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Comparative analysis of nutrient media efficiency for hydroponic green fodder production in NFT systems

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Abstract

Hydroponic systems offer a promising solution for sustainable green fodder production, but selecting appropriate nutrient media is crucial for optimizing plant growth and productivity. However, there is a lack of comprehensive studies evaluating the performance of different hydroponic nutrient media on green fodder crops, particularly in the context of nutrient film technique (NFT) systems. This study aimed to assess the performance of three hydroponic nutrient media (Cooper, Hoagland & Arnon, and ACI Vitamix) on the growth and yield of three hydroponic green fodder crops (maize, wheat, and Sudan grass) in NFT systems. Hydroponic experiments were conducted using NFT systems to evaluate the performance of the selected hydroponic nutrient media and green fodder crops. Parameters such as fodder length, root length, and fodder yield were measured at 14 days after sowing (DAS). Fluctuations in pH, TDS, and EC were monitored at regular intervals throughout the growth period. The results demonstrated significant variations in growth parameters among the different hydroponic nutrient media treatments. Maize fodder exhibited superior performance in terms of fodder length, root length, and fodder yield when grown in the Cooper nutrient media. Fluctuations in pH, TDS, and EC levels were observed, reflecting variations in nutrient concentrations and uptake dynamics. Maize fodder showed the highest performance in Cooper nutrient media, followed by wheat and Sudan grass. Fluctuations in pH, TDS, and EC were observed, indicating variations in nutrient availability and solution stability over the growth period. Based on the findings, it is recommended to prioritize the use of cooper nutrient media for maize fodder production in hydroponic NFT systems to optimize growth and yield. Additionally, close monitoring of nutrient levels and pH stability is recommended to ensure optimal nutrient management and system performance in hydroponic green fodder production.

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Introduction

Hydroponics nutrient media selection is paramount due to its direct impact on the growth, yield, and nutritional quality of hydroponically cultivated crops. By providing essential nutrients in precise concentrations and ratios, nutrient media play a crucial role in sustaining optimal plant health and maximizing productivity (Marschner, 2012). In the context of green fodder production, where rapid growth and nutrient uptake are vital, selecting appropriate nutrient media becomes even more critical to ensure optimal crop performance (Resh, 2012; Savvas and Gruda, 2018). Additionally, nutrient media influence not only the physical growth but also the nutritional composition of the green fodder, affecting its suitability for livestock feed and human consumption (Hochmuth and Hochmuth, 1997).

Hydroponics nutrient media serve as the primary source of essential nutrients for the cultivation of green fodder crops such as maize, wheat, and Sudan grass (Resh, 2012). These media are formulated to provide a balanced supply of macro and micronutrients necessary for robust plant growth and development (Hochmuth and Hochmuth, 1997; Cooper and Black, 2008). Through precise control of nutrient concentrations and availability, hydroponic systems optimize nutrient uptake efficiency, leading to enhanced biomass production and nutrient content in the green fodder (Bugbee and Salisbury, 1988).

The selection of appropriate nutrient media holds immense significance in green fodder production for several reasons. Firstly, nutrient media directly influence the growth kinetics and yield potential of hydroponically grown crops, impacting the overall efficiency and sustainability of green fodder systems. Secondly, nutrient media composition profoundly affects the nutritional quality of the harvested green fodder, determining its suitability for livestock feed and its potential impact on animal health and productivity (Cooper and Black, 2008; Li and Hu, 2020). Moreover, by optimizing nutrient availability and uptake, tailored nutrient media formulations can enhance the nutritional profile and economic value of green fodder crops, thereby contributing to food security and agricultural sustainability (Savvas and Gruda, 2018).

Standardizing nutrient media formulations is essential to ensure consistency, reliability, and reproducibility in hydroponic green fodder production systems (FAO, 2019). By establishing standardized nutrient solutions, researchers and practitioners can minimize variability in crop responses and facilitate comparative studies across different experiments and locations. Standardization also enables the development of best practices and guidelines for nutrient management in green fodder production, promoting efficiency, scalability, and adoption of hydroponic technologies in agriculture (Savvas and Gruda, 2018). Moreover, standardized nutrient media formulations facilitate knowledge exchange and collaboration among researchers, industry stakeholders, and policymakers, fostering innovation and advancements in hydroponic green fodder production techniques (Resh, 2012). The study was undertaken to compare the effectiveness of three nutrient media (Cooper, Hoagland & Arnon, and Aci vitamix) in supporting the growth and development of three hydroponic green fodders and assess the water quality parameters of nutrient media using NFT systems.

Materials and Methods

Plant material and growth conditions

Three hydroponic green fodder crops were selected for this study: maize (*Zea mays*), wheat (*Triticum aestivum*), and Sudan grass (*Sorghum sudanense*). Seeds of each crop were surface sterilized and germinated using standard procedures. Hydroponic growth chambers equipped with Nutrient Film Technique (NFT) systems were utilized for crop cultivation.

Nutrient media formulations

Three nutrient media formulations were selected for comparison: Cooper (1979), Hoagland & Arnon, and Aci vitamix. Each nutrient medium was prepared according to the specified concentrations and ratios of macro and micronutrients. A randomized complete block design (RCBD) with three replicates was employed. Each nutrient medium was assigned randomly to hydroponic systems containing one of the three green fodder crops.

Plant growth and monitoring

Seeds were sown in germination trays filled with sterile growing medium and transferred to the NFT systems upon germination. Plants were grown under controlled environmental conditions, including temperature, humidity, and photoperiod. Regular monitoring of plant growth parameters, including shoot height, leaf area, and biomass accumulation, was conducted throughout the experimental period.

Data on plant growth parameters and nutrient uptake were recorded and analyzed statistically using appropriate software. Analysis of variance (ANOVA) and DMRT's post-hoc test were performed to determine significant differences among treatments.

Results and Discussion

Comparison of nutrient media

Fodder length (cm)

The results presented in Table 1 show the evaluation of different hydroponic nutrient media on the growth of various green fodder crops, specifically focusing on fodder length (measured in centimeters) at 14 days after sowing (DAS). Three different nutrient media were tested: Cooper, Hoagland & Arnon, and ACI vitamix. From the data provided, it can be observed that there were no significant differences (ns) in the fodder length among the different nutrient media treatments. This suggests that, at this particular stage of growth (14 DAS), the choice of nutrient media did not have a statistically significant impact on the length of the green fodder. The similar mean values and the non-significant p-values indicate that the differences observed among the treatments are likely due to random variability rather than actual treatment effects.

Table 1. Evaluation of hydroponic nutrient media on different green fodder for agronomic characteristics (14 DAS)

Hydroponic nutrient media	Fodder length (cm)*	Root length (cm)	Fodder yield (kg)
Cooper	20.24 ± 1.53^{ns}	10.14±0.74 a	5.83±0.29 a
Hoagland & Arnon	18.48 ± 1.53^{ns}	9.31±0.74 a	5.25±0.29 a
ACI vitamix	16.14 ± 1.53^{ns}	6.65±0.74 b	3.94±0.29 b

Notes: *In a column, data are the mean values with standard error having different letters are significant as per DMRT. ns= Non-significance.

Table 2. Performance of different hydroponic green fodder on hydroponic nutrient media for agronomic characteristics (14 DAS)

Fodder	Fodder length (cm)*	Root length (cm)	Fodder yield (kg)
Maize	25.75±0.61 a	12.00±0.47 a	6.19±0.26 a
Wheat	16.58±0.61 b	8.52±0.47 b	4.84±0.26 b
Sudan grass	12.52±0.61 c	5.58±0.47 c	3.99±0.26 c

Notes: *In a column, data are the mean values with standard error having different letters are significant as per DMRT.

Root length (cm)

The differences in root length were statistically significant, as indicated by the letters assigned to each mean value based on Duncan's Multiple Range Test (DMRT). Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, green fodder crops grown in Cooper and Hoagland & Arnon nutrient media exhibited similar root lengths (10.14 cm and 9.31 cm, respectively), both labelled with the letter 'a', indicating no significant difference between these treatments. Conversely, the root length of crops grown in ACI vitamix nutrient media (6.65 cm), labelled with the letter 'b', was significantly shorter compared to those grown in Cooper and Hoagland & Arnon media.

The observed variations in root length among the nutrient media treatments suggest differential effects on root development and growth. Root length is a crucial parameter influencing nutrient and water absorption, as well as overall plant health and productivity (Hoagland and Arnon, 1950; Hochmuth and Hochmuth, 1997). Therefore, the differences observed in root length could have significant implications for the performance and yield of the green fodder crops (Bugbee and Salisbury, 1988). These findings underscore the importance of selecting appropriate nutrient media formulations to optimize root development and overall plant growth in hydroponic systems (Marschner, 2012).

Fodder yield (Kg)

In this study, green fodder crops grown in Cooper and Hoagland & Arnon nutrient media exhibited similar fodder yields (5.83 kg and 5.25 kg, respectively), both labelled with the letter 'a', indicating no significant difference between these treatments. Conversely, the fodder yield of crops grown in ACI vitamix nutrient media (3.94 kg), labelled with the letter 'b', was significantly lower compared to those grown in Cooper and Hoagland & Arnon media.

The perceive variations in fodder yield among the nutrient media treatments suggest differential effects on overall biomass production and productivity of the green fodder crops. Fodder yield is a critical parameter influencing the economic feasibility and efficiency of hydroponic green fodder production systems (Rakocy *et al.*, 2006; Li and Hu, 2020). Therefore, the differences observed in fodder yield could have significant implications for the profitability and sustainability of hydroponic fodder production operations (Cooper and Black, 2008). These findings underscore the importance of selecting appropriate nutrient media formulations to optimize fodder yield and overall crop productivity in hydroponic systems.

Evaluation of green fodder

Fodder length (cm)

The performance of different hydroponic green fodder crops in terms of fodder length at 14 days after sowing (DAS) on hydroponic nutrient media was evaluated, as presented in Table 2. Significant differences in fodder length among the green fodder crops were observed, as indicated by the letters assigned to each mean value based on Duncan's Multiple Range Test (DMRT). Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, maize exhibited the highest fodder length (25.75 cm), labelled with the letter 'a', indicating superior performance compared to wheat and Sudan grass. Wheat had an intermediate fodder length (16.58 cm), labelled with the letter 'b', while Sudan grass had the shortest fodder length (12.52 cm), labelled with the letter 'c'.

The observed variations in fodder length among the green fodder crops suggest differential growth rates and developmental patterns under the same hydroponic nutrient media conditions. Fodder length is an essential parameter reflecting the overall growth and vigor of the crops, with longer lengths indicating more robust growth and development (Hochmuth and Hochmuth, 1997). These findings highlight the importance of selecting suitable green fodder crops based on their growth characteristics and intended use in hydroponic systems. Maize, with its superior fodder length, may be preferred for applications requiring higher biomass production or feed quality (Li and Hu, 2020). Conversely, Sudan grass, with its shorter fodder length, may be more suitable for scenarios where rapid growth and turnover are prioritized.

Root length (cm)

Significant differences in root length among the green fodder crops were observed, as indicated by the letters assigned to each mean value based on DMRT. Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, maize exhibited the longest root length (12.00 cm), labelled with the letter 'a', indicating superior root development compared to wheat and Sudan grass. Wheat had an intermediate root length (8.52 cm), labelled with the letter 'b', while Sudan grass had the shortest root length (5.58 cm), labelled with the letter 'c'.

The observed variations in root length among the green fodder crops suggest differential root growth and development under the same hydroponic nutrient media conditions. Root length is a critical parameter influencing nutrient and water uptake, as well as overall plant health and productivity (Rakocy *et al.*, 2006). These findings highlight the importance of selecting suitable green fodder crops based on their root characteristics and intended use in hydroponic systems. Maize, with its longer root length, may be preferred for applications requiring efficient nutrient and water absorption or increased stability in the growing medium. Conversely, Sudan grass, with its shorter root length, may be more suitable for scenarios where rapid growth and establishment are prioritized.

Table 3. Combined effect of different hydroponic nutrient media and fodder types on NFT Systems for fodder agronomic characters (14 DAS)

Nutrient media × Fodder	Fodder length (cm)*	Root length (cm)	Fodder yield (kg)
Cooper × Maize	29.62±0.49 a	13.70±0.30 a	7.63±0.19 a
Cooper × Wheat	17.68±0.49 d	10.78±0.30 c	5.56±0.19 c
Cooper × Sudan grass	13.44±0.49 f	5.96±0.30 e	4.30±0.19 d
Hoagland & Arnon × Maize	26.32±0.49 b	12.30±0.30 b	6.64±0.19 b
Hoagland & Arnon × Wheat	16.56±0.49 de	9.56±0.30 d	5.12±0.19 c
Hoagland & Arnon × Sudan grass	12.56±0.49 fg	6.08±0.30 e	4.00±0.19 de
ACI Vitamix × Maize	21.32±0.49 c	10.02±0.30 cd	4.31±0.19 d
ACI Vitamix × Wheat	15.52±0.49 e	5.24±0.30 ef	3.84±0.19 de
ACI Vitamix × Sudan grass	11.58±0.49 g	4.70±0.30 f	3.68±0.19 e

Notes: *In a column, data are the mean values with standard error having different letters are significant as per DMRT

Fodder yield (Kg)

Significant differences in fodder yield among the green fodder crops were observed, as indicated by the letters assigned to each mean value based on DMRT. Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, maize exhibited the highest fodder yield (6.19 kg), labelled with the letter 'a', indicating superior performance compared to wheat and Sudan grass. Wheat had an intermediate fodder yield (4.84 kg), labelled with the letter 'b', while Sudan grass had the lowest fodder yield (3.99 kg), labelled with the letter 'c'.

The distinguished variations in fodder yield among the green fodder crops suggest differential biomass production and productivity under the same hydroponic nutrient media conditions. Fodder yield is a critical parameter influencing the economic feasibility and efficiency of hydroponic green fodder production systems (Cooper and Black, 2008). These findings highlight the importance of selecting suitable green fodder crops based on their yield potential and intended use in hydroponic systems. Maize, with its higher fodder yield, may be preferred for applications requiring higher biomass production or feed quality (Hochmuth and Hochmuth, 1997). Sudan grass, with its lower fodder yield, may be more suitable for scenarios where rapid growth and turnover are prioritized.

Combined effect of nutrient media and fodder types

Fodder length (cm):

The combined effect of different hydroponic nutrient media and fodder types on NFT systems for fodder length at 14 days after sowing (DAS) was investigated, as presented in Table 3. Significant differences in fodder length were observed among the different combinations of nutrient media and fodder types, as indicated by the letters assigned to each mean value based on Duncan's Multiple Range Test (DMRT).

Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, the highest fodder length was observed in the Cooper × Maize combination (29.62 cm), labelled with the letter 'a', indicating superior performance compared to other combinations. This suggests that maize grown in Cooper nutrient media exhibited the most robust growth in terms of fodder length (Fig. 1). On the other hand, the lowest fodder length was observed in the ACI Vitamix × Sudan grass combination (11.58 cm), labelled with the letter 'g'.

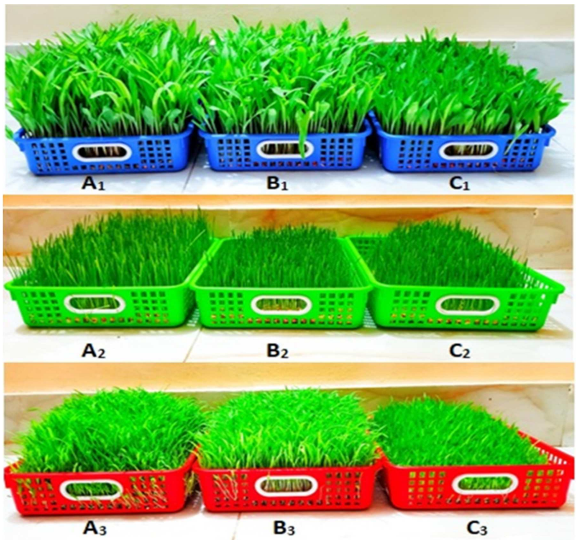

Fig. 1. Influence of hydroponic nutrient media on three green fodders. A_1-A_3: Cooper, B_2-B_3: Hoagland & Arnon, C_1-C_3: ACI Vitamix. A_1-C_1: Maize, A_2-C_2: Wheat, A_3-C_3: Sudan grass

These results indicate that both the choice of hydroponic nutrient media and the type of fodder crop significantly influence fodder length in NFT systems. Maize generally exhibited the highest fodder length across different nutrient media treatments, followed by wheat and Sudan grass. Additionally, the nutrient media also played a crucial role, with Cooper generally resulting in higher fodder lengths compared to Hoagland & Arnon and ACI Vitamix (Shukla and Dixit, 2018; Azad and Noor, 2021; Choukan and Ganai, 2020). Overall, these findings emphasize the importance of carefully selecting both the nutrient media and the fodder crop species to optimize fodder length and overall productivity in hydroponic NFT systems.

Root length (cm)

Significant differences in root length were observed among the different combinations of nutrient media and fodder types, as indicated by the letters assigned to each mean value based on DMRT. Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, the highest root length was observed in the Cooper × Maize combination (13.70 cm), labelled with the letter 'a', indicating superior performance compared to other combinations. This suggests that maize grown in Cooper nutrient media exhibited the most robust root development. On the other hand, the lowest root length was observed in the ACI Vitamix × Sudan grass combination (4.70 cm), labelled with the letter 'f'.

These results indicate that both the choice of hydroponic nutrient media and the type of fodder crop significantly influence root length in NFT systems. Maize generally exhibited the longest roots across different nutrient media treatments, followed by wheat and Sudan grass. Additionally, the nutrient media also played a crucial role, with Cooper generally resulting in longer roots compared to Hoagland & Arnon and ACI Vitamix. Overall, these findings emphasize the importance of carefully selecting both the nutrient media and the fodder crop species to optimize root development and overall productivity in hydroponic NFT systems (Srivastava *et. al.*, 2019; Islam *et. al.*, 2018)). Further research is warranted to elucidate the specific mechanisms underlying the observed differences and to explore potential strategies for maximizing root length in hydroponic green fodder production.

Fodder yield (Kg)

Significant differences in fodder yield were observed among the different combinations of nutrient media and fodder types, as indicated by the letters assigned to each mean value. Treatments sharing the same letter are not significantly different from each other, while treatments with different letters are significantly different. In this study, the highest fodder yield was observed in the Cooper × Maize combination (7.63 kg), labelled with the letter 'a', indicating superior performance compared to other combinations. This suggests that maize grown in Cooper nutrient media exhibited the highest biomass production. On the other hand, the lowest fodder yield was observed in the ACI Vitamix × Sudan grass combination (3.68 kg), labelled with the letter 'e'.

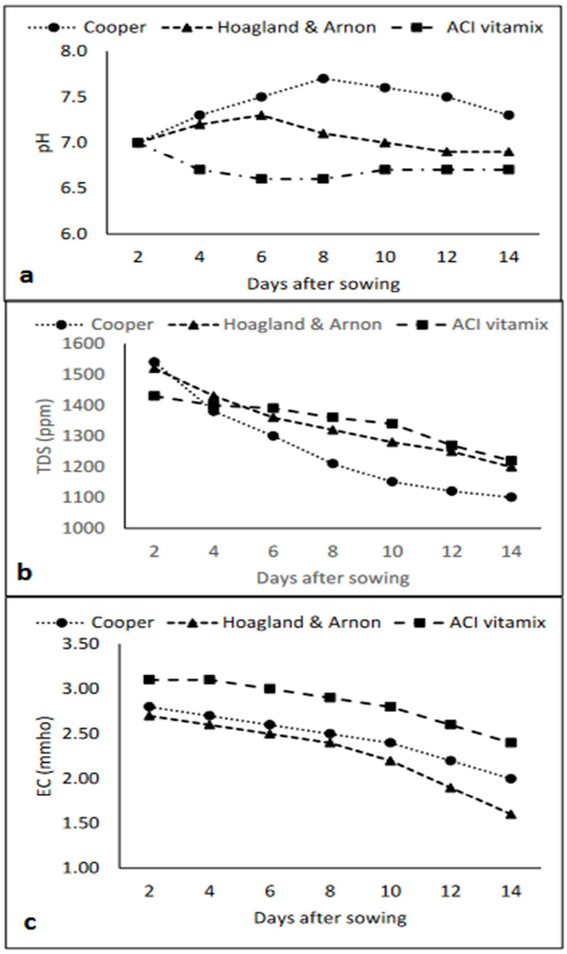

Fig. 2. Nutrient solution parameters of three hydroponics media. a; changes of pH of different nutrient media at two days interval. b; Total dissolved solids (TDS) of nutrient media at 2-14 day after sowing. c; Electrical conductivity (EC) of nutrient media after two days up to fourteen days

The choice of hydroponic nutrient media and the type of fodder crop significantly influence fodder yield in NFT systems. Maize generally exhibited the highest yields across different nutrient media treatments, followed by wheat and Sudan grass (Alkhazaleh *et. al.*, 2018). Additionally, the nutrient media also played a crucial role, with Cooper generally resulting in higher yields compared to Hoagland & Arnon and ACI Vitamix. Overall, these findings underscore the importance of carefully selecting both the nutrient media and the fodder crop species to optimize fodder yield and overall productivity in hydroponic NFT systems (Singh *et. al.,* 2017; Al-Raddad, 2019).

Fluctuations of pH

Fig.-2a illustrates the fluctuations of pH levels at different stages of maize fodder growth in three types of nutrient media: Cooper, Hoagland & Arnon, and ACI Vitamix. The pH levels were measured on days 2, 4, 6, 8, 10, 12, and 14 after sowing. In the Cooper nutrient media, the pH remained relatively stable throughout the growth period, ranging from 7.0 to 7.7. There was a slight increase in pH from day 2 (7.0) to day 8 (7.7), followed by a gradual decrease towards the end of the growth period. Overall, the pH levels in the Cooper nutrient media remained within the optimal range for plant growth and nutrient uptake. Similarly, in the Hoagland & Arnon nutrient media, the pH levels remained relatively stable, ranging from 7.0 to 7.3. There was a slight increase in pH from day 2 (7.0) to day 6 (7.3), followed by a gradual decrease towards the end of the growth period. The pH levels in the Hoagland & Arnon nutrient media also remained within the optimal range for plant growth. In contrast, the pH levels in the ACI Vitamix nutrient media showed a decreasing trend over the growth period, ranging from 7.0 to 6.7. There was a notable decrease in pH from day 2 (7.0) to day 6 (6.6), followed by relatively stable pH levels for the remainder of the growth period. While the pH levels in the ACI Vitamix nutrient media remained within an acceptable range for plant growth, the decreasing trend may indicate potential challenges in nutrient availability or pH stability.

The fluctuations in pH observed in the different nutrient media highlight the importance of monitoring and managing pH levels in hydroponic systems to ensure optimal nutrient availability and uptake for plant growth. The stability of pH observed in the Cooper medium suggests effective pH regulation, contributing to consistent nutrient availability for maize plants throughout the growth period (Marschner, 2012).

In contrast, the Hoagland & Arnon medium exhibited minor fluctuations, indicating some variability in pH control but still within an acceptable range for plant growth. The declining pH trend observed in the ACI Vitamix medium raises concerns about potential nutrient imbalances or pH drift over time. Acidification of the nutrient solution can impact nutrient availability and compromise plant health if left unaddressed (Taiz *et. al*., 2015; Savvas and Gruda, 1018).

Changes of TDS (ppm)

Fig.-2b illustrates the changes in Total Dissolved Solids (TDS) levels at different growing stages of maize fodder in three types of hydroponic nutrient media: Cooper, Hoagland & Arnon, and ACI Vitamix. In the Cooper nutrient media, TDS levels showed a gradual decrease over the growth period, starting from 1540 ppm on day 2 and reaching 1100 ppm by day 14. This decreasing trend in TDS levels may be attributed to nutrient uptake by the growing plants, indicating efficient nutrient utilization. Similarly, in the Hoagland & Arnon nutrient media, TDS levels exhibited a gradual decrease from 1520 ppm on day 2 to 1200 ppm on day 14. This decline in TDS levels suggests active nutrient uptake by the maize fodder plants throughout the growth period. In the ACI Vitamix nutrient media, TDS levels remained relatively stable over the growth period, ranging from 1430 ppm to 1220 ppm. While there were minor fluctuations in TDS levels, the overall trend indicates consistent nutrient availability in the hydroponic system.

The changes in TDS levels observed in the different nutrient media reflect variations in nutrient concentrations and uptake dynamics during the growth of maize fodder. Monitoring TDS levels is crucial for assessing nutrient availability and ensuring optimal nutrient management in hydroponic systems (Resh, 2012; Savvas and Gruda, 2018). Overall, the results suggest that the three types of hydroponic nutrient media provided adequate nutrient supply for maize fodder growth, as indicated by the observed trends in TDS levels.

Changes of EC (mmho)

In the Cooper nutrient media, EC values decreased gradually from 2.80 mmho on day 2 to 2.00 mmho on day 14. This decline in EC indicates a decrease in the concentration of dissolved salts in the solution over the growth period, possibly due to nutrient uptake by the growing maize fodder plants. Similarly, in the Hoagland & Arnon nutrient media, EC values decreased steadily from 2.70 mmho on day 2 to 1.60 mmho on day 14. This decreasing trend in EC suggests a reduction in the concentration of dissolved salts in the solution as the maize fodder plants utilized nutrients for growth and development. In contrast, the ACI Vitamix nutrient media exhibited relatively stable EC values over the growth period, ranging from 3.10 mmho to 2.40 mmho. While there were minor fluctuations in EC values, the overall trend indicates consistent nutrient concentrations in the hydroponic solution.

The observed changes in EC across the different nutrient media provide insights into nutrient availability and uptake during maize fodder growth in hydroponic systems. The consistent decrease in EC over time in all three media indicates effective nutrient uptake by the plants, demonstrating the suitability of the nutrient solutions for supporting maize growth (Bugbee and Salisbury, 1988). The declining trend in EC reflects the active uptake of ions and salts by the maize plants as they develop. This uptake is essential for promoting healthy growth and development, as it ensures that the plants receive sufficient nutrients for optimal performance (Resh, 2012; Cooper and Black, 2008). Overall, monitoring EC levels allows growers to assess nutrient availability and adjust nutrient concentrations in the solution as needed to maintain optimal growing conditions for maize fodder production. These findings underscore the importance of managing EC in hydroponic systems to support healthy plant growth and maximize yield.

Conclusion

In this study, the performance of maize fodder in hydroponic systems using three different nutrient media (Cooper, Hoagland & Arnon, and ACI Vitamix) was evaluated based on various growth parameters including fodder length, root length, and fodder yield. Additionally, fluctuations in pH, Total Dissolved Solids (TDS), and Electrical Conductivity (EC) were monitored to assess nutrient availability and solution stability over the growth period. The results revealed significant variations in growth parameters among the different nutrient media treatments. Maize fodder grown in the Cooper nutrient media generally exhibited superior performance in terms of fodder length, root length, and fodder yield compared to the other nutrient media. This suggests that the composition of the nutrient solution significantly influences the growth and productivity of maize fodder in hydroponic systems. Furthermore, fluctuations in pH, TDS, and EC levels over the growth period were observed, reflecting variations in nutrient concentrations and uptake dynamics. While the Cooper and Hoagland & Arnon nutrient media showed relatively stable pH and EC levels, indicating consistent nutrient availability, the ACI Vitamix nutrient media exhibited more fluctuation in these parameters. In conclusion, hydroponic systems offer a promising approach for efficient and sustainable green fodder production.

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