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SUSTAINABLE TEA PRODUCTION: A COMPARATIVE ASSESSMENT OF THE GROWTH, YIELD, AND QUALITY OF TEA UNDER CONVENTIONAL AND ZERO-INPUT ORGANIC MANAGEMENT AT QUEENSBERRY ESTATE, SRI LANKA

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Abstract

Sri Lanka, a leading global tea producer and a pioneer in organic tea cultivation, holds strong potential for expanding the organic tea sector. Comprehensive scientific validation through systematic assessment of organic and conventional tea management systems can generate evidence to promote the expansion of organic tea in Sri Lanka. Growth, yield, and quality attributes of tea (cultivar DN) were evaluated under organic with zero inputs (T1) and conventional with chemical inputs (T2) at Queensberry Estate, Nawalapitiya, Sri Lanka, using a Randomized Complete Block Design (RCBD) with three replicates. Growth and yield parameters, soil and leaf nitrogen content, and leaf chlorophyll content (measured with SPAD) were recorded. Additionally, the quality of brewed tea was assessed through sensory evaluation by untrained panelists. Growth, yield, and chemical parameters were analyzed using one-way ANOVA in R, while sensory data were evaluated through the Friedman test in Minitab. Results revealed that soil available nitrogen was significantly higher ($p<0.05$) in conventional treatment (0.090%) compared to organic treatment with zero inputs (0.065%). Similarly, leaf total nitrogen content in T2 (1.145 %) is significantly greater ($p<0.05$) than in T1 (0.898%). Correspondingly, leaf area, shoot growth rates, and mean shoot length were significantly ($p<0.05$) higher in T2 (6.60 cm) compared to T1 (4.23 cm). In contrast, the mean number of shoots in 100g was significantly greater ($p<0.05$) in T1 than in T2. Leaf chlorophyll content and yield were not significantly different ($p>0.05$), yet greater in T2 than in T1. Sensory evaluation showed no significant quality differences between T1 and T2. In conclusion, conventionally managed tea has superior growth, yield, and quality attributes compared to organically managed tea with zero inputs. A long-term application of organic inputs is recommended to achieve better growth, yield, and quality in organically managed tea.

Keywords: Leaf nitrogen, Made tea, Shoot growth, Soil nitrogen, Zero inputs

1. Introduction

Tea is one of the most widely consumed beverages globally, and Sri Lanka ranks as the 4th largest tea producer, with an average production of 278.9 million kg, from tea plantations covering approximately 202,000 ha over the country, contributing 0.6% to the national GDP (Central Bank of Sri Lanka, 2020; Ministry of Plantation Industries & Export Agriculture, 2020). Since the 1950s, with the onset of the Green Revolution, Sri Lankan tea farmers have increasingly relied on synthetic agrochemicals to boost yields. However, these practices led to adverse effects, including soil degradation, health risks to humans and animals, and deterioration of water, air, and soil quality. Moreover, high production costs, limited market security, reduced export potential, and chemical toxicity have undermined the profitability, prompting a shift toward more sustainable tea farming methods (Reganold et al., 1990; Jayasinghe and Toyoda, 2004; Thushara, 2015).

As the global pioneer in organic tea cultivation, Sri Lanka established its first certified organic tea estates in the early 1980s and began organic tea exports in 1987 (Zoysa & Munasinghe, 2004). Over time, organic production expanded across estates and smallholders, gaining access to premium international markets (Vidanapathirana & Wijesooriya, 2014). Strict pesticide residue limits imposed by the EU (Mohamed and

Zoysa, 2006), along with Sri Lanka's 2021 fertilizer ban targeting 100% organic agriculture (Gazette No. 2226/48), have accelerated farmers' transition towards organic tea cultivation (Malkanthi, 2020), creating ecologically sustainable plantations.

Sustainable tea production offers environmental, economic, and social benefits. It encourages responsible farming that conserves biodiversity, protects natural resources, and supports farmer livelihoods. Thus, sustainable teas are increasingly favored in global markets for their ethical and environmental value (Rainforest Alliance, 2023). The growing global demand for sustainable tea benefits countries like Sri Lanka by improving access to premium markets and higher economic returns. Organic tea commands premium prices in international markets, resulting in a higher benefit-cost ratio (3.13) than conventional tea (2.41) and greater profitability despite lower yields (Herath et al., 2001; Kodagoda & Dharmadasa, 2020).

Growing consumer awareness and preference for safer, health-enhancing products have led to a decline in conventional tea consumption in developed countries, including the USA, Europe, and Japan (Thushara, 2015; James, Hu, & Leonce, 2019). Organic tea is increasingly preferred for its perceived antioxidant, detoxifying, and overall wellness benefits, with consumers showing strong demand for toxin-free, aromatic, and sustainably certified products (El-Hack et al., 2020). This shift is reflected in the broader global organic tea market, which is projected to expand significantly, with valuation expected to more than double by 2035. Despite the market growth, organic tea production remains a niche in Sri Lanka, covering only 0.7% of total tea area in 2010 and producing 1.87 million kg in 2019 (Dharmadasa et al., 2019; SLTB, 2019). There is limited comparative research on the physiology, growth, yield, and quality of organically versus conventionally grown tea in Sri Lanka, restricting evidence-based guidance for farmers considering a shift to organic cultivation. This study addresses this gap by systematically evaluating both cultivation systems, generating evidence to inform the long-term agronomic, economic, and socio-environmental viability of organic tea production.

2. Materials and Methods

The study was conducted in Queensberry Estate, Kahawatta plantation, Nawalapitiya (1652 m.a.s.l.). Queensberry estate spans 251.56 ha, including 1.5 ha under organic conversion (not yet certified). The estate, established in 1984 with VP Tea Clone DN, was conventionally managed before organic conversion about 2.5 years ago. Pruned tea fields of 0.5 ha each of organic and conventional were selected for experimentation. Three plots (40 m^2, 50 bushes each, surrounded by guard rows) per treatment were selected to minimize external influence. Treatments followed a Randomized Complete Block Design (RCBD) with three replicates. Treatment 1 (T1) was organic with zero input, and Treatment 2 (T2) was conventional with chemical inputs (U709 fertilizer 120 kg/acre, Zn Urea 4 kg/acre foliar, Cu fungicide 0.5 kg/acre as per TRI-SL recommendations). All plots were harvested weekly by the same plucker to maintain consistency.

2.1. Data Collection

Tea Yield: Shoots with 2–4 leaves and a terminal bud were harvested weekly, and fresh leaf weight was recorded per plot (Balasuriya, 1996; Agric, 2009).

Shoot Number in 100g: The number of shoots per 100g of harvested shoots was counted (Yilmaz, 2004).

Leaf Area: Leaf area was measured non-destructively using ImageJ software on 3 shoots each from 5 bushes per plot weekly (Cosmulescu et al., 2020).

Shoot Length: Three shoots from five randomly selected bushes per plot were tagged and weekly measurements were taken from the node above the tag to the uppermost visible node (Cheruiyot et al., 2009).

Nutrient Analysis: Leaf and soil samples were collected monthly, and nitrogen content was determined using Kjeldahl method (Bremner & Mulvaney, 1982).

Relative Leaf Chlorophyll Content: Chlorophyll content was measured with a SPAD-502 at three leaf points, 15 days before and after fertilizer application in conventional plots (Liu et al., 2012; Lin et al., 2010; Wahono et al., 2021).

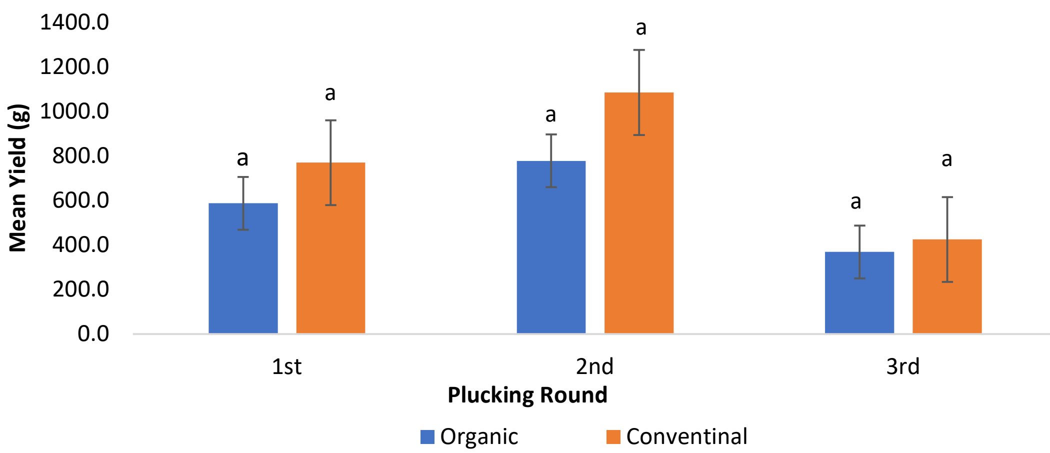
Quality of Made Tea: Black tea from both treatments was evaluated by five untrained panelists for flavor, taste, color, and overall acceptability (Adnan et al., 2013).

Data were explored graphically in Excel 2019, and statistical analysis was performed using R version 4.2.2 and Minitab version 21.1.0. Growth, yield, and chemical parameters were analyzed by one-way ANOVA in R, while sensory data were evaluated using the Friedman test in Minitab.

3. Results and Discussion

Tea Yield and Number of Shoots per 100g

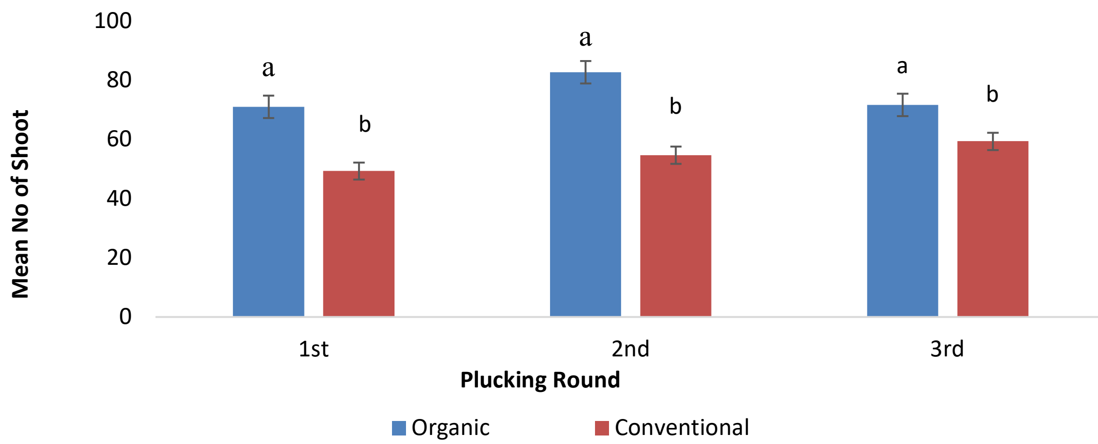
Tea yield did not differ significantly ($p < 0.05$) between conventional (T2) and organic (T1) management, indicating minimal impact of crop management practices on yield (Figure 4.1), consistent with observations in Wuyi County, China, where organic and conventional tea exhibited comparable yields and economic performance (Zhang et al., 2023). The increased yield during the second plucking round may be attributed to favorable rainfall, as high precipitation can enhance harvested yields (Oksuz, 1987). Zhang et al. (2023) reported that organic conversion tea farms, which utilize organic fertilizers, achieved yields comparable to those of conventional farms while reducing environmental impacts.



Note: Means with the same letter in each plucking round do not significantly differ at $p<0.05$.

Figure 1: Tea yield in each plucking round

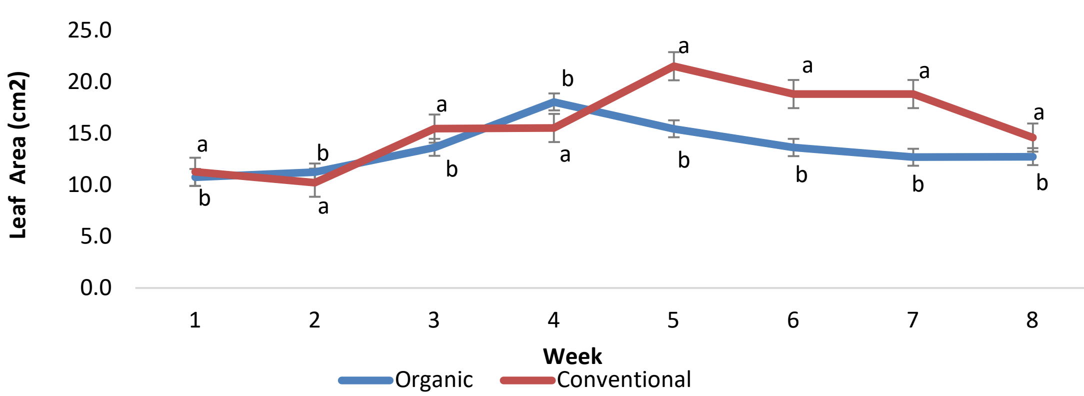
A significant difference ($p< 0.05$) was observed in the number of shoots per 100g of the yield between organic (T1) and conventional (T2) treatments, T1 producing more shoots in all plucking rounds (Figure 4.2). The number of tea shoots per 100 g of green leaf generally ranges between 30 and 80 shoots (Eden, 1976; Willson & Clifford, 1992), which is consistent with the findings of the present study. The higher shoot count in the zero-input organic system suggests a lower mean shoot weight, possibly due to the absence of external nutrient supply in the zero-input system. These findings are consistent with the results reported by Yilmaz et al. (2004). However, recent studies have shown that supplementing organic tea cultivation with organic manures, such as vermicompost or farmyard manure, can significantly enhance tea yield and shoot quality. Kocaman et al. (2024) demonstrated that application of 4000 kg ha^{-1} of biotechnologically developed vermicompost significantly enhanced tea yield and nutrient status of the tea plant, offering a viable alternative to chemical fertilizers. Similarly, Zhang et al. (2023) reported that organic tea farms in the conversion stage utilizing organic fertilizers achieved yields comparable to conventional farms while reducing environmental impacts.



Note: Means with the same letter in each plucking round do not significantly differ at p<0.05.

Figure 2: Number of shoots per 100g of harvested yield

Leaf area is an important parameter because it influences photosynthetic efficiency, biomass accumulation, and overall yield. Significant differences ($p < 0.05$) were observed between treatments, with conventionally managed tea (T2) exhibiting consistently larger leaf area compared to organically managed tea (T1) over the study period (Figure 4.3). Enhanced nutrient availability under conventional systems is correlated with greater uptake of essential elements like nitrogen and phosphorus, contributing to larger leaf development in tea plants (Lu et al., 2025).

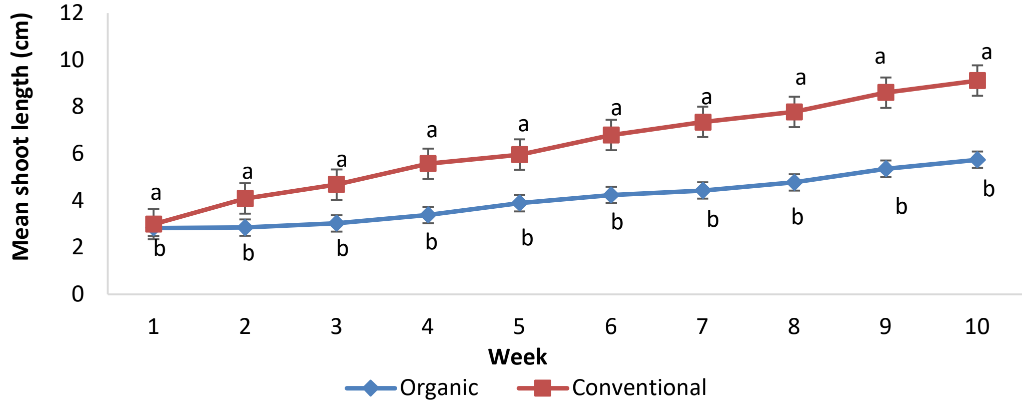


Note: Means sharing the same letter each week does not significantly differ at p<0.05.

Figure 3: Variation of the leaf area over time

Shoot Length

Shoots represent the harvested portion of the tea plant. As shown in Figure 4.4, shoot length differed significantly ($p<0.05$) between the two management systems. Conventional tea (T2) exhibited the longest shoot length, reaching 9.1 cm, whereas the organically managed tea under a zero-input system (T1) recorded the shortest shoot length (5.7 cm) at the 10th week. Shoot length is widely recognized as a key indicator of vegetative growth in tea, with studies documenting distinct shoot growth patterns and dynamics under varying conditions. The enhanced shoot elongation observed in T2 may be attributed to the external application of chemical fertilizers, including U709, and Zn-urea foliar sprays, which likely improved nutrient uptake and stimulated shoot growth compared to the nutrient-limited conditions in the zero-input organic system.

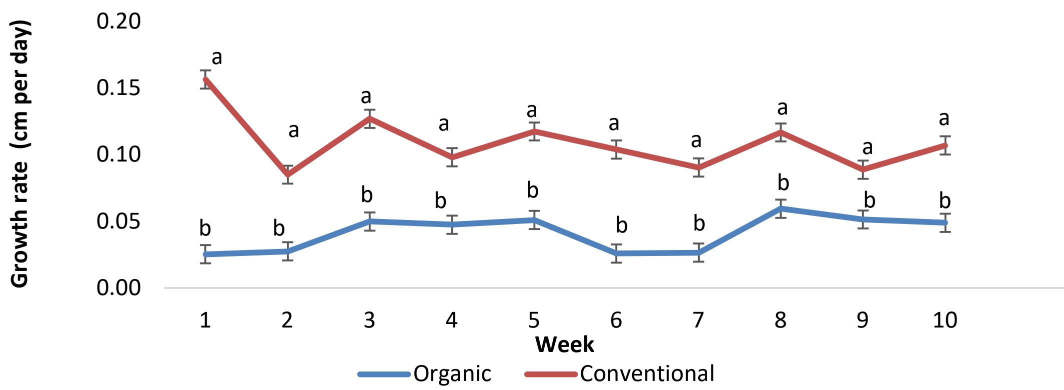


Note: Means with the same letter in each week are not significantly different at $p<0.05$.

Figure 4: Variation of the shoot length over time

Growth Rate of Tea Shoot

Shoot growth rate differs significantly ($p < 0.05$) between two management systems (Figure 4.5), with conventionally managed tea (T2) exhibiting a higher growth rate than organically managed tea (T1). The enhanced shoot growth in T2 may be attributed to the application of foliar Zn-urea, which likely improved nutrient availability and physiological activity, thereby promoting shoot elongation. In contrast, previous studies have reported greater shoot growth under organic management (Islam et al., 2017; Han et al., 2018). The discrepancy of results may be explained by the transitional status of the organic field, which is still under conversion and receives no external organic inputs, potentially limiting nutrient supply and suppressing shoot growth during the early conversion phase. Choudhary et al. (2024) demonstrated that applying vermicompost at 10 t ha^{-1} combined with Jeevamrit at 10% concentration notably enhanced tea growth parameters and overall yield.

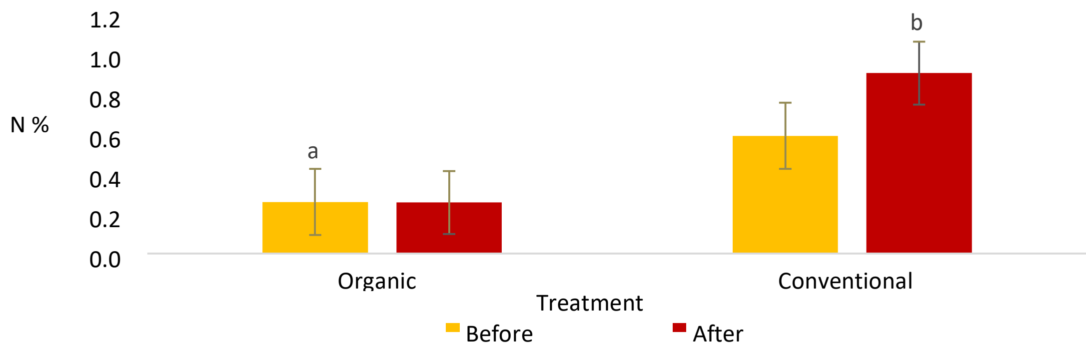


Note: Means with the same letter in each week are not significantly different at $p>0.05$.

Figure 5: Shoot growth rate over time

Nitrogen Status in Soil

Soil available nitrogen increased significantly after urea zinc sulfate foliar application in the conventional field (T2) (0.090%) (Figure 4.6), whereas no significant change was observed in the organically managed field (T1), which remained around 0.065%. The limited response in T1 may reflect the slow nutrient release from organic sources due to delayed mineralization (Chin et al., 2014). The soil available nitrogen levels recorded in this study (0.065–0.090%) fall within the lower to moderate range of total/available nitrogen commonly reported for agricultural mineral soils, particularly under tropical conditions (Brady & Weil, 2017). This may be attributed to nitrogen loss through leaching and denitrification under high rainfall conditions, as nitrogen is highly mobile and can be washed to deeper soil layers during heavy rainfall (Tisdale & Nelson, 1985).

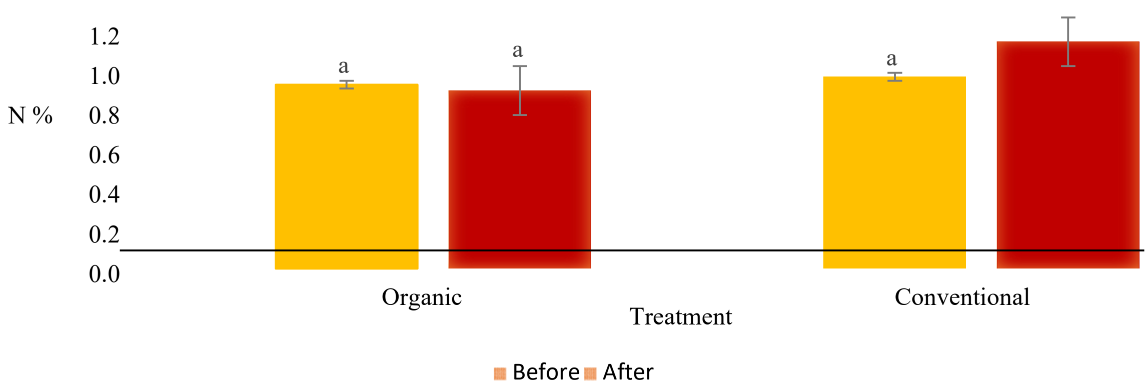


Note: Means with the same letter in each treatment are not significantly different at $p<0.05$)

Figure 6: Available N% in soil

Nitrogen Status of Leaves

Total N% in leaves was also significantly different in T1 and T2 (Figure 4.7). T2 has a significantly higher leaf N% (1.145 %), while T1 (0.898%) has a lower total N% in leaf at the end of the experiment. Application of foliar N may have increased the total N% in T2, as mentioned by Liu et al. (2021). Tea plants always require more N for high yield and quality (Ruan et al., 2007; Xie et al., 2021); thus, the low yield levels recorded in the present study may be due to a lack of N. Nitrogen is deficient in the tea plant if the leaf N content is less than 3%, mildly deficient when the leaf N content is between 3% and 3.5%, and sufficiently supplied when the leaf N content is greater than 3.5% (Cheruiyot et al., 2009; Mokaya et al., 2016). Accordingly, tea plants in both treatments are in a nitrogen- deficient condition, thus requiring an external application of nitrogen.

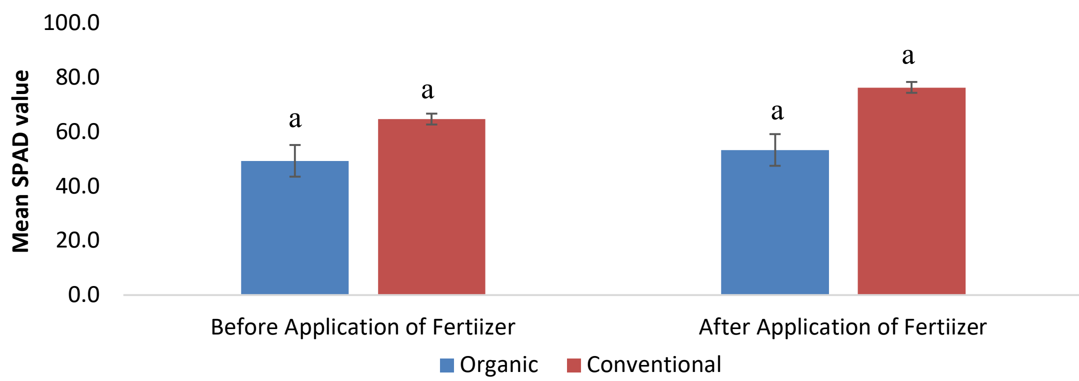


Note: Means with the same letter do not significantly different at $p<0.05$.

Figure 7: Total N% of leaves

Relative Leaf Chlorophyll Content

Relative leaf chlorophyll content did not differ significantly between treatments T1 and T2. However, T1 exhibited slightly lower chlorophyll levels, while T2 showed slightly higher values, corresponding with similar trends observed in soil and leaf nitrogen contents. Previous research findings also revealed that chlorophyll content was low in organically grown teas as compared to conventional farming (Sultana et al., 2016), which confirmed the findings of this research.



Note: Means with the same letter are not significantly different at $p<0.05$)

Figure 8: Relative leaf chlorophyll content

Sensory Evaluation of Made Tea

Miniature manufactured tea samples from the organic (T1) and conventional (T2) fields were evaluated by untrained panelists, and no significant differences were observed in flavor, aroma, color, or texture. Han et al. (2018) reported that organic tea had higher polyphenols and catechins but lower free amino acids, resulting in better taste and aroma. However, in this study, the conventional tea (T2) exhibited slightly superior taste and aroma, possibly because T1 is still in the process of organic conversion. Njogu et al. (2014) noted that foliar urea improves tea quality by increasing chlorophyll and amino acids, supporting the better quality observed in conventional tea here.

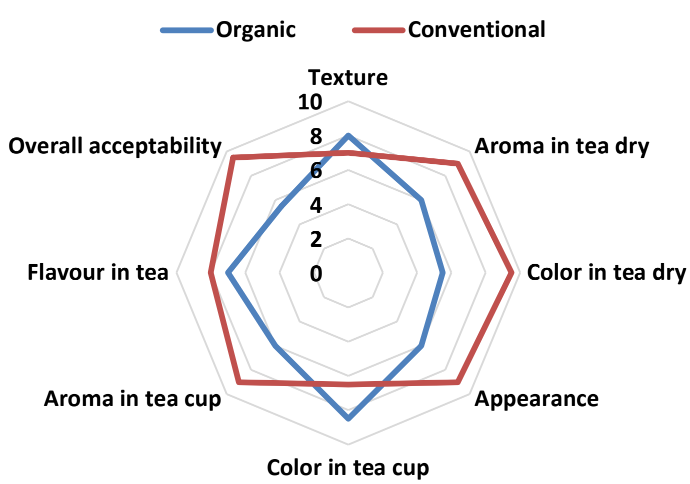


Figure 9: Sensory evaluation of made Tea

Conclusions

The findings indicate that soil nitrogen availability was significantly higher under conventional treatment compared to the organic treatment with zero inputs. In line with that, total nitrogen content in tea leaves was considerably greater in conventionally managed tea than in organically managed tea. This enhanced nutrient status contributed to a significant increase in leaf area, shoot growth rate, and mean shoot length in the conventional treatment (T2) compared to the organic treatment (T1). The number of shoots per 100 g was significantly different, with higher shoot counts observed in the zero-input organic treatment compared to the conventional treatment. However, key parameters such as leaf chlorophyll content (SPAD values), sensory attributes, and overall yield did not differ significantly between treatments, highlighting that the organic system, even without external inputs, performs comparably in yield-related traits. Conventional tea management outperformed the zero-input organic system in terms of vegetative growth and nitrogen-related parameters, factors that can influence tea quality. Nevertheless, the comparable performance observed in chlorophyll content and yield under organic conditions highlights its potential for sustainable production. The low nitrogen (N) content observed in the zero-input organic tea system is primarily attributed to the absence of external nutrient inputs, leading to suboptimal plant growth and reduced shoot weight. Incorporation of organic amendments such as vermicompost, farmyard manure, or compost can substantially improve soil fertility and tea yield. These findings suggest that supplementing organic tea cultivation with appropriate organic manures can mitigate nitrogen deficiencies inherent in zero-input systems, improving productivity, while supporting the sustainable production of tea in response to growing market demand for organic tea.

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