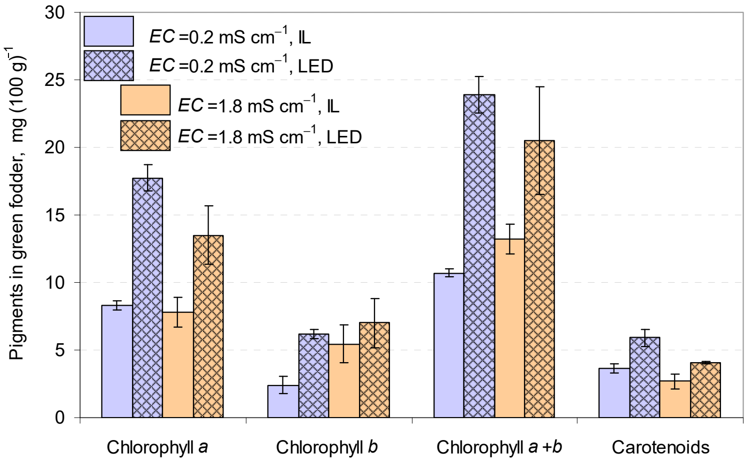

Figure 10. Pigment content in green fodder after seven days of cultivation depending on lighting (indoor lighting or LED) and nutrient solution (electrical conductivity (EC)). Each *vertical bar* is *95% confidence interval*.

Table 2. Cost (EUR with value added tax (VAT)) of 1000 kg hydroponic feed (14.7% dry matter).

Costs, EUR	Unit	Quantity	Unit Price, EUR with VAT	Price, EUR	Share of Total, %
Grains for sowing	kg	185.40	0.16	29.66	34.83
Heating	kWh	46.70	0.15	7.01	8.22
Electricity *	kWh	8.40	0.15	1.26	1.48
Water	m^3	5.59	2.50	13.98	16.41
Fertilizers					
Calcium nitrate	kg	5.40	1.50	8.10	9.51
Magnesium sulfate	kg	1.50	1.70	2.55	2.99
Potassium nitrate	kg	8.10	2.20	17.82	20.92
Universol violet complex fertilizer	kg	1.50	3.20	4.80	5.64
				33.27	39.06
Cost of cultivation of 1000 kg hydroponic feed, EUR				85.18	100

* Consumed electricity of indoor luminescent lamps was used to calculate the total electricity cost.

This economic assessment aimed to demonstrate the impact of fertilizer withdrawal on the cost of feed production. However, to evaluate the benefits of this feed to a particular farm, other parameters must be considered, such as employee salaries and labor costs.

4. Discussion

Most research on the influence of the slope angle of trays in hydroponics has been conducted on food crops, such as lettuce. Scientists found that the growth of 4.0% sloped NFT channels displayed up to 15% improved yield over the 2.0% slopped channels [36]. For Chinese cabbage (*Brassica rapa chinensis*), researchers suggested using a slope angle of 5.0%, which had the greatest effect on plant growth (leaf number, plant height, and root length) and overall weight [49]. So far, the scientific literature has not offered detailed investigation on the influence of tray slope on fodder plants.

Our research showed that using a slope angle of more than 6.5% impaired the germination process of sprouted wheat seeds as the grain began to dry. At a slope angle of less than 5.0%, the main symptoms of soaking began to appear, such as disturbed physiological processes in the plant and the onset of acidification because of lack of oxygen, namely, hypoxia. In hydroponics, plant hypoxia has been extensively studied [50]. Suzuki and Maekawa [51] found that when germinating rice and using a low-dissolved oxygen nutrient solution (in this case, tap water) for irrigation, the germination process began later than when using an oxygen-enriched nutrient solution. Que et al. [52] studied the influence of oxygen deficiency on hydroponically grown carrots. The results showed that hypoxia could enhance lignification (lignin (wood) accumulation in plant cells) and affect the anatomical structure of carrot root.

Researchers have discussed the disadvantages of feed grown using a hydroponic system and highlighted the dry matter loss [53]. In hydroponic growing, dry matter loss occurs because of metabolic activity and respiration with germination [24]. On the third day of germination, chloroplast formation and photosynthesis start, but in this short time (seven days), the dry matter accumulation by photosynthesis cannot meet the loss [54]. Ali et al. [55] studied the dry matter content of germinated wheat and maize. Loss of dry matter is inevitable, although there is no scientific literature on how to reduce the loss.

Furthermore, the dry matter content in green fodder was higher with LED lighting at various slope angles of the growing trays (2.0%, 3.5%, 5.0%; 6.5%, and 8.0%) than indoor lighting. This was influenced by the luminous flux used for LED illumination within the blue spectrum [56].

Summarizing the research, it can be stated that tap water without any additives can be used as a nutrient solution for growing wheat fodder hydroponically for seven days. The analysis of the results showed that the yield of wheat fodder after illumination with LED lamps for seven days was about 10% lower than when using indoor lighting (Figure 2). However, the number of pigments in wheat fodder when using LED lamps was higher: 50% for chlorophyll *a* and *b* and about 35% for carotenoids (Figure 10). When the influence of macro- and micronutrients in the nutrient solution on growing wheat fodder hydroponically was evaluated, it revealed that the content of chlorophyll *a* and *b* was about 20% higher in the macro- and micronutrient-enriched solution than when using tap water (Figure 10). Macro- and micronutrient-enriched nutrient solutions account for about 40% of the cost of feed for wheat fodder without using a nutrient recycling system.

Regarding the influence of LED illumination on chlorophyll and carotenoid concentrations, Amoozgar et al. [57] found that light treatments also significantly affected phytochemical concentrations and nutritive value. Chlorophyll and carotenoid concentrations increased in plants that were grown under 70% red + 30% blue LED compared to those grown in a greenhouse [57].

We estimated the influence of structural parameters on yield and found that a 6.5% slope angle of the growing tray was the most suitable for hydroponic fodder cultivation. After using it in further experimental studies, we confirmed the hypothesis that using macro- and micronutrients in the nutrient solution does not significantly affect wheat fodder grown hydroponically for seven days. Agius et al. [58] also discussed the enrichment of the nutrient solution with fertilizer. They confirmed that growing fodder hydroponically does not require additional fertilization because the grain uses resources and energy from the grain itself.

Areas of Further Research

1. At the beginning of the germination of wheat seeds, the slope angle (α) of the growing trays should (could) be lower (i.e., 2%). At that time, the seeds have no roots and no solid bedding. At the beginning of germination, if the trays are set at a higher angle (i.e., 6.5% or 8.0%) and watering of the seeds (irrigation) is set at a certain flow of nutrient solution (water) (e.g., 3.3 L min^{-1}), it poses a risk of leaching the seeds. Therefore, in further studies, the hypothesis that the slope angle of the growing trays could be lower at the beginning of seed germination and could automatically increase after a certain stage of plant growth should be evaluated. Another study could investigate changing the flow rate of the nutrient solution for seed irrigation, namely, that at the beginning of the germination of wheat seeds, the slope angle (α) of the trays should (could) be high (i.e., 6.5% or 8.0%), but the nutrient solution flow rate (l min^{-1}) could be lower. With the growth of seed root systems where there is no risk of seed leaching, this flow rate could be increased. Thus, hydroponically grown wheat fodder for feed should (could) be automated by changing the tray slope angle and/or nutrient solution flow rate for seed irrigation.
2. Our study showed that plant yield was not uniform over the growing tray length. A significant decrease in yield was observed in the lower part of the tray length (about 150 mm). In the upper part of the tray (about 100 mm), the yield of wheat fodder was also slightly lower. This was probably because of the nutrient solution passing through the roots of the plants. The velocity of the solution was not uniform in the individual parts of the tray length. At the bottom, the roots of the plants were soaked. Therefore, in future studies, it would be appropriate to justify the shape of the bottom of the growing tray.
3. A more detailed assessment of the environmental impact of using a hydroponic system in the production of fresh fodder should be conducted using a life-cycle assessment.

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