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Service Economy Strategies for Addressing Fluoride Levels in Tea Leaves: Insights from Science and Management

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Purpose: The natural buildup of fluoride (F) in tea leaves presents possible health hazards, despite the fact that tea is one of the most consumed beverages worldwide (Camellia sinensis (L.) O. Kuntze). Researching what causes fluoride to build up in tea leaves and coming up with long-term solutions to control the problem are the main goals of this project. In order to reduce the negative health effects of drinking too much fluoride-laced tea, this study seeks to combine theoretical understanding with real farming methods.

Method: The study involved a controlled experiment where 12-month-old tea plant cuttings were cultured hydroponically and exposed to varying concentrations of selenium (Se) and calcium (Ca). The treatments included different levels of fluoride (F) and the nutrients Se and Ca. Fluoride, selenium, and calcium levels in tea leaves and roots were measured using standard analytical techniques. Data analysis was performed using one-way ANOVA and LSD tests to determine the significance of differences.
Results: The results demonstrated that selenium application increased fluoride concentration in roots but significantly reduced it in tea leaves. Similarly, calcium supplementation decreased fluoride uptake in both leaves and roots. The findings suggest that Se and Ca can effectively mitigate fluoride accumulation in tea plants. The formation of Ca-F complexes and the role of Se in reducing fluoride translocation within the plant were identified as key mechanisms.
Conclusion: This study highlights the critical need for managing fluoride levels in tea leaves to ensure consumer safety and product quality. By integrating scientific insights with agricultural practices, tea producers can develop sustainable strategies to control fluoride levels. Selenium and calcium supplementation, along with precision agriculture techniques, were found to be effective in reducing fluoride uptake in tea plants.
Recommendations: It is recommended to focusing on developing and cultivating tea plant varieties with lower fluoride accumulation. Reducing the use of fluoride-containing pesticides and adopt integrated pest management practices. Conducting additional studies to fully understand fluoride uptake mechanisms and explore the interactions between soil amendments, water quality, and environmental factors.

Key-words: hydrogen fluoride, brick kilns, air pollution, sustainable management, environmental impact, agricultural practices, South Asia, Peshawar

INTRODUCTION

The Camellia sinensis (L.) O. Kuntze (Tea Plant) is an evergreen shrub commonly found in temperate, to regions of Asia. Tea, which is primarily derived from the leaves of the tea plant holds a status as a beverage worldwide. It stands as the consumed drink globally yet its susceptibility to natural fluoride accumulation in the leaves poses potential health risks. The presence of fluoride in tea leaves raises concerns due to its effects on health when consumed excessively. The fluoride content of tea plant can be influenced by different factors such, as climate conditions soil contaminated with pollutants and processing techniques.

To develop better management strategies, it is imperative to know about the possible mechanism of the uptake of fluoride and its translocation in tea leaves. By exploring the previous studies on fluoride in tea leaves, the objective of the current study is to provide insights into the science behind the accumulation of fluoride accumulation and provide possible management methods to reduce health risks linked with high fluoride consumption through tea drink. By incorporating scientific information with management strategies, the current study looks to find ways for enhancing sustainable solutions development for regulating fluoride concentration in tea leaves to protect public health.

Tea Production and Importance in the Economy

Tea crop production is important to several regional economies around the globe that contribute not only to agriculture sector but to global trade as well. Kenya, India and China are main players regulating the production of tea that includes millions of tea farmers from its growing to harvesting and distribution. Due to which the tea industry is responsible to give employment opportunities especially to smallholder farmers in rural areas that the tea industry provides employment opportunities in rural areas, supports smallholder farmers, and produces much needed income for the governments through tea exports.

Tea type	Median fluoride concentration, ppm	Interquartile range
Control	0.33	0.0078
Sri Lanka	3.58	0.1425
China	6.83	0.140
South Korea	5.36	0.0975
Japan	1.88	0.1375

The following tea types were significantly different at the $p < 0.001$ level: control versus Sri Lanka, control versus China, control versus South Korea, Sri Lanka versus China, China versus Japan, and South Korea versus Japan. The following types were significantly different at the $p = 0.029$ level: control versus Japan, Sri Lanka versus South Korea, Sri Lanka versus Japan and China versus South Korea.

Table 1: Differences in the fluoride concentration Asian tea, measured in 20 samples of each (Ing et al, (2021).

Reported by Ing et al[2], found that tea samples, from countries varied in their content. Chinese tea had the highest fluoride concentration while Japanese tea had the lowest. Specifically, Chinese tea contained 6.83 ppm of fluoride Korean tea had 5.36 ppm, Sri Lankan tea contained 3.58 ppm. Japanese tea had only 1.88 ppm of fluoride as depicted in Table 1. The differences in levels among the teas might be attributed to factors such as the types of tea used and environmental conditions like air quality, soil composition, groundwater quality and pollution near the tea plantations. All influencing the presence of fluoride and its absorption, by plants.

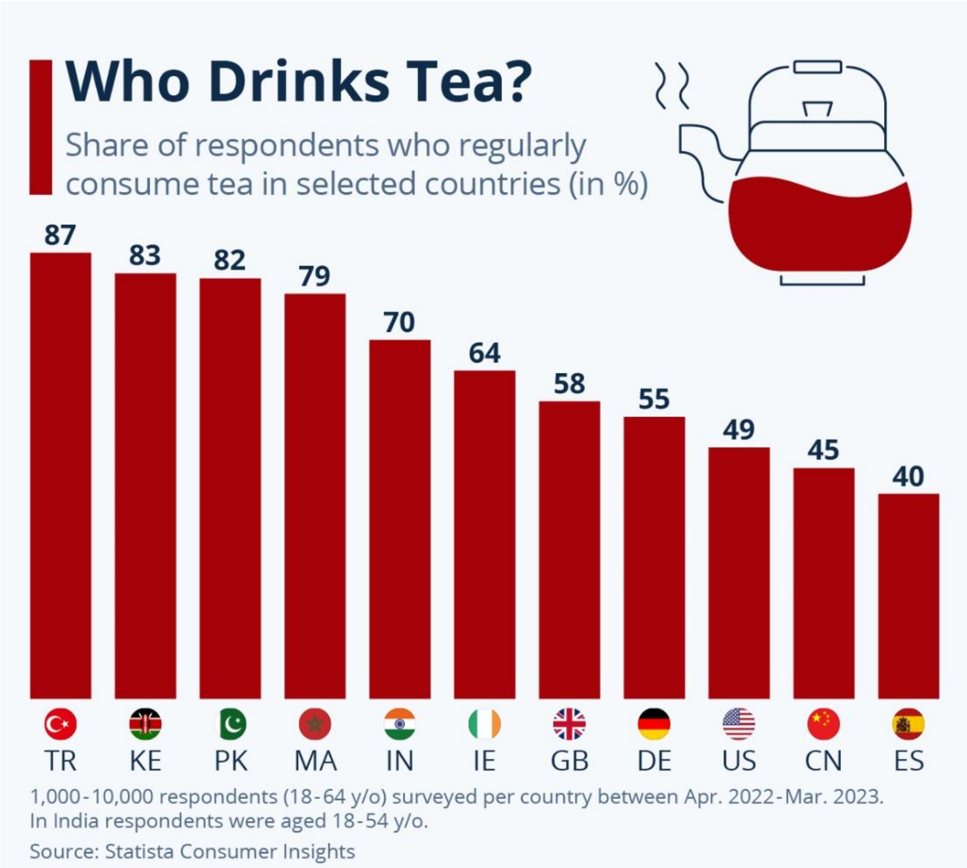

Figure 1. 1000-10,000 respondents (18-64 y/o) surveyed per country between April, 2022 to Mar, 2023.

Source: Statistica Consumer Insights (2024)

Moreover, in several societies it is a symbol of social and cultural significance, due to its taste and also for its apparent health benefits. According to the Statistica Consumer Insight (2024), the top 3 tea consumers are Turkey, Kenya and Pakistan (Figure 1). Kenya stands out among the 56 countries, significantly producing and exporting tea, with 83% of its respondents indicating they regularly drink tea. In contrast, the United Kingdom, a country that enjoys its tea, came in slightly lower with 58 percent of respondents. This is six percentage points less than the nearby tea-drinking nation of Ireland, despite still being high.

Tea is of enormous economic importance despite facing challenges like environmental and climate change factors and its unstable price in global market. UN celebrates the 21st May as International tea Day that aims not only to celebrate economic significance and health benefits, but also to protect tea industry that can play important role in reducing poverty alleviation, hunger and protecting natural assets.

F content of tea leaves

There has been inconsistent report of fluoride levels in tea leaves from the previous studies; some have found that fluoride accumulation in tea plants is high, while others have suggested that the concentrations are comparatively lower. Agrochemical practices, soil composition, species of tea plants, and the geographic location of tea plantations are just a few of the variables that can be blamed for the variation in these results. For instance, the fluoride content of tea leaves can be considerably increased by exposure to high levels of airborne fluoride emissions from industrial sources.

Moreover, the final fluoride concentration in the finished product may also be impacted by the processing techniques used in the production of tea, such as fermentation and withering. Comprehending the history of fluoride concentrations in tea leaves is essential to formulating sensible plans to control and lessen possible health hazards linked to excessive fluoride intake from tea drinking.

Scientific Insights on Managing Tea Leaves and Fluoride Levels

The tea leaves having high fluoride levels has been linked with health risks for consumers, according to earlier research, scientific studies[3,4] have shed important light on the connection among tea leaves and fluoride levels and how to manage them. Research[4] has demonstrated that a variety of factors, including water quality, processing techniques, and soil composition, can affect the amount of fluoride in tea leaves. For instance, studies have shown that applying fertilizers containing fluoride can greatly raise the fluoride content of tea plants[5]. Moreover, it has been discovered that some processing methods, like fermentation and roasting, lower the fluoride levels in tea leaves[6]. Utilizing these scientific discoveries, regulators and tea producers can put plans into place to efficiently control the amount of fluoride in tea leaves, guaranteeing the creation of consumer-safe, premium tea products.

Factors Influencing Fluoride Accumulation in Tea Plants

Previous research has determined that a number of critical variables, including as soil pH, the availability of other minerals in the soil, and irrigation techniques, which can negatively affect the accumulation of F in tea plants[7]. Fluoride availability to the roots of tea plants is largely dependent on the pH of the soil, with acidic soils generally absorbing more fluoride[8]. Furthermore, the mineral content of the soil, namely the amounts of iron and aluminum, might affect how well fluoride is absorbed in tea leaves[9].

Fluoride translocation from the soil to the plant can also be influenced by the kind and frequency of irrigation, with too much water having the potential to leach fluoride into the root system[10]. Gaining an understanding of these elements is essential to create strategies that effectively control the amount of fluoride in tea leaves, thereby guaranteeing the safety and quality of tea products. To completely understand the intricate relationships between these different elements and their unique effects on fluoride accumulation in tea plants, more extensive investigation is required.

Selenium (Se) is a vital micro element in humans and animals[11]. Se will have positive effects on human health by preventing carcinogenic particles in the body by providing immunity and enhancing antioxidant activities and lowering fluorosis in humans[12,13,14,15]. Se deficient body can be prone to weak immune system, high risk of cancer, diseases and nervous system abnormalities[16,17,18].

A part from human body, Selenium is also important for plant health in small concentration. Several research studies have reported that it protects plants by blocking the uptake of toxic elements like, arsenic, mercury, cadmium and lead[19,20]. Se in low concentrations can reduce the content of toxic elements by increasing the antioxidant activity and blocking lipid peroxidation[21].

Role of Ca in Plants

Because of its function as a universal second messenger, calcium (Ca) is a critical macro-nutrient for plant development and important for plant growth in general. As a divalent cation (Ca^{2+}), its main function is to strengthen the cell walls and other membranes and work as a counter-cation for anions (organic and inorganic) in vacuoles and also act as intra-cellular messenger inside the cytosol of the plant cell[22].

The previous literature reports a variety of influence by Ca ion on the biochemical and physiological processes like aid in photosynthesis[23] and its effects on the flavor and shelf life of the fruits[24]. [25]Plant can also adapt to specific environmental conditions due to Ca. For instance, plant can tolerate biotic stress if supplied with Ca supplementation e.g. heat[26], cold[27], and to toxic ion stress[28,29] that may be linked to Ca-induced changes in the ion profile of tissues in plants[30]. However, there is no specific research on the effects of Ca on Fluoride tolerance in the tea plants.

The current study focuses on the sustainable management strategies for cultivation of tea crop to control and monitor the fluoride levels in tea leaves via Se and CaO supplements that are crucial for long-term viability of tea industry and human health. In the current study selenium and Ca was added hydroponically to tea plant in a controlled experiment to assess whether Se can reduce the uptake of F in tea leaves that will have positive effect on human health and to safeguard the continued success of tea crop production and its positive influence on local as well as global economies.

INSIGHTS FROM RUSSIA

The management techniques applied in Russia on tea plants gives new information. There have been several studies on the production of ta in Russia with varying results. The results suggested that fluoride concentration in tea plants should be regularly monitored to guarantee the consumer safety. The tea growers in Russia have implemented several techniques to control fluoride levels in tea plants, which involves the choosing of a tea variety that is resistant to fluoride uptake and reducing fluoride uptake through modern processing procedure. In addition, implementing safety protocols like regular testing is important for monitoring the fluoride in tea plant effectively.

These effective management strategies are shown in Table-2 due to which the tea farmers are keeping the fluoride levels in tea under check. By regularly checking the scientific research, agricultural methods we can obtain and enhance useful knowledge to reduce fluoride levels in tea goods.Fluoride in tea can also be reduce via a rigorous strategy, which includes consumer know-how, legislation, policies and quality assurance in addition to technical advancement. From Russian tea research we can get valuable knowledge to reduce health hazards related to fluoride by consuming tea drink.

Table 2: Effective tea management strategies in Russia

Paper	Highlight of the study	Source
Risk Assessment of Fluoride Daily Intake from Preference Beverage:	This study discusses the fluoride content in various beverages, including tea, in Russia. It reports that more than 96% of the total fluoride content in tea leaves is soluble in tea infusion, emphasizing the importance of managing fluoride levels in tea	Satou, R., Oka, S., & Sugihara, N. (2021). Risk assessment of fluoride daily intake from preference beverage. *Journal of dental sciences*, *16*(1), 220-228.
A Tool for General Quality Assessment of Black Tea Retail:	This paper compares the fluoride levels in tea from different countries, including Russia. It highlights that the fluoride levels in loose-packed tea from Russia are significant, underlining the need for quality assessment and regulation	Khaydukova, M., Cetó, X., Kirsanov, D., del Valle, M., & Legin, A. (2015). A tool for general quality assessment of black tea—Retail price prediction by an electronic tongue. *Food Analytical Methods*, *8*, 1088-1092.
Public-health Risks from Tea Drinking: Fluoride Exposure:	This research measures fluoride releases from commercially available teas, including Russian Earl Grey tea, and assesses the public health risks associated with tea consumption in low-fluoride regions	Krishnankutty, N., Storgaard Jensen, T., Kjær, J., Jørgensen, J. S., Nielsen, F., & Grandjean, P. (2022). Public-health risks from tea drinking: fluoride exposure. *Scandinavian Journal of Public Health*, *50*(3), 355-361.

METHODOLOGY

Tea plantation and Se-F, Ca-F treatment

12 month old cuttings were purchased from Shinkyari Research station Abbott-abad, KP province, Pakistan and were cultured hydroponically in greenhouse in Abbott-abad city, Pakistan at 25^{o}C natural sunlight. The media nutrient content of the culture solution contained (ppm/mg/Kg): 10.8 Al, 0.05 Mo, 0.025Cu, 0.1Zn, 0.1B, 0.35Fe, 25Mg, 30Ca, 40K, 3.1, PO43, 10 NO3, 30 NH4+. Upon developing roots, the tea cuttings were transferred to a plastic container (4 plants/container) containing 1.5liters of the aforementioned nutrient solution. The plants were exposed to Se in solution in a form of Na2SeO3 having 3 treatments (levels: 0, 0.5 and 1.0 mg/L), while F in form of NaF having 3 treatments (levels: 0, 5, or 20 mg/L). The pH of the culture media was adjusted to 5.0 ± 0.2 with strong alkali and acid of 0.2M each after the addition of Se and F. The calcium was supplied in form of $Ca(NO_3)_2$ having 3 treatments (levels: 0, 10, 20, 40mg/L).

The following combinations of the treatments were prepared (F:Se): 0:0, 0:0.5, 0:1.0, 5:0, 5:0.5, 5:1.0, 20:0, , 20:0.5, and 20:1.0. For (F:Ca): 0:0, 0:10, 0:20, 5:0, 5:10, 5:20, 20:0, , 20:10, and 20:20. All treatments having 3 replicates that were supplied with air bubble with the help of O_2 generator continuously. The culture media was changed every week. After four weeks of treatment, the fully grown leaves and roots were harvested. Until further analysis, the collected samples were kept at a temperature of -80°C.

The levels of fluoride (F) selenium (Se) and calcium (Ca) were determined as follows;

To analysis tea leaves and roots were dried at 80 °C for 48 hours. Fluoride content, in the leaf and root samples was analyzed using the fusion method[31]. Fluoride concentration was measured using a fluoride ISE device (Hanna HI 2211, Italy). Selenium levels in roots and leaves were determined through ICPMS analysis (NexION 350D PerkinElmer, USA) after microwave digestion. Calcium content, in the samples was measured using ICPES analysis (Optima 8300 PerkinElmer, USA) following microwave digestion.

STATISTICAL ANALYSIS

SPSS 20.0 software was employed to analyze the data. To ascertain the significance of differences, one-way ANOVA and LSD tests were implemented ($P < 0.05$). The means ± standard deviation (SD) from at least three separate replicates are used to display the results.

RESULTS AND DISCUSSION

Response of Tea leaves and roots to Se application

The Se content in the tea roots were directly proportional to it concentration as it increased with the rise in its concentration (Figure 3). At 0 Se content, the fluoride concentration was 453 at 0ppm fluoride, 705 at 5ppm and 805ppm at 20 F concentration. At 0.5 Se, the fluoride content was 473, 731 and 876ppm at 0, 5 and 20mg/Kg, respectively. The fluoride concentration further alleviated at 1.0ppm Se concentration, which was 467, 784, 902 at 0, 5 and 20mgF/Kg, respectively. The concentration of fluoride in the roots increased several folds (from 400 to 800mgF/Kg) with the increase in Se concentration as shown in Figure 2.

In contrast, the fluoride content decreased significantly in the tea leaves by Se application in the culture solution. The fluoride content ranged from 770-960mgF/Kg at 0 Se application, 540-621mgF/Kg at 0.5 Se concentration and 377-473mgF/Kg at 1.0 Se concentration. More than 2-fold decrease was noted in the fluoride content of tea leaves with the increase in concentration of Se in the culture solution as shown in Figure 3.

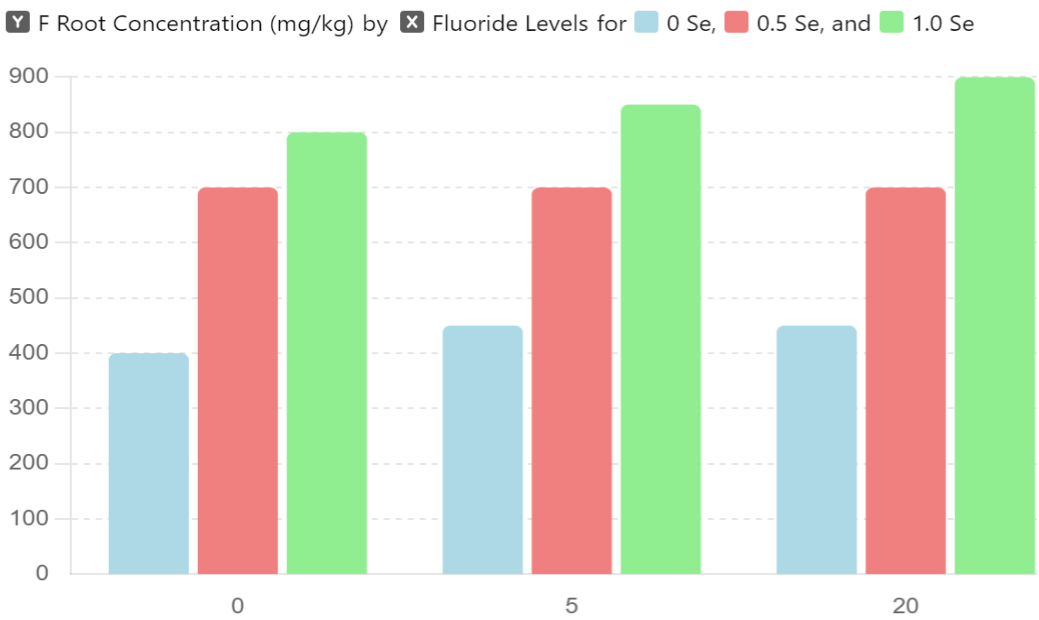

Figure 2. Response of F treatments to different Se content on tea roots. Error bars are there the mean of 3 replicates

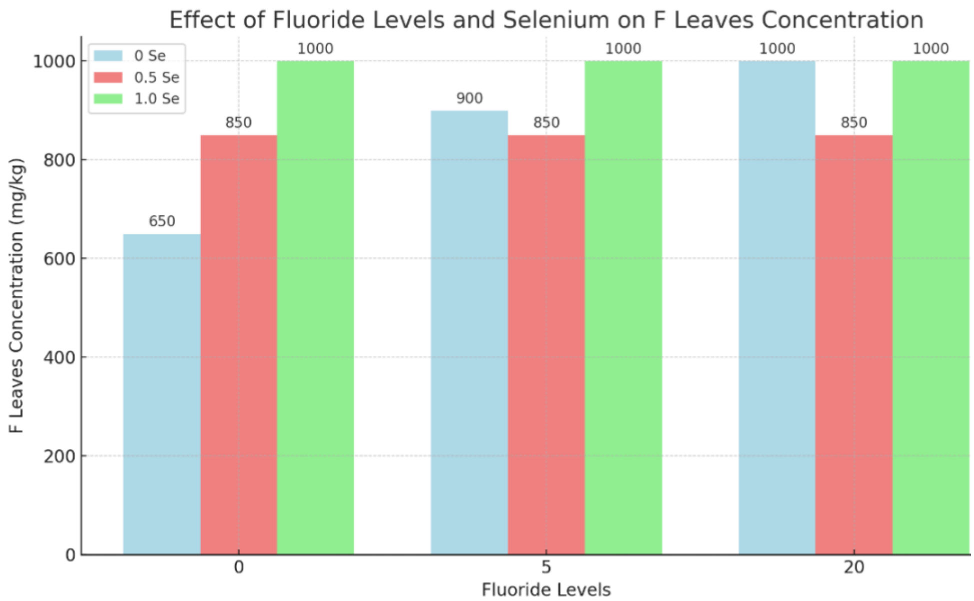

Figure 3. Response of F treatments to different Se content on tea leaves. Error bars are there the mean of 3 replicates

[32]Tea plants are known to accumulates fluoride but also have strong affinity to enrich Se. Tea current study also revealed that by applying Se in the solution, its concentration was increased significantly in tea roots samples (Figure 2), which was in line with the previous report of Hu et al[33] and Niu et al[34].

Remarkably, the low F content increases the bio-availability of Se in tea roots and leaves. However, high F concentration has the contrasting effects as it inhibits the Se concentration in tea plant. But it is worth noting that the high Se concentration reduces the fluoride content in the leaves of tea plant but were significantly increased in tea roots. Similar results were obtained by

Feng et al[35] and Han et al[36]. They reported that Se uptake is enhanced by low As content as high As inhibits the concentration of Se. Other studies suggested that the accumulation of Se in plants may be because of some enzyme demand like glutathione peroxidase (GSH-Px), which stops the excessive production of ROS[37]. That is why we assume that low fluoride concentrations might also enhances the GSH-Px that ultimately increase the Se uptake in tea plants.

Response Tea leaves and roots to Ca application

The CaO application in cultural media enhanced the Ca, K and Mg contents significantly in tea plant but decreased the concentration of Al. The fluoride concentration was significantly reduced by the addition of CaO application to the tea leaves. The concentration of Fluoride ranged from 50 to 35mgF/Kg at 0 CaOµm/l addition. 60 to 40mgF/Kg at 50 CaOµm/l that further reduced significantly at 75 CaOµm/l from 70 to 50mgF/Kg in tea leaves (Figure 4). The increase CaO concentration in the culture media has significantly reduced the uptake of F in the leaves by several folds. The root concentration of Fluoride was also decrease by the addition of CaO at low concentration, but was not significantly different. However, F concentration in the roots remained unchanged with the increase of CaO in the media (Figure 5).

The uptake of F was dramatically reduced as a result of the incorporation of CaO into the culture medium. Possible causes include the formation of a Ca-F combination in the roots or in the solution, which prevents the uptake of F by the tea leaves[38,39]. A passive process involving the endodermal barrier at the root tip or the endodermis that creates the side roots appears to be the way that plants take up F, according to the literature[39,40]. According to Rual et al[41], Tea plants may also undergo a similar process, as calcium is essential for the structure of cell walls and the stabilization of membranes[42].

The reduction in the F uptake might be related to reduce passage of F as it alters the chemical composition of the cell wall or membrane permeability through Ca addition. This might be the reason that F uptake has been reduced in the tea leaves by the addition of Cao in the solution. It is thought that F translocation is inhibited by Ca complex in the root xylem as Ca retain F in the roots due to which the F concentration is lower in the transpiration stream and leaves[39].

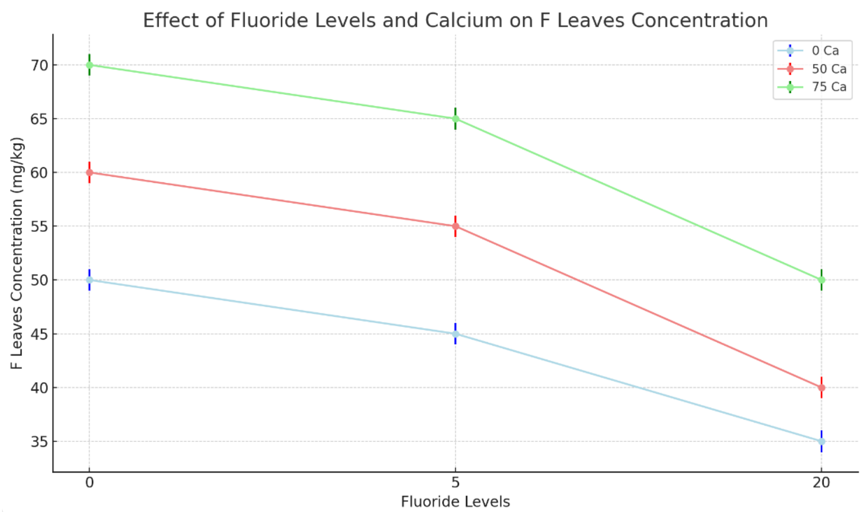

Figure 4.Response of F treatments to different Ca content on tea leaves. Error bars are there the mean of 3 replicates

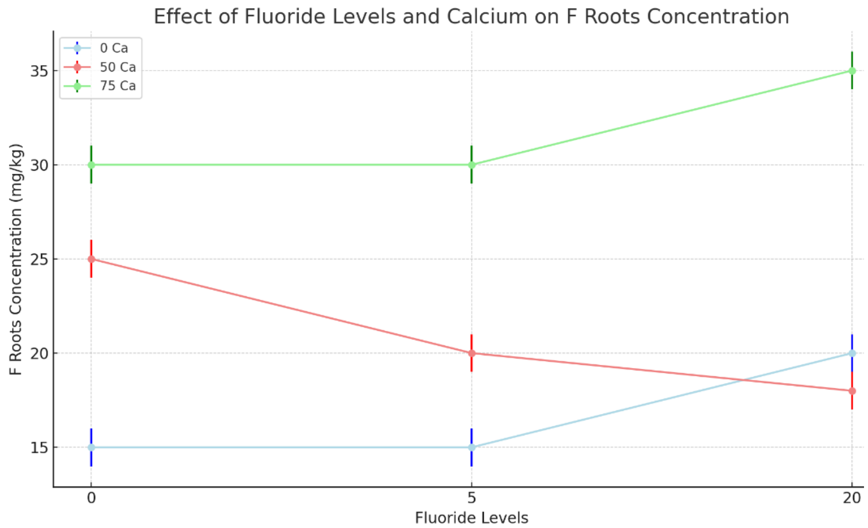

Figure 5.Response of F treatments to different Ca content on tea roots. Error bars are there the mean of 3 replicates

Other Management Strategies for Controlling Fluoride Levels in Tea plant

The potential health risks involved with the high concentration of fluoride in tea leaves, it is imperative for tea farmers and stockholders to adopt management strategies that are effective enough to monitor and control the elevated quantities of fluoride in tea plants. Combining different soil management practices, along with nutrient use efficiency methods and water quality monitoring, it is possible to reduce the bio-availability of fluoride to tea plants. According to Scholz et al[43], efficient water irrigation practices can normalize fluoride levels in soil, thereby lowering its buildup in plant tissues. In addition, by adopting smart agriculture techniques like efficient/specific nutrient application can help in controlling fluoride contents in tea plantations[44]. By incorporating science-based methods with effective management practices, tea farmers can safeguard the production of high-quality and safe tea yields for customers while reducing the possible health threats linked with high fluoride concentrations in tea leaves.

Best Practices for Reducing Fluoride Uptake in Tea Plants

Multiple best methods have been highlighted in the literature regarding reducing the bio-availability of fluoride to tea plants that is crucial for the safety and quality of the tea consumers. One of the strategy is to choose the best tea variety that is resistant to fluoride accumulation from the soil in its tissues. Moreover, typical crop management practices like irrigation, soil Additionally, crop management practices such as, appropriate irrigation techniques, amendments in soil by adjusting pH can aid in mitigating fluoride uptake by tea plant. Combining these methods with Se and Ca added fertilizers has shown promising results to reduce fluoride content in tea leaves that improve plant resistance to fluoride toxicity. Integrated pest management practices can also reduce the fluoride uptake by not using pesticides that containing traces of fluoride containing compounds[45].

CONCLUSION AND RECOMMENDATION

The current research study emphasizes on the importance of controlling fluoride content in tea plant to protect customer's health and maintain the quality of tea products. Through a combination of scientific research and practical management strategies, it is concluded in the current study that the fluoride content in the tea leaves can be significantly influenced by various factors such as soil composition, water quality, and fertilization practices. Our experiments with selenium (Se) and calcium (Ca) have shown promising results in reducing fluoride uptake by tea plants. Selenium application, while increasing fluoride concentration in roots, effectively reduced fluoride levels in tea leaves. Similarly, calcium supplementation also decreased fluoride uptake, possibly due to the formation of Ca-F complexes that hinder fluoride translocation within the plant. These findings underscore the potential of using targeted nutrient management and soil amendments to control fluoride levels in tea leaves. By integrating these scientific insights with agricultural practices, tea producers can develop sustainable strategies to ensure the production of safe and high-quality tea.

The main limitation of the study is that it was conducted on small scale. As the tea plant is gown in several regions, it can respond differently according to varied environmental stress. It is there for recommended to conduct a large scale experiment related to the fluoride accumulation in tea plants in different regions at the same time. It is also recommended to implement soil management practices to optimize pH levels and nutrient composition, thereby reducing fluoride availability to tea plants. By regularly monitor soil and water quality to prevent excessive fluoride uptake. Using controlled applications of selenium and calcium based on environmental conditions and tea plant varieties to effectively reduce fluoride levels in tea leaves. Employing precision agriculture techniques, such as soil sensors, automated irrigation systems, and targeted fertilization, to enhance nutrient delivery and minimize fluoride uptake. Focusing on breeding and cultivating tea plant varieties that exhibit lower fluoride accumulation to provide a long-term solution for managing fluoride levels. Reducing the use of fluoride-containing pesticides and adopt integrated pest management practices to lower the overall fluoride burden on tea plants. Conducting further studies to fully understand the mechanisms of fluoride uptake and translocation in tea plants and explore the interactions between different soil amendments, water quality parameters, and environmental factors.

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