ISSN 1391-0256

Journal of the Sri Lanka Association for the Advancement of Science

Volume 7 Issue 2, 2025

JSLAAS

Founded in 1944 and incorporated by the Act of Parliament No 11 of 1966

Journal of the Sri Lanka Association for the Advancement of Science is a biannual publication. Selected research work from annual research sessions (based on scientific merit) as well as other research articles are invited to submit research manuscripts as per the guidelines provided by SLAAS. SLAAS members may also separately submit their papers for publication. The Journal can be accessed on-line to view and download the full text of the articles published respective to the volumes free of charge

Submission Manuscript

Only online submission, Web: https://journal.slaas.lk, e-ISSN: 2682-6992

Exchanges: Please address all requests to the Secretary, *Sri Lanka Association for the Advancement of Science, "Vidya Mandiraya" 120/10, Wijerama Mawatha Colombo 07, Sri Lanka*

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Harnessing regional potential in banana farming: A quantitative analysis of agricultural-ecological differences

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ABSTRACT

Although banana production is essential to Sri Lanka's agricultural economy, productivity varies greatly around the nation as a result of variations in agricultural-ecological conditions, resource availability, and farming methods. The impact of regional agricultural-ecological variations on Sri Lanka's national banana productivity is investigated quantitatively in this study. A multiple linear regression model is used to examine the contribution of five key banana-producing districts - Rathnapura, Kegalle, Anuradhapura, Monaragala, and Jaffna- to the country's banana productivity using district-level data covering 23 years (2001–2023). The findings show that while the effects of other districts are not statistically significant, Rathnapura makes a positive and statistically significant contribution to the country's output. The model highlights the significance of regional dynamics in influencing national agricultural performance by explaining 89.5% of the variation in national banana productivity. The results emphasize the necessity of zone-specific agricultural policies and focused interventions to improve farmer incomes, productivity, and the banana industry's overall performance.

Keywords: agriculture value chain, regional discrepancies, regression analysis, Sri Lanka, and banana productivity

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INTRODUCTION

Bananas, one of the most extensively cultivated and consumed fruits in Sri Lanka, significantly boost rural income and food security. Bananas, a major fruit crop in Sri Lanka, are vital to rural livelihoods, domestic trade, and food security. This business accounts for about 54% of total land used for fruit cultivation (Department of Census and Statistics [DCS], 2022). However, there is significant variance in banana yield between places due to differences in agricultural ecological conditions, resource availability, and agricultural strategies (Ranathilaka et al., 2020). Improving overall efficiency and competitiveness in the banana value chain requires an understanding of regional productivity variations. District-level evaluations can uncover specific performance determinants and pinpoint areas that need policy attention, but national-level analysis offers a broad picture. The contributions of five significant banana-growing districts, Rathnapura, Kegalle, Anuradhapura, Monaragala, and Jaffna, to national trends in banana productivity during 23 years are examined in this study using multiple linear regression.

Literature

The agronomic and economic elements of Sri Lankan banana cultivation have been studied in a large body of literature. Because of their versatility and very low input requirements, bananas can be grown in a variety of climatic zones, according to FAO (2023). However, soil fertility, irrigation infrastructure, pest and disease management, and access to extension services all have an impact on yield performance, which varies significantly between locations. While Hewageeganage (2023) shows that the use of intelligent and precision-based farming systems can lower input costs and increase yields, Ranathilaka et al. (2020) stress the significance of institutional support and regional infrastructure in boosting productivity. Despite these results, national agricultural policies frequently ignore spatial variation, leading to homogeneous interventions that have little local efficacy. This work fills a significant gap in the literature by finding regional drivers of national banana productivity in Sri Lanka through the application of a regression-based approach to district-level data.

METHODOLOGY

Data Collection

Banana productivity is calculated using banana extent and production. Records of banana productivity for five districts, Rathnapura, Kegalle, Anuradhapura, Monaragala, and Jaffna, from 2001 to 2023 are included in the statistics. Data was gathered from the Department of Census and Statistics from 2001 to 2023.

Model of Analysis

The following linear regression model is estimated:

$$Productivity_{t} = \beta_0+\beta_1 Rathnapura_t+\beta_2 Kegalle_t+\beta_3 Anuradhapura_t+\beta_4 Monaragala_t+\beta_5 Jaffna_t+\epsilon_t$$

$Productivity_t$: National banana productivity in year t

$District_t$: Production output from each district

ϵ_t: error

District indicators served as the independent variables, and banana productivity served as the dependent variable in a multiple linear regression model. Standard metrics such as R Square, Adjusted R Square, Standard Error, and ANOVA were used to assess the model.

Theories

The following theories were developed to evaluate the impact of regional production patterns on the productivity of bananas nationwide:

Hypotheses Null (H_0)

- H_{01}: Rathnapura banana production has no statistically meaningful impact on the country's banana output.
- H_{02}: The national banana productivity is not statistically impacted by Kegalle banana production.
- H_{03}: The national banana productivity is not statistically impacted by Anuradhapura banana production.
- H_{04}: Monaragala banana cultivation has no statistically meaningful impact on the country's banana output.
- H_{05}: The national banana productivity is not statistically impacted by Jaffna banana production.

Various Hypotheses (H_1)

- H_{11}: Rathnapura banana production has a major impact on the country's banana output.
- H_{12}: Kegalle banana production has a major impact on the country's banana output.
- H_{13}: Anuradhapura's banana production has a major impact on the country's banana output.
- H_{14}: Monaragala banana cultivation has a major impact on the country's banana output.

H_{15}: The output of bananas nationwide is greatly impacted by Jaffna banana production.

The p-values from the regression output were used to test the hypotheses at a significance level of 5%.

RESULTS AND DISCUSSION

Performance of the Model

The findings of the regression revealed:

Table1: Regression statistics

Regression Statistics	
Multiple R	0.945948
R Square	0.894818
Adjusted R Square	0.863882
Standard Error	2.502284
Observations	23

The district factors account for 89.5% of the variation in banana productivity, according to the R Square of 0.895.
After adjusting for degrees of freedom, the model's adjusted R-squared of 0.864 indicates that it still has a high explanatory power.

Table 2: Anova test results

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	905.5558	181.1112	28.92491	9.59E-08
Residual	17	106.4442	6.261425		
Total	22	1012			

Overall model significance is confirmed by the F-statistic of 28.92 and the Significance F value of 9.59E-08.

Analysis of Coefficients

Analysis was done for the following variables;
X Variable 1 - Productivity of Rathnapura District
X Variable 2- Productivity of Kegalle District
X Variable 3 – Productivity of Anuradhapura District
X Variable 4 – Productivity of Monaragala District
X Variable 5 – Productivity of Jaffna District

Table3: Coefficients, Error, t&p values

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1998.789	2.389729	836.4081	1.14E-40	1993.747	2003.831	1993.747	2003.831
X Variable 1	14.18112	3.511063	4.03898	0.000852	6.773419	21.58881	6.773419	21.58881
X Variable 2	-8.22321	8.366616	-0.98286	0.339459	-25.8752	9.428808	-25.8752	9.428808
X Variable 3	1.258838	1.252266	1.005248	0.328872	-1.38321	3.900887	-1.38321	3.900887
X Variable 4	2.556737	10.24004	0.24968	0.805827	-19.0479	24.16133	-19.0479	24.16133
X Variable 5	-1.05963	0.866379	-1.22305	0.237994	-2.88753	0.768272	-2.88753	0.768272

At the 5% level, only Rathnapura exhibits a statistically significant coefficient. This implies that particular regional factors, such as farming methods, irrigation systems, and soil quality, may greatly increase output.

Intervals of Confidence

Rathnapura's statistical significance is further supported by the fact that its coefficient (CI: 6.77 to 21.59) excludes zero. Weak explanatory power was indicated by the broad intervals in other districts, including zero.

Rathnapura District's Banana Production vs. Extent

The relationship between the area under banana cultivation (measured in hectares) and production (measured in metric tons) in Rathnapura between 2001 and 2023 is depicted in the following Figure 1:

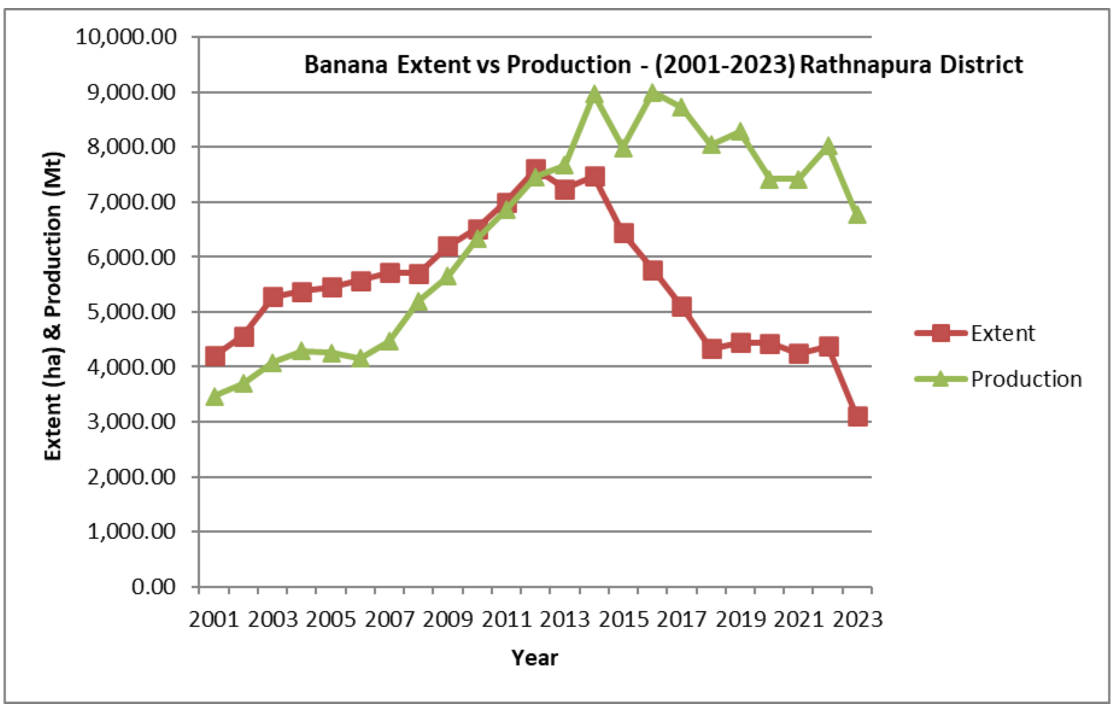

Figure 1: Banana extent and production in Rathnapura District 2001 -2023

Source: Census and Statistics Dept., Government of Sri Lanka

As can be seen, both production and extent rose gradually until around 2013, at which point the extent started to drastically decrease. For a few more years, though, production stayed comparatively high, suggesting productivity increases. Both measures have decreased recently, suggesting that the region's banana production may be impacted by structural or environmental problems.

Kegalle District's Banana Production vs. Extent

The relationship between the area under banana cultivation (measured in hectares) and production (measured in metric tons) in Kegalle between 2001 and 2023 is depicted in the following Figure 2:

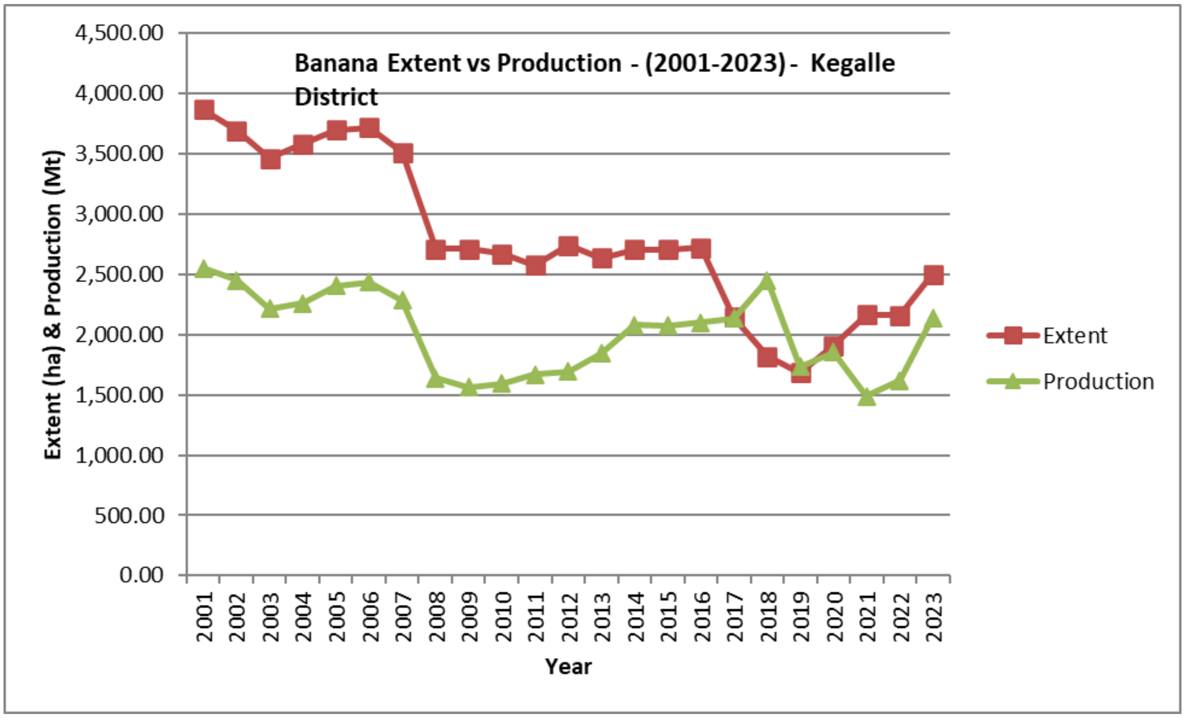

Figure 2: Banana extent and production in Kegalle District 2001 -2023
Source: Census and Statistics Dept, Government of Sri Lanka

As can be seen, both production and extent decreased gradually until around 2003, at which point the extent started to gradually increase till 2003 and drastically decreased in 2007. There is no significant change in the extent till 2016 and a drastic decrease from 2017 to 2019, while the production has increased from 2007 to 2018. There is a significant decrease in production from 2017 to 2019. While the extent is gradually increasing, Production has a sharp decrease in 2021. This may be due to the fertilizer band and fuel issue. Both extent and production show a gradual increase from 2021 onwards.

Anuradhapura District's Banana Production vs. Extent

The relationship between the area under banana cultivation (measured in hectares) and production (measured in metric tons) in Anuradhapura between 2001 and 2023 is depicted in the following Figure 3:

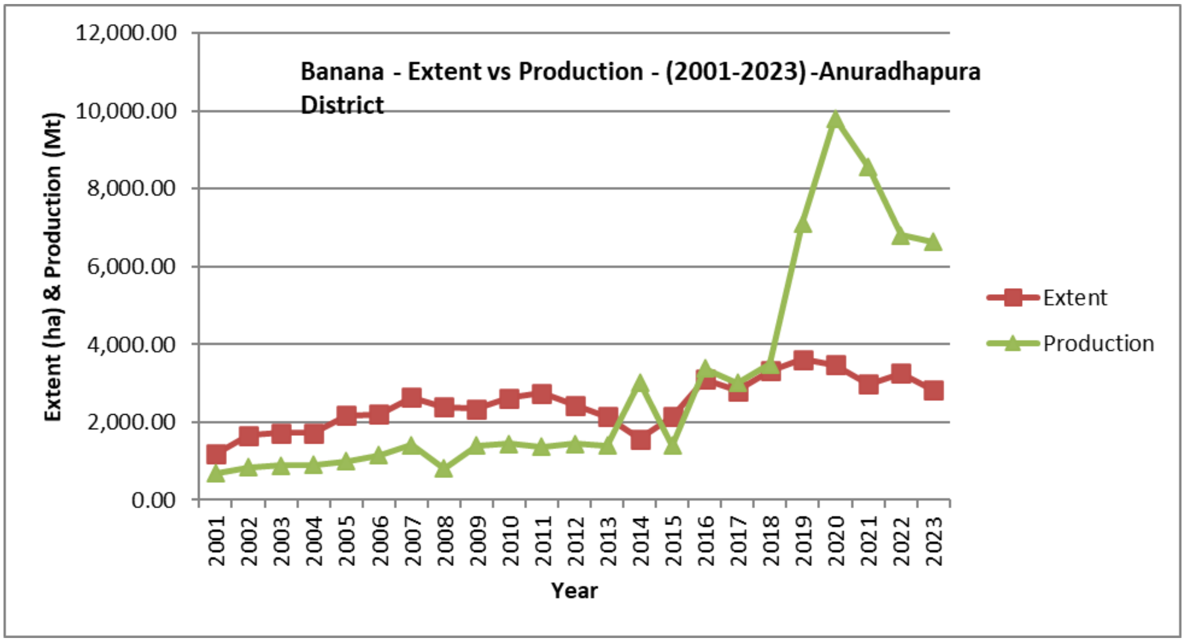

Figure 3: Banana extent and production in Anuradhapura District 2001 -2023
Source: Census and Statistics Dept, Government of Sri Lanka

As shown in Figure 3 above, both production and extent rose gradually until around 2007, at which point the extent and production started to drastically decrease. While the extent shows a gradual increase from 2009 to 2011, and then a gradual decrease till 2014, there is no significant increase or decrease in production from 2009 to 2013. There is a significant increase in production in 2014 and a sudden decrease in 2015. Again in 2016 production has significantly increased slight decrease in 2017. Extent has increased slightly, and production has increased remarkably high 2019 to 2020, with a sharp decline in 2021. This increase may be due to the implementation of commercial agriculture and the downfall due to fertilizer band and fuel issues in Sri Lanka. For a few more years, though, production stayed comparatively high, suggesting productivity increases. Both measures have decreased recently, suggesting that the region's banana production may be impacted by structural or environmental problems.

Monaragala District's Banana Production vs. Extent

The relationship between the area under banana cultivation (measured in hectares) and production (measured in metric tons) in Monaragala between 2001 and 2023 is depicted in the following Figure 4:

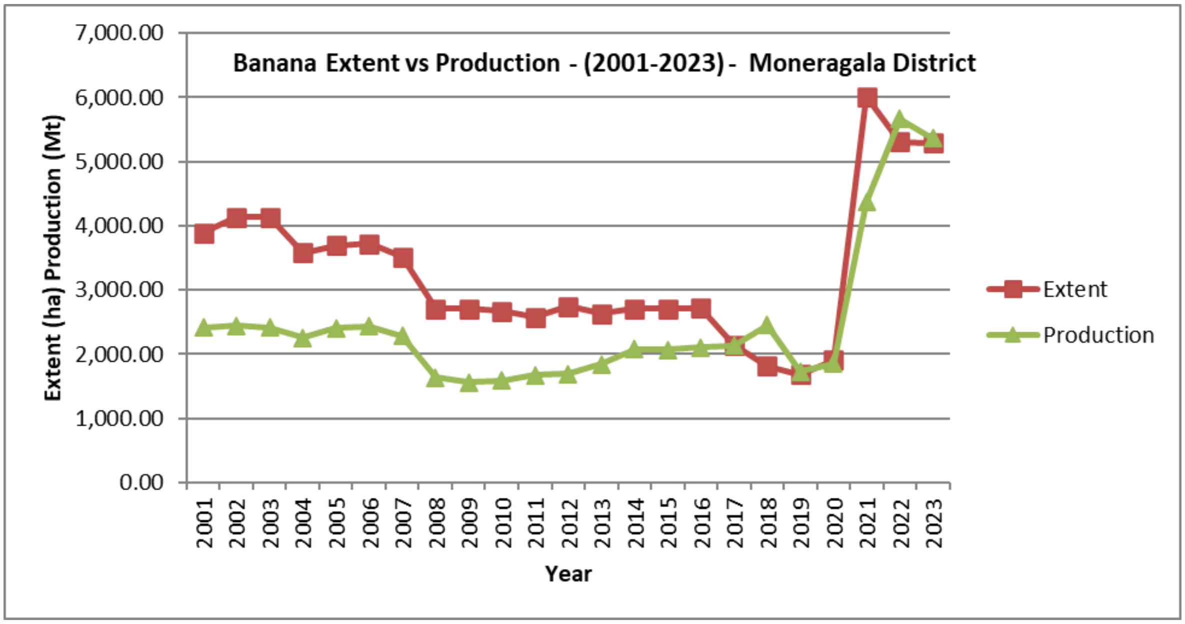

Figure 4: Banana extent and production in Monaragala District 2001 -2023
Source: Census and Statistics Dept, Government of Sri Lanka

As can be seen, both production and extent rose gradually until around 2003, at which point the extent and production both decreased in 2004 and then started to drastically increase till 2006 and drastically decreased in 2008. From 2008 to 2017, there was no significant variation in the extent, and production shows a gradual increase till 2018. The extent has decreased gradually from 2016 to 2019, and has remarkably high growth in 2020. Production also showed a sharp increase and a slight decrease in 2022. This sharp increase is due to the agriculture modernization project and the introduction of high-yielding varieties. For a few more years, though, production stayed comparatively high, suggesting productivity increases. Both measures have decreased recently, suggesting that the region's banana production may be impacted by structural or environmental problems.

Jaffna District's Banana Extent vs Production

The relationship between the area under banana cultivation (measured in hectares) and production (measured in metric tons) in Jaffna between 2001 and 2023 is depicted in the following Figure 5:

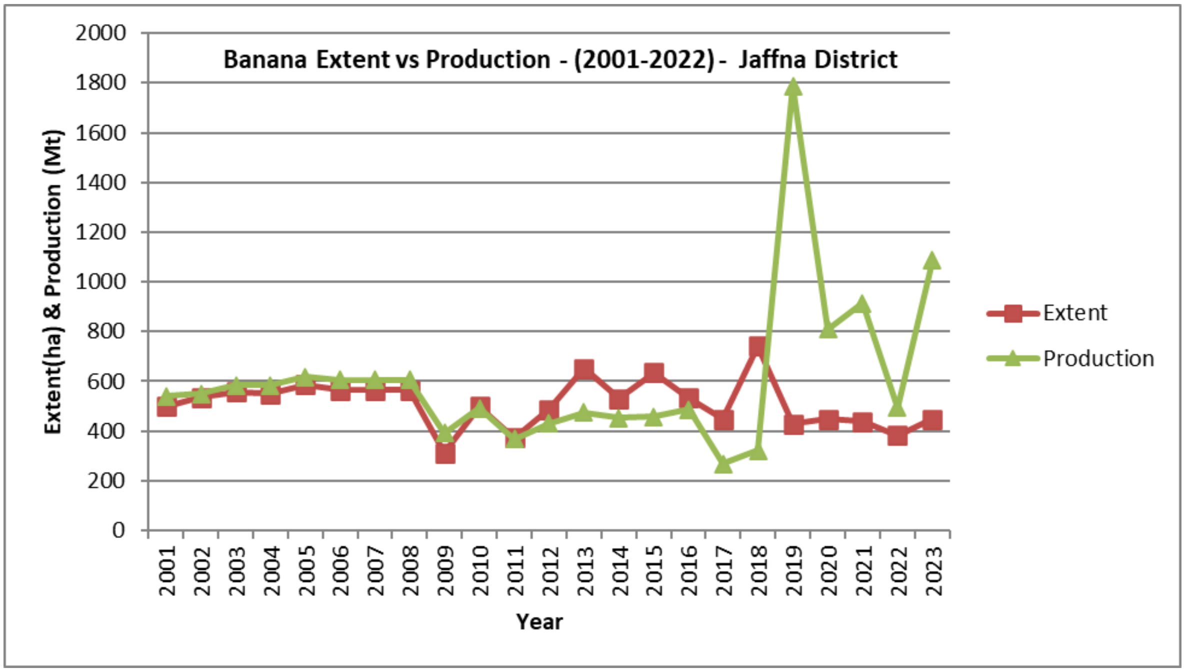

Figure 5: Banana extent and production in Jaffna District 2001 -2023
Source: Census and Statistics Dept, Government of Sri Lanka

As can be seen, both production and extent rose gradually until around 2008, at which point the extent and production started to drastically decrease in 2009. The extent has increased from 2011 to 2013and a decline in 2014. But production has not shown any significant change from 2012 to 2016. There is a drastic decrease in Production in 2017, and remarkable increase in 2019, and a sharp downfall in 2020. There is no significant increase in extent and a sharp decrease in production in 2022, and a sharp increase in 2023. For a few more years, though, production stayed comparatively high, suggesting productivity increases. Both measures have decreased recently, suggesting that the region's banana production may be impacted by structural or environmental problems.

Implications for Policy

Given Rathnapura's beneficial impact, policymakers ought to look into and adopt its methods in areas that aren't operating up to par. Focused expenditures on infrastructure, resource supply, and agronomic training could balance output levels and improve the resilience of the national supply chain.

Summary of District Efficiency

This study shows obvious differences in banana production efficiency between districts:
The most effective district with a statistically meaningful beneficial impact is Rathnapura. It combines comparatively steady production patterns with increased yields.

Kegalle: It has a negative coefficient despite having a moderate geographical coverage, which suggests inefficiencies in productivity or problems with the environment. From the survey, farmers complained that they have challenges protecting their harvest from animals. Some farmers have reduced the farming site as they don’t have the resources to look after the farm site and to protect it from animal threats.

Anuradhapura: Efficiency is still poor, but there is potential shown by a slightly positive but statistically insignificant coefficient. Farmers in the Anuradhapura district had a problem accessing water. Increase may also be due to commercial agriculture.
Monaragala: Despite a vast agricultural area, it exhibits little effect on productivity, much like Anuradhapura.
Jaffna: A negative coefficient denotes low efficiency, most usually brought on by resource or agroclimatic limitations.
These differences highlight how crucial it is to overcome inefficiencies with region-specific support and customized tactics.

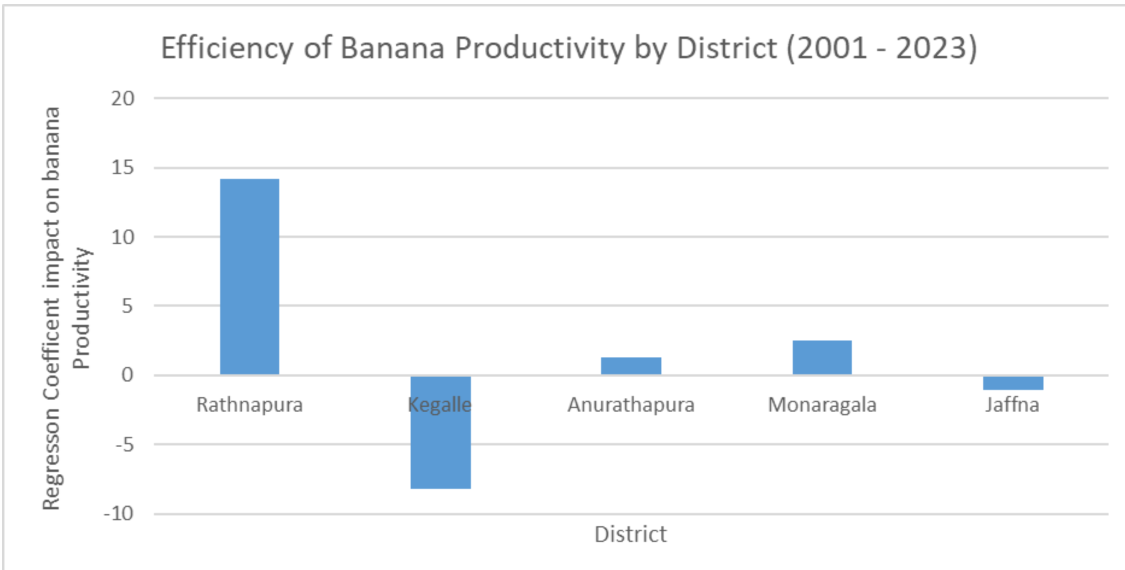

Figure 6: Efficiency of Banana Productivity by District
Source: Census and Statistics Dept, Government of Sri Lanka

Based on the model's regression results, the above bar chart, as shown in Figure 6, illustrates the effectiveness of banana production per district:
Rathnapura has the greatest beneficial influence. Lower productive efficiency is indicated by negative coefficients in Kegalle and Jaffna. The benefits of Anuradhapura and Monaragala are marginal but not statistically significant.

Regional Differences

The study's main goal of measuring the impact of agricultural-ecological regions on national banana productivity in Sri Lanka is supported by the empirical findings of the multiple regression analysis. Banana production is not geographically homogeneous and is heavily influenced by regional variables, as evidenced by the notable variety in district-level contributions. With a statistically substantial and favorable contribution to national productivity, Rathnapura stands out as the most powerful district. Its advantageous mid-country agricultural ecological circumstances, which include regular rainfall patterns, ideal temperatures, fertile soils, and a comparatively larger adoption of enhanced farming techniques, are responsible for this achievement.

Districts like Jaffna and Monaragala, on the other hand, have relatively smaller contributions, which is indicative of ongoing structural limitations. Water scarcity, restricted access to contemporary irrigation systems, climate stress, and a poorer uptake of cutting-edge technologies and extension services are some of these. These results are in line with previous research showing regional differences in agricultural productivity associated with institutional support and resource availability (FAO, 2023; Ranathilaka et al., 2020). Overall, the regression results support the goal of the study by actually showing that regional agricultural ecological variations explain a significant portion of the variation in national banana output, as shown by the model's strong explanatory power.

Implications for Policy

The study's goal of influencing the development of evidence-based, regionally relevant agriculture policy is directly supported by the findings. Differentiated interventions, as opposed to standard national policies, have a practical foundation thanks to the explicit identification of high- and low-performing districts. Policy initiatives should focus on increasing productivity and adding value by investing in post-harvest handling, export-oriented processing, and market integration in high performing areas areas like Rathnapura.

On the other hand, particular interventions are needed to overcome region-specific limitations in districts that are comparatively underperforming. These include strengthening Good Agricultural Practices (GAP) training through extension services, promoting disease-resistant and climate-resilient banana cultivars, and investing in irrigation infrastructure. Crucially, including district-level productivity statistics into value chain planning frameworks and national banana development initiatives would increase the effectiveness of policies and the efficiency of resource allocation.

Advantages and Stakeholder Targets

Advantages of the Analysis

By offering a solid, quantitative evaluation of regional productivity patterns, the study fulfills its analytical goal. In particular, it

finds long-term productivity patterns and inefficiencies at the district level.

Prioritizing actions in areas with the highest potential or need makes evidence-based planning possible.

facilitates optimal resource allocation, monitoring, and forecasting throughout the banana value chain.

Table 4: Target Stakeholders and Purpose

Target Stakeholders	Purpose
Government Ministries	Formulation of region-specific agricultural and value chain policies
Researchers and Academics	Basis for advanced econometric, spatial, and policy-oriented studies
Extension Officers and Field Agents:	Customization of farmer training and technical support
Development Organizations (FAO, IFAD)	Identification of priority regions for investment and aid
Private Sector (Exporters, Investors)	Identification of high-productivity sourcing regions

Farmer Cooperatives	Advocacy for district-specific support grounded in empirical evidence

CONCLUTION

This study used 23 years' worth of district-level data to apply multiple linear regression analysis in order to statistically evaluate the impact of regional agricultural ecological variations on banana yield in Sri Lanka. The results unequivocally show that regional characteristics are crucial in determining the country's banana production, with Rathnapura contributing the most significantly and statistically favorably of the five districts examined. The model's high explanatory power further demonstrates that a significant amount of the variation in national production can be attributed to regional productivity dynamics.

The need for region-specific policy support rather than uniform national actions is highlighted by the statistically lesser influence seen in other districts. The findings provide strong empirical support for evidence-based agricultural planning and highlight the significance of spatial analysis in the creation of banana value chain development strategies by empirically connecting regional performance to national productivity outcomes.

Although the study accomplishes its main goals, other socioeconomic, institutional, and agricultural environmental factors could be included in subsequent studies to increase explanatory power. Such additions will reinforce policy suggestions meant to create a more resilient and inclusive banana industry in Sri Lanka and offer a more thorough knowledge of productivity disparities.

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Validation of competencies and performance of homestay tourism entrepreneurs in Sri Lanka

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ABSTRACT

This study examines the effect of competencies on the performance of homestay entrepreneurs in Sri Lanka. Homestay is a community-based tourism practice and majority of homestay entrepreneurs are not successful in Sri Lanka as per the recent researches conducted in the Sri Lankan context. But, homestay tourism has been identified as a main sector to develop entrepreneurs and give a considerable contribution to the Sri Lankan economy. Resource Based View (RBV) theory is the base for this study and entrepreneurial competencies were considered as the main predictor for the entrepreneur performance in the conceptualization. For this study 252 homestay entrepreneurs were selected who engaged in Community Based Tourism in Sri Lanka. The Structural Equation Modelling (SEM) was used to analyse the data. As per the findings of the study, entrepreneurial competencies are essential for entrepreneur performance. This study will help for the development of productive entrepreneurs in Community Based Tourism in Sri Lanka by enhancing their competencies.

Keywords: Competencies, Entrepreneur Performance, Homestay Tourism

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INTRODUCTION

Entrepreneurship has gained wide popularity around the globe. Entrepreneur is a prime mover of economic activity in any nation (Vashishtha, 2021). The last decades have witnessed the rapid spread of entrepreneurship all over the world (Catalin, George and Razvan, 2017). Entrepreneurship pays a major role in economic growth, social development, competitiveness, innovation, providing employment opportunities and poverty alleviation in any country. Entrepreneurship is a practice of setting up a novel business to manufacture and sell innovative, original or prevailing good or service while SMEs can be considered as a platform for the entrepreneurs to execute them (Kaluarachchige et al., 2021a).

Entrepreneurship is always recognised practice in tourism industry. Tourism development in any country encourages entrepreneurial practices. Considering the opportunities of entrepreneurship in tourism industry, it is one of the major areas where the opportunities are unlimited. Tourism has immense potentiality to empower the communities (Sikari, 2018). Community participation positively relates towards entrepreneurial success among the homestay entrepreneurs (Yong and Hassan, 2017). Competent entrepreneurship shows that it is very important to develop the Community Based Tourism (Witchayakawin, et al., 2020). Homestay is the best Community Based Tourism programme and it is a prospective business process for local entrepreneurs in Sri Lanka as well (Ranasinghe, 2015).

Community Based Tourism allows communities to get involved in tourism activities through managing homestays and alternative accommodation businesses for community groups who wish to engage in tourism activities (Junaid et al., 2019). Homestays have become popular in many countries all over the world due to this immense experience to tourists who want to interact with local culture, social system, lifestyle, language, people and helping the community to develop their socioeconomic status via the tourism industry (Wijesundara and Gnanapala, 2015). Homestay is also a type of accommodation sectors in tourism which allows to tourists to stay with local families in the destination and become familiar with local style (Ahmad, et al., 2019).

The government in many of the less developed and developing countries take strategic actions to link the local community to the tourism sector with the aim of ensuring more competitive advantages and sustainable development in the tourism sector. According to Witchayakawin, et al. (2020) Community Based Tourism development should be focused on various factors such as competencies. Sri Lanka Tourism Development Authority (SLTDA) took initiations by empowering the local community to utilize their expertise and ability to become entrepreneurs in tourism sector in Sri Lanka (Sriyani, 2018). There are some challenges as well as more opportunities in Community Based Tourism in Sri Lanka (Ranasinghe, et al., 2020). The purpose of the study is to measure the influence of competencies towards the performance of homestay entrepreneurs in Community Based Tourism in Sri Lanka.

PROBLEM STATEMENT

Majority of the homestay entrepreneurs are not successful in Sri Lanka as per the recent researches conducted in the Sri Lankan context (Sriyani, 2018; Wijesundara and Gnanapala, 2015; Ranasinghe, 2015). Sriyani (2018) highlighted that nevertheless the popularity in homestays, severe problems may hinder the success and survival of the homestay entrepreneurs in Sri Lanka. Wijesundara and Gnanapala (2015) revealed that homestay tourism does not work well in Sri Lanka as an alternative tourism product. As per the recent research conducted by Croos, et al., (2020) in the Sri Lankan context, there is a huge potential to develop Community Based Tourism by overcoming the barriers. There are more opportunities in Community Based Tourism in Sri Lanka (Sumithra, 2020; Ranasinghe, et al., 2020; Madushi, et al., 2020), but there are some challenges and issues (Jayasundara, et al., 2020).

Hashim, Raza and Minai (2018) discovered that the association between the competencies of entrepreneurs and organizational performance is doubtful because the outcome of studies related to this association are incompatible. Mitchelmore and Rowley (2013) specified that there would be a base for advance exploration to the competencies of entrepreneurs which influence organizational performance. Parida et al. (2016) stated that further research is essential to recognize the competencies for the aim of refining the remaining body of knowledge.

Moreover, there may be a research gap in knowledge linked to the competencies of entrepreneurs (Yusuff et al., 2016). Thus, studies are required to further investigate the association between competence and entrepreneur performance (Hashim, Raza and Minai, 2018). The entrepreneurs' performance is very important to the economic achievements chiefly in the developing countries which research into entrepreneurship is limited (Hyder and Lussier, 2016; Coder et al., 2017). So, there would be a crucial necessity to conduct research in small size organizations in the arena of entrepreneurship (Hashim, Raza and Minai, 2018). Related research ought to be done probably in developing countries and similar studies should be repeated to confirm these results (Ibrahim and Abu, 2020).

LITERATURE REVIEW

Resource Based View (RBV) theory is the base for this study. RBV underlines the organizations' assets or resources as the key determinants of competitive advantage and performance. Due to the RBV, resources have four dimensions for sustainable advantages which are valuable, rare, inimitable and non-substitutable (Barney, 1991). There are tangible and intangible resources in nature (Wernerfelt, 1984). RBV treats human capital characteristics such as competencies as intangible resources (Barney, 1991). Traits, capabilities, and skills can be transformed into a set of internal unique resources which small businesses need to trust (Lerner and Almor, 2002). RBV application in the context of small businesses, entrepreneurial competences are unique management skills which are considered as resources for achieving exceptional enterprise performance.

Competencies refer to the characteristics possessed by entrepreneurs in order to perform their functions effectively; knowledge, skill and motives/ attitude are the major components of competencies (Sajeena, 2020). Besides, competencies are the unique abilities and skills that drive an organization to perform exceptionally well (Aliyu, 2017). Entrepreneurial competencies are recognized as a gathering of competencies which are linked to a successful entrepreneurship (Kaluarachchige et al., 2021b). To date, researchers have examined different types of competencies (Competency Clusters) of entrepreneurs such as opportunity, organizing, relationship, commitment, strategic, conceptual, analytical, operational, human, learning, personal, technical, ethical, familism, knowledge, networking competencies etc. (Man, 2001; Man et al., 2002; Ahmad, 2007; Man, Lau and Chan, 2002; Aruni, Akira and Hironori, 2014; Noor, Hasliza and Siti, 2010). Tehseen and Ramayah (2015) defined competencies of entrepreneurs as a valued asset which improve business performance and it helps to achieve a sustainable competitive advantage. Among the most significant resources of enterprises, competencies are the most valuable and intangible resources which are related with the entrepreneur performance (Sozuer et al., 2017; Tehseen and Ramayah, 2015). This supportive action will eventually bring to the entrepreneur performance when there is an existence of their competencies. It is discovered that entrepreneurial competencies are very essential, because it can drive growth that is led by business performance (Sok et al., 2017). Furthermore, the existing studies have exposed the significance of competencies for entrepreneur performance, especially in small and medium-sized businesses (Sajilan and Tehseen, 2015). Similarly, Wahid et al. (2017), emphasized that lack of competency is one of the major challenges that small enterprises must overcome in order to survive in the market.

METHODOLOGY

The schematic diagram was developed based on the fundamental principles of Resource Based View (RBV) theory. Competency is the predictor variable on entrepreneur performance which is the outcome variable. Strategic competency, commitment competency, organizing competency, opportunity competency, relationship competency and conceptual competency are the main dimensions in competencies of entrepreneurs. Financial and strategic factors are dimensions of entrepreneur performance. A structured questionnaire was developed to collect the primary data and measured the variables in the deductive approach.

The population of the study is all entrepreneurs of homestay units which operate as a Community Based Tourism (CBT) practice, that are registered in the Sri Lanka Tourism Development Authority (SLTDA). There were 645 homestay entrepreneurs which are registered under SLTDA and those individual homestay entrepreneurs were considered as the unit of analysis in the current study. Data were collected covering all districts in Sri Lanka as per the disproportionate stratified random sampling method. The final sample was confirmed as 252 homestay entrepreneurs with 83% response rate in the present study.

RESULTS AND DISCUSSION

The Structural Equation Modelling (SEM) by using AMOS software with the two-stage approach such as measurement model and structural model, was used to analyse data in the Confirmatory Factor Analysis (CFA).

The measurement model was developed with the combination of 15 items related to the final CFA results [Competencies (E.C.)- 9 items, Entrepreneurs Performance (E.P.)- 6 items etc.] Recommended values of fit indices and model fit statistics are presented in the bellow table.

Table 1: Results of the measurement model

Fit indices (Goodness of Fit)	Accepted values (Cut off Value)	Result	Model Evaluation
Chi square/df	<3	1.412	Good Fit
CFI	>0.9	0.973	Good Fit
RMSEA	<0.08	0.041	Good Fit

The fit indices of Chi square, CFI and RMSEA are evaluated in good fit with the recommended values. Therefore, 15 items in the final measurement model adequately fit with the data. Further it emphasized that all items make a comparable contribution to the operationalization of each construct.

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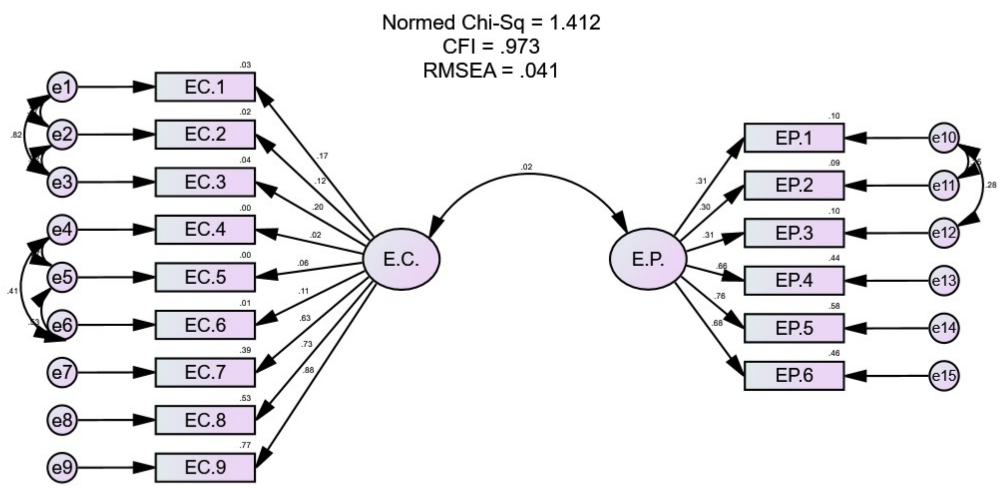

Figure 1: Measurement model

Co-variances of the measurement model of the study are presented in below table.

Table 2: Co-variances of measurement model

			Estimate	S.E.	C.R.	P	Correlation
E.C.	<-->	E.P.	.308	.061	5.064	***	.411

This section explained the first stage which is validation of the measurement model and the structural model can be assessed and presented as the second stage of structural equation modelling (Hair, et al 2006; Kline, 2005) as below,

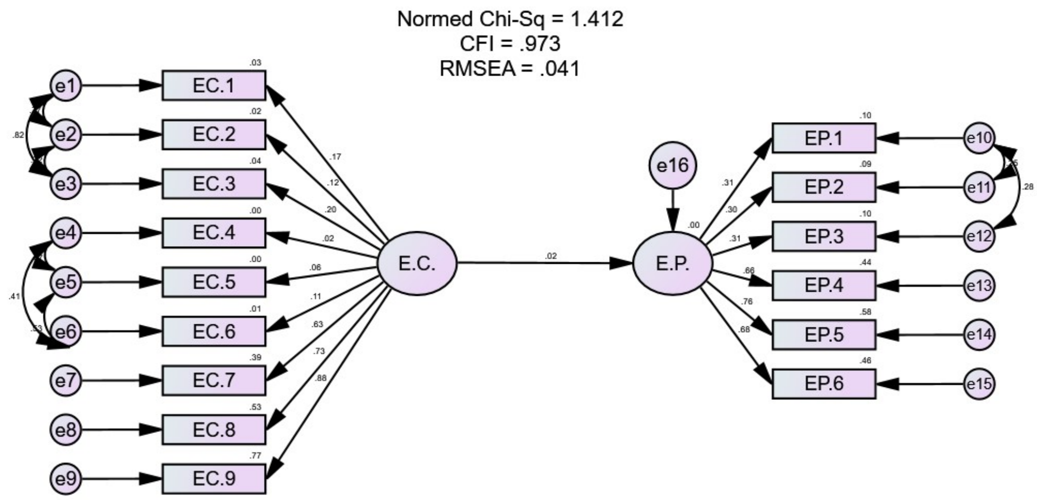

Figure 2: Structural model

The outcomes of the association between variables in the final structural model are shown in the table below.

Table 3: The regression weights of structural model

			Unstd. Estimate	S.E.	C.R.	P	Std. Estimate
E.P.	<---	E.C.	.236	.045	5.293	***	.357

As per above regression weight, competencies significantly effect on the entrepreneur performance (P <.01).

CONCLUSION

Based on the findings of the study, competencies significantly impact on entrepreneur performance. Competencies should be developed in order to achieve high level of performance of entrepreneurs in homestay tourism operations. Training programmes should be introduced to develop competencies to enhance the performance of homestay entrepreneurs.

Homestay tourism can be used to develop entrepreneurs in community-based tourism in Sri Lanka by utilizing their competencies in their local communities to take a considerable contribution to the Sri Lankan economy. This research would also be important for trainers in entrepreneurship development because this study has focused the competencies of entrepreneurs. It defines the importance of competencies that should be acquired and developed by entrepreneurs in order to survive and succeed in homestay tourism. This study has focused only few competencies even though more competencies are described in the literature. Those all competencies can be considered in further research.

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Quantifying losses and bottlenecks in Sri Lanka's formal rice seed certification system: Evidence from seed producing areas (2018–2024)

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ABSTRACT

Sri Lanka's national rice seed requirement is approximately 124,435 metric tons, yet only 12–15% of this is currently met with certified or quality-assured seed. Ideally, 25% should be provided as certified seed, given its ability to maintain quality across four generations and its potential to increase yields by 20–25%. Despite the Department of Agriculture (DoA) supplying basic seed, farmer access to high-quality seed remains significantly below demand.

This study examines the underlying reasons for limited availability of quality rice seed and quantifies losses in the seed production and certification process. It analyzes data from the Seed Certification Service (SCS) of the DoA from 2018 to 2024. The findings reveal a statistically significant reduction (p = 0.05) in seed quantities through various certification stages across different seed-producing areas (SPAs).

SPA classification was found to be a strong predictor of success at key certification stages, including field acceptance, sampling, and final certification. Category type also significantly influenced registered extents and sampled/accepted quantities. However, no consistent trend was found over time in registration extents.

Among SPAs, minor areas had the lowest rate of certified seed relative to expected quantities (~28%), while moderate SPAs had the highest (~39%). Major SPAs performed moderately (~35%). Overall, only about 66% of the expected seed output was deemed quality-assured, which translates to just 14.9% of the national requirement.

These findings highlight a significant gap between the certified seed supply and national needs, underscoring the urgency to strengthen Sri Lanka's quality seed production systems.

Keywords: Erosion of basic rice seed, Seed certification, Seed quality, Wastages.

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INTRODUCTION

The current (2025) approximate annual rice requirement in Sri Lanka at population 23.23 million and at per head consumption of 127.8 kg/year is 2.97 million tons of milled rice Thus, the national paddy production needed at farm level to fulfill consumption needs at milling out-turn 62% would be 4.79 million tons. The yield potential of rice varieties grown in Sri Lanka is nearly 10 mt/ha under favorable conditions. However, the present average paddy yield of 4.2 mt/ha is far below the expected–potential (Sirisena *et.al* 2008). It is generally accepted that at least 20-25% yield increase is possible from a self-pollinated crop if the seeds possess quality traits regarding high vigour and varietal purity (Weerasena *et.al* 2019). The farmer would earn LKR 153,750/ha of additional income at Paddy price LKR 120/kg and at Paddy yield of 5.125 mt/ha by using quality rice seed. Thus, a strong seed improvement programme which emphasizes high coverage with quality seeds of improved varieties would be a pre-requisite to realize national goals in rice production.

Based on the average paddy lands cultivated from 2018-24, the national seed paddy requirement for direct sowing was nearly 124,435 mt whereas, only 50% of it was obligatory for transplanting. In the ideal situation, 25% of this requirement should be supplied as certified or quality assured seed (Udari *et al,* 2022) since such seed would be multiplied at least another 4 generations devoid of draining its quality.

The local rice seed industry is comprised of formal, semi-formal, and informal supply systems. The formal seed supply system provides basic seed of recommended varieties for producing later generations of seeds. In principle, the Department of Agriculture's (DoA) crop improvement policy of maintaining genetic purity of its own varieties at the highest level is in line with those of most countries. Quality of all generations of rice seeds is certified by the Seed Certification Service **(**SCS) in compliance with quality standards through a systemic procedure. It undergoes field registration, inspection of the growing crop, drawing samples, seed lab testing, and finally labelling the ac-cepted seeds as certified. The percentage coverage of the extent planted with quality certified or assured seed arising from the formal system is low (Weerasena *et.al* 2019), probably 10-12% of the requirement (Udari *et.al* 2022). The semi-formal sector multiplies some amount of DoA's basic seeds and seeds of unknown origin and consequently would not qualify to earn official certification labels. The share covered by informal ways such as farmer-saved seeds, self-seed programmes, and seeds from village-based companies is unknown (Weerasena *et.al* 2019). Therefore, in the general analysis, the low share of quality certified seed would significantly affect the quality of rice seeds available in the country.

The following study undertaken focus on the present seed improvement programme in the country and could expose the trend of the quality rice seed production, quantify the resultant wastage. The outcome of the study could be shared with stakeholders as a means to further develop the industry.

METHODOLOGY

The current status of the formal rice seed sector in Sri Lanka was assessed by collecting seed certification data of seven years from 2018-2024. Data were collected from the reports generated in three phases of the seed certification process explicitly, field registration, final field inspection, and seed laboratory testing in both *Yala* and *Maha* seasons across 23 regional units of the SCS. The average regional data of registered extents showed a wide variation, ranging from 16 to 1,043 ha (Table 1). For the convenience of interpreting the results, based on the scale of registered extents, regions could be broadly grouped into three sets as major, moderate, and minor seed-producing areas (SPAs). SCS regions where the registered extents exceeded 400 ha, were categorized under major SPA, whereas the extents between 100 - 400ha were under the moderate while extents below 100 ha were placed under the minor SPA. Comparisons were made among extents registered, inspected, accepted, quantities sampled, accepted, and rejected in laboratory testing within three SPAs. The mixed model was used to evaluate the effects of seed producing category, year, and their interaction on the registered extent, quantities accepted at field and laboratory testing. A logistic regression (Probit procedure) was used to assess the effect of category on the probability of accepted extent relative to the registered extent, probability of the field accepted quantity for sampling, probability of the sampled quantity, and probability of the labeled quantity out of the expected quantity**.**

The quantity estimated was the potential seed yield based on the registered extent. The accepted quantity for sampling was the estimated potential yield of the extent accepted during final inspection.

Table 1 : Average regional data on extent registered, and accepted (ha) during 2018-24.

Region		Registered extent		Inspected extent		Accepted extent		Rejected extent	
Major	POL	1043.5		964.6		873.6		91.0	
	MAL	965.5		874.8		850.8		24.0	
	MIL	621.7		539.7		504.3		35.4	
	BAT	609.7		525.4		421.1		104.3	
	ALU	594.7		527.6		453.6		74.0	
	Subtotal	3835.1	59%***	3432.1	89% **	3103.4	81% **	328.7	9%**
Moderate	KAR	379.5		310.2		253.8		56.4	
	HIN	323.8		264.5		240.4		24.1	
	PAR	256.6		219.3		197.4		21.9	
	MAT	256.1		233.2		191.5		41.7	
	KAN	167.7		158.2		154.9		3.3	
	NIK	163.5		152.1		143.9		8.1	
	PEL	140.1		132.2		119.1		13.1	
	LAB	140.4		136.3		111.5		24.7	
	COL	108.2		85.2		78.0		7.2	
	VAU	106.6		90.9		80.3		10.6	
	BIB	111.4		108.3		94.2		14.1	
	Sub total	2153.9	33%***	1890.4	88%**	1665	77% **	225.2	10%**
Minor	KUN	94.9		85.2		78.9		6.3	
	BGD	91.4		87.9		81.4		6.5	
	PAL	80.2		72.8		56.2		15.3	
	MATH	74.3		62.2		43.8		18.5	
	MUR	68.4		54.4		51.4		8.3	
	JAF	60.0		56.6		52.0		4.6	

RIK	16.1		14.1		13.8		0.4	
Subtotal	485.3	7%***	433.1	89%**	377.4	78% **	59.9	
Grand Total	6474.2		5755.5	88%*	5145.7	79% *	613.7	**9%**

*Shares of each subtotal from each extent registered ** Shares from total extent registered
*** Share contributed to the total extent registered

POL- Polonnaruwa, MAL- Malwaththa, MIL- Mahailuppallama, BAT- Bataatha, ALU- Aluththarama, KAR- Kkaradiyanaru, HIN-Hingurakgoda, PAR- Paranthan, MAT- Mathara, KAN- Kanthale, NIK-Nikaweratiya, PEL- Pelwehera, LAB- Labuduwa, COL- Colombo,VAU-Vaunia, BIB- Bibila, KUN-Kundasale, BGD- Bathalagoda, PAL- Palmadulla, MATH- Mathugama, MUR- Murunkkan, JAF-Jaffna, RIK- Rikillagaskada

RESULTS AND DISCUSSION

Quantity Expected, Quantity Sold Prior to Drawing Samples, and Quantity Sampled

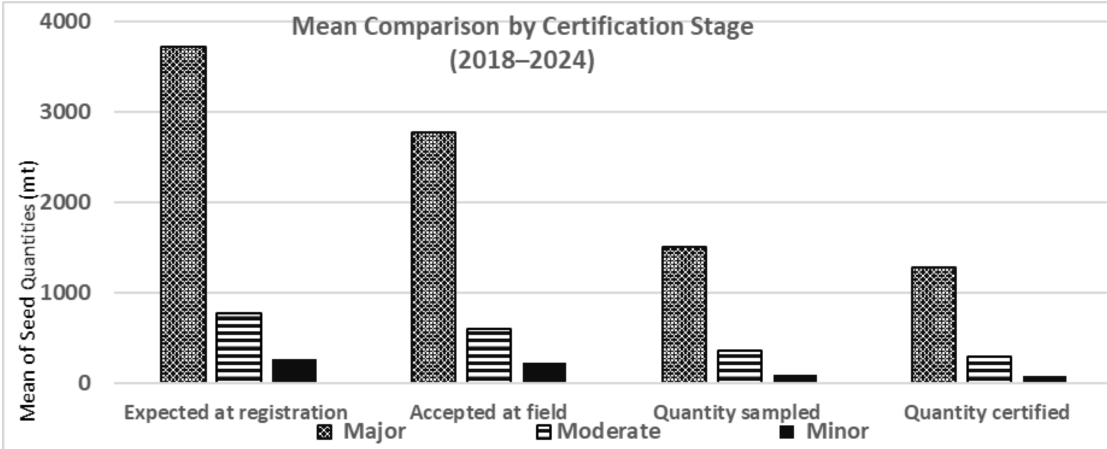
Data revealed that there was a significant difference (Table 2) between field accepted quantity and expected quantity in the major SPA whereas it was not in moderate category and minor category. It was revealed, a sizable amount of the seed quantity expected was wasted in the field prior to harvesting due to the 15% of rejections at field inspection in the major SPA. Some seed farmers were registered only for the purpose of purchasing basic seeds from DoA. As per the evaluated data, eleven percent (11%) of the expected seed quantities were wasted due to such misuse of basic seed (Table 3). However, even a 1% reduction would significantly affect the seed paddy production in these regions (Senevirathna *et.al* 2008).

Table 2: Mean Comparison by Certification Stage

Seed Quantities (mt)	Major	Moderate	Minor
Expected at Registration	3715[a]	768[a]	256[a]
Field accepted	2764[b]	591[a]	216[a]
Sampled	1500[c]	353[b]	90[b]
Certified	1280[c]	295[b]	72[b]
LSD 0.05	822	210	91

The sampled quantity from the accepted quantity at field inspection has significantly reduced in all SPAs (Table 2). Some seed producers sell the seeds prior to sampling due to monetary requirements such as for settling loans, the fear of lots being rejected at seed processing (Weerasena et.al 2019), and to sell seeds when its demand is high in the market. Seed producers often sell seeds of compromised or unknown quality using labels approved under the Seed Act. However, these labels are frequently granted without proper testing of seed quality according to certification standards, undermining the entire effort of ensuring quality seed production.

Further, the lengthy delays in the certification process (Udari et al, 2022) the delay of obtaining basic seeds to sow at the time of irrigation water is released, compelled some farmers to plant with substandard seed of farmers.



Different letters indicate significant differences (p = 0.05)

Figure 1: Mean Comparison by Certification Stage

quantity accepted and rejected at seed laboratory testing

Seed lots testing used prescribed procedures for the minimum percentage of seed germination (G), maximum moisture content (MC), maximum allowable count of weed seeds (WS), maximum count of Other Distinguishable Varieties (ODV), pests, and other factors. Seed lots that did not comply with any of the seed quality standards will be rejected. However, the certified quantity and the sampled quantity were not significantly different in all SPAs (Table 2).

The mixed model analysis

The mixed model was used to evaluate the effects of seed producing category, year, and their interaction on the registered extent, accepted seed quantity for sampling, and accepted seed quantity at laboratory testing.

The accepted quantity for sampling compared to the seed category and year

Seed category had a highly significant effect on accepted quantity for sampling ($F = 286.61$, $p < 0.0001$), with least squares means indicating that major category significantly exceeded moderate category and minor category (Tukey-Kramer, $p < 0.001$). Year also significantly influenced the accepted quantity for sampling ($F = 3.54$, $p = 0.0027$), and the Category and Year interaction was marginally significant ($F = 1.72$, $p = 0.0693$), primarily due to lower acceptance in major category during 2018, while other interactions were not significant.

An interaction analysis between year and category type revealed distinct temporal trends in the accepted quantity for sampling over the seven-year period (2018–2024), as presented in Figure 2. The data reflect dynamic shifts, particularly in the Major category, and suggest meaningful associations with broader operational and economic contexts.

The Major category consistently recorded the highest volume of accepted samples throughout the study period. A marked peak occurred in 2021, reaching 3,501.8 metric tons, the highest value observed across all categories and years. This surge may be attributed to the post-COVID-19 recovery phase, alongside regulatory actions such as intensified inspections and improved availability of agrochemicals. In 2022, however, a substantial decline to 2,385.6 mt was observed—coinciding with the ban on agrochemical imports, as well as rising input costs, including fuel and electricity, which impacted agricultural machinery use amid an economic downturn. As these constraints eased, a gradual recovery in seed production was reflected by increases in accepted quantities in 2023 and 2024. These fluctuations suggest that the Major category is highly sensitive to external factors and may serve as an effective indicator of systemic changes in the agricultural supply chain and quality control environment.

In contrast, the Moderate category displayed a more stable trend over time, with accepted quantities ranging from 479.0 mt (2018) to a maximum of 715.64 mt (2021), before a modest decline to 608.91 mt (2024). Despite minor fluctuations, the trend indicates consistent detection and prioritization of moderately classified issues. This stability suggests that such issues are less influenced by abrupt regulatory or economic shifts, potentially representing routine operational concerns.

The Minor category consistently reported the lowest accepted quantities, ranging from 116.72 mt (2019) to 281.29 mt (2024). Although a gradual upward trend is observed from 2020 onward, the variation remains minimal. This relatively flat trajectory suggests that minor issues are either infrequent or deprioritized in sampling processes.

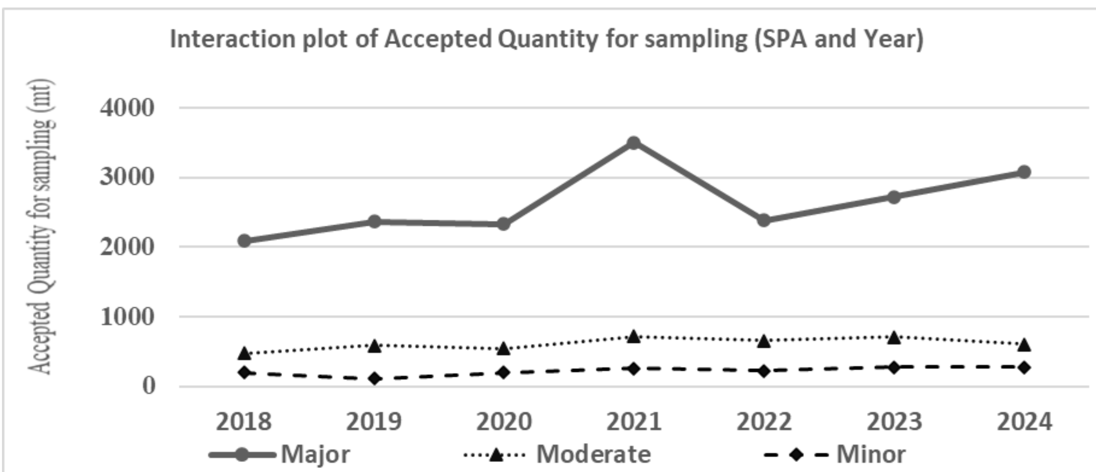


Figure 2: Interaction plot of category and year for field accepted quantity

The accepted seed quantity compared with year and seed producing area
Accepted seed quantity is determined primarily by region ($F = 384.74$, $p < .0001$), but also fluctuates across years ($F = 7.50$, $p < .0001$). Region × Year interaction: Significant ($F = 3.93$, $p < .0001$). Major SPA consistently produces much higher accepted quantities than moderate and minor categories.

Yearly fluctuations are significant, with some years notably 2021 and Year 2024, having much higher acceptance, while 2020 was notably poor. The COVID-19 pandemic seriously affected production, certification, distribution, and the cost of seeds in 2020. (Udari *et al* 2022).

Major SPA is highly productive overall, but its acceptance sharply drops in 2020 and 2022. In 2022, the ban of the importation of agrochemicals, the economic crisis, and price fluctuations of rice seed severely affected seed production and certification.

In contrast, moderate SPA is more stable, though at a lower level. Minor SPA is consistently underperformed, with very low accepted quantities and little change over years (Figure 3).

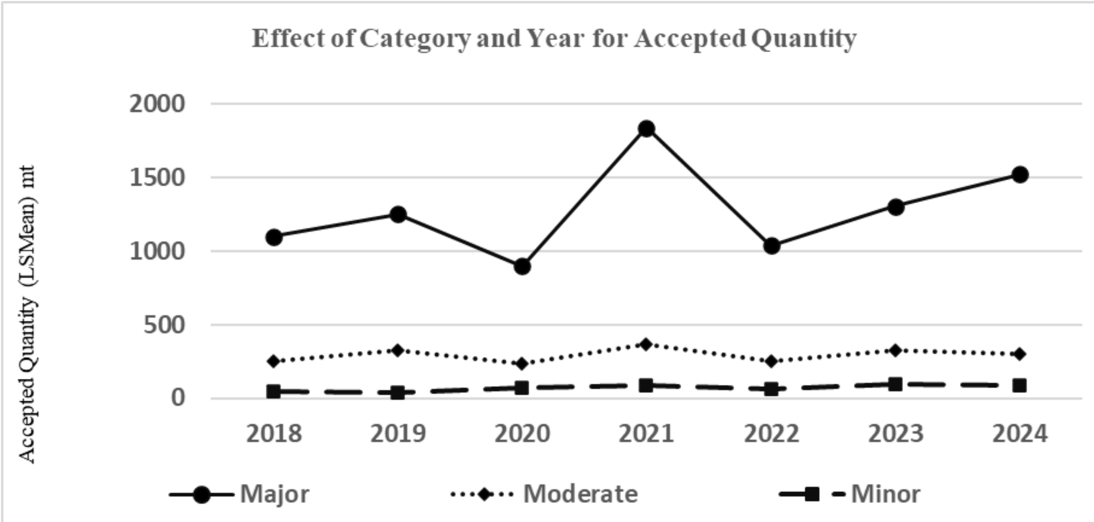


Figure 3: Interaction plot of SPA and year for accepted

The effect of year and seed producing area of registered extent

Registered extent was strongly determined by SPA. Major SPA recorded the highest mean registered extent, followed by moderate and minor SPAs. Pairwise comparisons confirmed significant differences between all categories ($p < 0.0001$). This suggests that the SPA is the strongest determinant of registered extent.

Major SPA contributed disproportionately higher registered extent, which may indicate a higher capacity, resources, or institutional role in seed production.

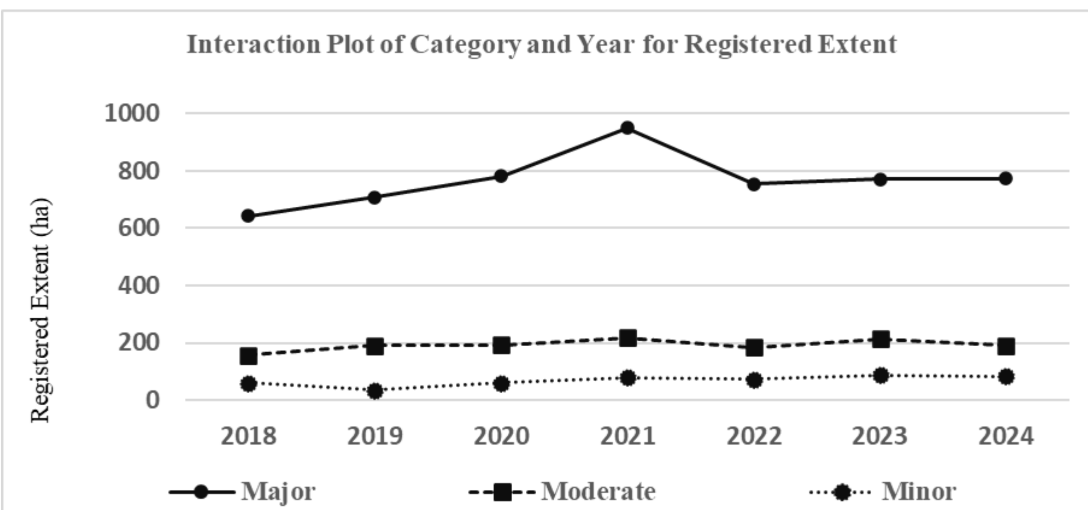


Figure 4: Interaction plot of SPA and year for registered extent

Year effect on registered extent was not statistically significant overall (F = 1.56, p = 0.1643) also the interaction effect (Seed producing area × Year) was not significant (F = 0.56, p = 0.8716) (Figure 4).

Logistic Regression (Probit Procedure) Analysis

Accepted Extent out of the Registered Extent

The overall effect of SPA on the accepted extent at field level was not statistically significant (Wald Chi-square = 0.707, *p* = 0.7022), indicating no evidence that category type influences acceptance probability in this dataset. This result implies that, at the extent registration level, quality or compliance differences between categories are either minimal or not captured in this measure.

The Accepted Quantity for Sampling Relative to the Expected Quantity

This exposed that SPA has a significant effect on the likelihood of acceptance. Relative to minor SPA, the probability of accepted quantity for sampling is significantly lower for major and moderate SPAs.

Overall, these results show a clear hierarchy: minor SPA has the highest likelihood of acceptance, followed by moderate and then major SPA, highlighting strong category-dependent differences in acceptance outcomes.

The predicted probabilities of the accepted quantity for sampling for minor SPA was 84.1%, for major SPA was 74.4% and moderate SPA was 76.9%. (See Figure 5, Table 3) The confidence intervals and highly significant p-values indicate that these differences are statistically robust. This indicates that differences in quality, processing, or management practices among categories are likely driving acceptance rates. Interventions aimed at improving lower-performing categories could therefore have a substantial impact on overall seed acceptance rates

Table 3. Average Regional Seed Production (mt) by Certification Stage of the Formal System (2018–2024)

Region		*Expected Quantity*	*Quantities*				*Quantity Sold before sampling*	*Quantity Sampled*	*Quantities in lab testing*	
		Registration	*Inspection*	*Failed/ left*	*Field Accepted*	*Rejected*			*Accepted*	*Rejected*
Major	POL#	4755	4396	360	3524	872	2101	1423	1192	231.1
	MAL	4889	4430	459	3042	1388	889	2153	1708	445.1
	MIL	2833	2459	374	2246	213	931	1315	1127	188.7
	BAT	3087	2660	427	2550	110	1136	1414	1296	119.1
	ALU	3011	2672	340	2460	212	1265	1195	1080	112.8
Subtotal		18,576/64%*	16,617/89%**	1,959 /11%**	13,822/74%**	2795/15%**	6322/34%**	7500/40%**	6403/ 34%**	1097/6%**
	KAR	1153	942	211	776	166	300	476	361	114.9
	HIN	1312	1071	240	1024	47	329	695	592	102.5
	PAR	1104	944	161	780	164	324	456	376	68.7
	MAT	973	886	87	737	149	221	516	483	33.0
	KAN	807	761	46	751	10	249	502	472	29.3
	NIK	745	693	52	547	146	246	301	255	46.1
	PEL	674	636	38	554	82	328	226	173	53.0
	LAB	427	414	12	319	95	126	193	147	46.2
	COL	362	285	77	275	10	169	106	72	33.4
	VAU	324	276	48	274	2	129	145	85	60.8
	BIB	564	548	16	459	89	194	265	228	36.2
Subtotal		8443/29%*	7457/88%**	987/12%**	6496/77%**	961/11%**	2615/31%**	3881/46%**	3244 /38%**	624.1/8%**
Minor	KUN	336	302	34	297	5	177	120	94	25.5
	BGD	384	369	15	365	4	226	139	112	28.9
	PAL	325	295	30	284	11	200	84	69	14.7
	MATH	271	227	44	180	47	136	44	21	22.9
	MUR	242	193	50	180	13	44	136	121	14.6
	JAF	182	172	10	160	12	75	85	70	12.8

RIK	55	48	7	45	3	24	21	17	3.7
Subtotal	1,796/6%*	1,606/89%**	190/10%**	1,511/84%**	95/5%**	882/49%**	629/35%**	505/28%**	123.1/7%**
Grand Total	**28815**	**25679/89%***	**3136/11%***	**22100/77%***	**3,850/12%***	**10,719/37%***	**12,010/42%***	**10,152/35%***	**1,858/6%***

** Percentages of each Subtotal from Expected Quantity *Percentages of Total Expected Quantity # POL & other Abbreviations– See Page 4

Probability of the Sampled Quantity out of the Expected Quantity

The overall effect of category was statistically significant (Wald $\chi^2(2) = 109.22$, $p < 0.0001$), indicating that probabilities of sampled quantity differ significantly across the major, moderate, and minor categories.

Predicted event probabilities as per the major, moderate, and minor SPAs were 40.4%, 45.9% and 35.0% respectively. (See Figure 5, Table 3) The likelihood of the sampled quantity out of the expected quantity was highest for moderate SPAs, followed by major, and lowest for minor SPA.

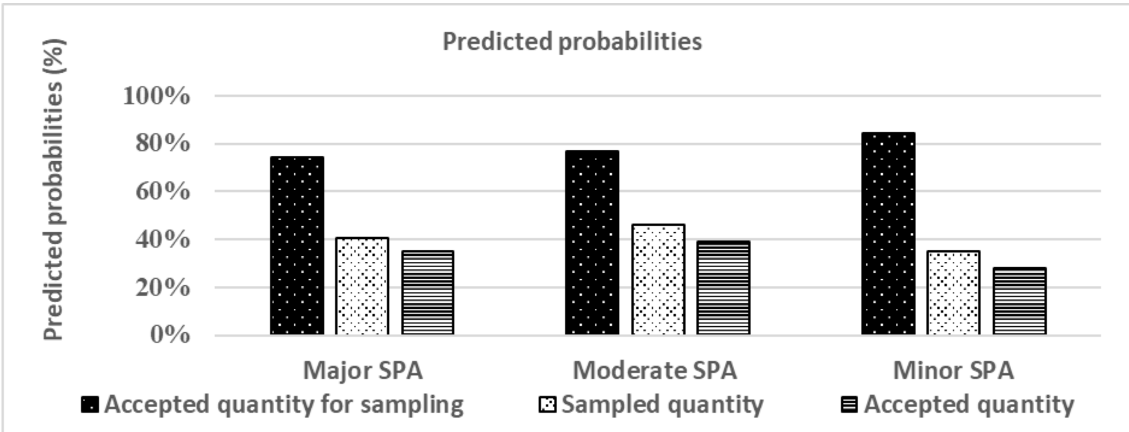


Figure 5: Predicted probabilities of quantities sampled, accepted at the field and laboratory

Produced Certified Seed Paddy (CSP) out of the Expected CSP from Registered Seed Paddy (RSP) Issued by the SPMDC, DoA.

The analysis indicated a highly significant overall effect of year on certification rates (Wald $\chi^2(6) = 1815.40$, $p < 0.0001$). Parameter estimates, with 2024 as the reference category, revealed substantial variation between years. In 2021, exhibited the significantly higher predicted probabilities of certification compared with 2024. In contrast, 2020 had the lowest predicted probability ($p < 0.0001$), reflecting a decrease relative to 2024. 2019 and 2022 also showed significantly lower probabilities, whereas 2018 and 2023 did not differ significantly from 2024 ($p > 0.45$).

Adjusting for parameter estimates, predicted certification probabilities ranged from about 8.0% in 2020 to 13.7% in 2021, highlighting notable inter-annual variation in certification performance. Further, lower predicted probabilities of CSP production indicated the wastages of the basic seeds produced by DoA (Figure 6).

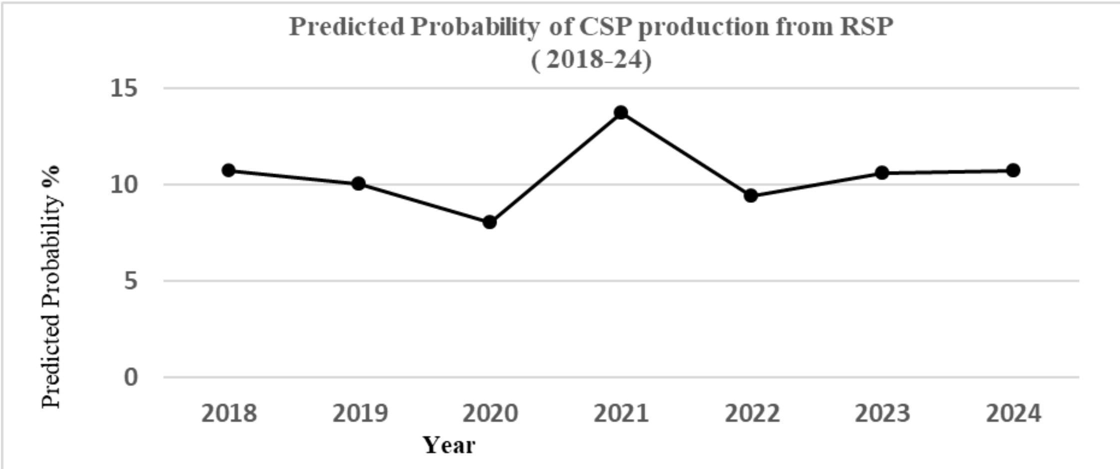


Figure 6: Predicted certification probabilities (reference: 2024)

As per the data in 2023 and 24, a 96% of the RSP requirement was produced collectively by state and private seed farms (DOA Annual Report). However, the out of the total issued quantity, only 31% was used to multiply of seed with quality confirmation and the rest was issued to seed production short of quality confirmation, and or self-seed production. The RSP multiplied without experiencing Certification by SCS, is automatically converted to commercial seed sidestepping CSP.

CONCLUSION

Out of the total expected seed quantity, only 66% was available as quality-assured seed, representing just 14.9% of the national paddy requirement. A significant decline was observed between the expected and accepted quantities for sampling, particularly in major Seed Producing Areas (SPAs). Additionally, the quantity sampled from the accepted field quantities was substantially lower across all SPAs.

The seed-producing category emerged as the most influential factor affecting registered extent, accepted quantity for sampling, and laboratory-accepted quantities. Temporal factors significantly influenced accepted quantities at both field and laboratory levels but did not impact registered extent. Predicted probabilities for accepted quantities for sampling ranged between 74% and 84%. Sampling and certification probabilities were lowest in minor SPAs (~35% and ~28%, respectively), moderate in major SPAs (~40% and ~35%), and highest in moderate SPAs (~45% and ~39%). Probabilities of Certified Seed Production (CSP) ranged from 8.0% to 13.7%.

To ensure rational and adequate availability of quality seeds vital for national food security, the entire seed production network must adhere to strict quality standards. The Department of Agriculture (DoA) should mandate certification of all produced seed, restrict basic seed distribution to professionally qualified producers with laboratory-confirmed seed quality, and enforce participation in SCS training programs, ideally integrated with NVQ certification. Non-compliance with SCS standards should result in blacklisting and prohibition from accessing basic seeds. Conversely, compliant producers delivering CSP over five consecutive seasons should be eligible for priority access to basic seeds and recognition through Certificates of Excellence.

Policy recommendations include implementing targeted, SPA-specific interventions to optimize resource allocation and enhance the performance of categories with high potential for rice seed production. Tailored improvement packages should be deployed to fully harness each category's potential. Additionally, follow-up studies are needed to explore performance disparities across varietal, agro-climatic, and management factors, with findings used to guide policy decisions on seed certification and system improvements.

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Effect of different potting media on growth and yield responses of cucumber (*Cucumis sativus* L.) under shade net condition.

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ABSTRACT

Cucumber (*Cucumis sativus* L.) is a widely cultivated vegetable crop valued for its nutritional and economic importance. Its quality is frequently compromised under open-field cultivation due to adverse climatic conditions and pest infestations, leading to inconsistent and reduced marketable yields. The adoption of controlled or protected cultivation systems is therefore essential to stabilize production and improve crop performance. In addition, the selection of appropriate potting media plays a crucial role in optimizing plant growth and productivity under controlled environments, as it influences nutrient availability, water retention, and root development. The objective of this study was to evaluate the effects of different potting media on the growth and yield performance of cucumber grown under shade net conditions. The pot (9 kg media combination) experiment was arranged in a completely randomized design (CRD) with six treatments and twelve replicates in 'Gannoruwa White' cucumber variety. The treatments consisted of the following potting media combinations: T1 (control: topsoil: compost, 1:2 v/v), T2 (topsoil:compost:Gliricidia,1:1:1), T3 (topsoil:compost:Moringa, 1:1:1), T4 (topsoil:compost:peanut shell, 1:1:1), T5 (topsoil:compost:mesquite [Prosopis juliflora], 1:1:1), and T6 (topsoil:compost:Azolla, 1:1:1). Growth (number of leaves and branches) and yield (number of fruits, fruit length, diameter, weight ant total yield) parameters were collected. Data were analyzed using SAS 9.1 software, and mean separation was performed using Duncan's Multiple Range Test (DMRT). The results revealed that the composition of potting media significantly influenced the growth and yield attributes of cucumber under shade net conditions ($p < 0.05$). Treatment T3 recorded the highest number of leaves, branches, and male flowers per plant, while T5 produced the greatest fruit length, diameter, and individual fruit weight. Treatment T6 resulted in the highest number of fruits per plant and the greatest total yield per plant, demonstrating superior overall performance. Study concludes that dried Azolla–based potting media significantly improve cucumber growth and yield under protected cultivation

Keywords: Cucumber, Growth, Treatments, Potting media, Yield, Cucumis sativus L

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INTRODUCTION

Vegetables constitute an essential component of human nutrition and are among the most highly demanded agricultural commodities in Sri Lanka. They serve as a primary source of n utraceuticals required for a balanced diet, contributing significantly to food and nutritional security (Ramya & Patel, 2019). A large proportion of Sri Lankan consumers regularly purchase vegetables for daily consumption, highlighting their socio-economic importance (Mahaliyanaarachchi, 2003). Among vegetable crops, cucumber (*Cucumis sativus* L.) is a widely cultivated annual climber that produces cylindrical fruits harvested at the immature stage for fresh consumption and processing (Acha et al., 2022). Cucumber fruits are characterized by a high-water content (approximately 95%) and contain modest amounts of carbohydrates, proteins, lipids, and essential micronutrients such as vitamin C, thiamine, niacin, iron, and phosphorus, which contribute to their recognized health benefits (Uthpala, 2020; Acha et al., 2022).

Cucumber cultivation plays a vital economic role in smallholder farming systems due to its short crop duration, rapid returns, and consistent market demand (Islam *et al*., 2016). In addition to fresh salad consumption, cucumbers are extensively used in processed products such as pickles, further enhancing their commercial value (Rahman et al., 2012). However, cucumber production under open-field conditions is often constrained by adverse climatic conditions, pest infestations, nutrient deficiencies, and inconsistent pollination, leading to reduced yield and quality.

Globally, there is increasing emphasis on sustainable and organic agricultural practices to ensure environmental protection, soil health, and human well-being (Malkanthi, 2020). In tropical agriculture, organic inputs such as green manures and organic residues play a crucial role in improving soil fertility, microbial activity, and nutrient cycling (Palm *et al*., 2001). In this context, potting media (lightweight substrates used for containers or poly-bag cultivation) have gained importance due to their ability to enhance root development, improve nutrient availability, and reduce the incidence of soil-borne diseases and pests (Akanbi *et al*., 2002). Organic materials such as compost, leaf litter, crop residues, and husk wastes have been shown to improve the physical, chemical, and biological properties of growing media, including water-holding capacity, aeration, and microbial activity (Gopinath *et al*., 2008).

Protected cultivation systems, particularly shade net houses, have emerged as effective technologies for vegetable production in tropical regions. Shade nets help moderate extreme temperatures, reduce radiation stress, lower pest pressure, and create a favorable microclimate for crop growth (Rajput & Yadav, 2013). For heat- and stress-sensitive crops such as cucumber, shade net cultivation can significantly improve yield stability, fruit quality, and overall productivity (Singh *et al*., 2014). When combined with appropriate growing media, protected cultivation systems offer considerable potential to enhance resource-use efficiency and crop performance.

The utilization of organic waste materials as soil or media amendments contributes to increased soil organic carbon, reduced reliance on synthetic fertilizers, and improved soil health. Continuous and excessive use of agrochemicals has raised concerns due to their negative environmental impacts, rising production costs, and potential risks to human health and food quality (Nalluri & Karri, 2018; Ruhul, 2020). In Sri Lanka, many agricultural soils are characterized by low fertility, with nitrogen deficiency being a common constraint, particularly in degraded tropical soils. Therefore, alternative nutrient management strategies that integrate organic inputs are increasingly being explored to sustain crop productivity.

The pot method, also referred to as open-system container cultivation, is widely practiced in vegetable production due to its efficient land use, flexibility, and suitability for protected environments. The selection of appropriate potting media is critical, as it directly influences plant growth through its effects on moisture retention, aeration, nutrient availability, and pH balance (Rani et al., 2021). Compared to conventional topsoil, organic potting substrates offer superior physical properties and can be modified to meet crop-specific requirements (Suthamathy & Seran, 2011; Ginnis et al., 2009; George & Kelvin, 2004; Lalande et al., 2000).

In Sri Lanka, cucumber is cultivated across several agro-ecological regions, including Ampara, Mahaweli System B, Monaragala, Polonnaruwa, Badulla, Puttalam, Matale, Anuradhapura, Kurunegala, and parts of the Northern Province such as Alaveddy and Sandilipay. Despite its wide cultivation, cucumber production faces major challenges, including poor nutrient availability, inadequate pollination affecting fruit set, and pest infestations such as cucumber beetles, which collectively reduce yield and fruit quality. Although several studies have examined cucumber cultivation under different environments globally, research focusing on shade net cultivation combined with organic potting media in Sri Lanka, particularly in the Northern region, remains limited.

Therefore, the objective of this study was to evaluate the growth and yield performance of cucumber grown under shade net conditions using different organic-based potting media combinations in Northern Sri Lanka.

METHODOLOGY

Location of the Study

The experiment was conducted at the Faculty of Agriculture, Ariviyal Nagar, Kilinochchi, located in the Northern Province of Sri Lanka. The study area falls within the agro-ecological zone DL3 and is situated at an average elevation of approximately 67 m above mean sea level. The soil of the experimental site is clay loam in texture with good drainage characteristics. The region receives an annual rainfall ranging from 1,040 to 1,560 mm, and the mean minimum and maximum temperatures are approximately 28 °C and 33 °C, respectively.

Selection of Crop and Variety

Cucumber (*Cucumis sativus* L.) was selected for the study due to its short growth duration and economic importance. The variety ‘Gannoruwa White’ was chosen based on its desirable agronomic characteristics, including long cylindrical fruits of medium size and a white external fruit colour at both immature and mature stages.

Seedling Establishment

Seeds were obtained from an authorized seed center. To obtain healthy, uniform, and vigorous seedlings, seeds were sown in small black polythene bags (4-inch diameter) using a potting medium composed of topsoil, compost, and partially burned paddy husk mixed in a 1:1:1 ratio (v/v). The growing medium was treated with the fungicide captan at a concentration of 12 g per 10 L of water, applied once daily for three consecutive days to prevent fungal contamination. The treated medium was then filled into polythene bags. Watering was carried out using a hand sprayer twice daily (morning and evening) until seed germination. Seedlings were transplanted after two weeks of growth.

Experimental Design and Treatments

The experiment was conducted under shade net conditions using a completely randomized design (CRD) with six treatments and twelve replicates, with each pot considered as one replicate. All crop management practices were carried out in accordance with the recommendations of the Department of Agriculture, Sri Lanka. The treatment combinations of potting media are presented in Table 1.

Table 1: Composition of potting media used as treatments

Treatment	Potting media composition	Ratio (v/v)
T1 (Control)	Topsoil + Compost	1:2
T2	Topsoil + Gliricidia leaves + Compost	1:1:1
T3	Topsoil + Moringa leaves + Compost	1:1:1
T4	Topsoil + Peanut shell + Compost	1:1:1
T5	Topsoil + Prosopis juliflora leaves + Compost	1:1:1
T6	Topsoil + Azolla + Compost	

Collection and Preparation of Organic Materials

Azolla pinnata, Gliricidia sepium leaves, Moringa oleifera leaves, peanut shells (Arachis hypogaea), and mesquite (Prosopis juliflora) leaves were collected from different field locations. The collected materials were spread evenly under direct sunlight and air-dried until a constant weight was achieved. The dried materials were then ground uniformly to obtain a consistent particle size for use in potting media preparation.

Preparation of Potting Media

All potting media components were treated with captan fungicide at a rate of 12 g per 10 L of water for four consecutive days to prevent fungal contamination. After treatment, the materials were thoroughly mixed and prepared according to the respective treatment ratios. The potting media were homogenized to ensure uniform distribution of components.

Filling of Pots and Transplanting

Plastic pots measuring 30 cm in diameter and 25 cm in height were filled with approximately 9 kg of the prepared potting media. Two-week-old seedlings were transplanted into the pots, one plant per pot. Crop management practices, including irrigation and plant care, were carried out in accordance with the guidelines of the Department of Agriculture. Cucumber fruits generally reached harvest maturity 10–12 days after flowering. Harvesting was commenced 52 days after sowing.

Special Management Practice: Hand Pollination

Pollination under shade net conditions was limited due to the absence of pollinating insects, particularly bees. Cucumber is a monoecious plant bearing separate male and female flowers on the same plant. The first male flowers appeared approximately 30 days after sowing, and individual flowers remained viable for only one day after anthesis. To ensure effective pollination and fruit set, hand pollination was performed during the flowering period. Anthesis in cucumber typically occurred between 5:30 and 6:30 p.m. During the experimental period, pollination was occasionally affected by unpredictable rainfall, which influenced yield performance

Data Collection

Growth and yield parameters recorded included the number of leaves per plant, number of branches per plant, number of male and female flowers per plant, number of fruits per plant, fruit length (cm), fruit circumference (cm), fruit weight per plant (g), and average yield (t ha^{-1}). Three plants were randomly selected and tagged as sample plants for data collection in each treatment.

Statistical Analysis

The collected data were analyzed using SAS statistical software (version 9.1). Analysis of variance (ANOVA) was performed to determine treatment effects. Mean separation was conducted using Duncan's Multiple Range Test (DMRT) at the 5% significance level to identify statistically significant differences among treatments.

RESULTS AND DISCUSSION

Number of Leaves

The number of leaves per plant varied significantly among treatments during the growing period (Table II). No significant differences were observed in leaf number among treatments between two and four weeks after sowing. However, from the fifth week onward, significant differences ($p < 0.05$) were recorded. The highest mean number of leaves per plant was observed in treatment T3 (topsoil : Moringa leaf : compost, 1:1:1) under shade net conditions, whereas the lowest leaf number was recorded in the control treatment T1 (topsoil : compost, 1:2). Compared with the control, all other treatments produced a greater number of leaves after five weeks of growth. These results indicate that organic amendments, particularly Moringa leaf-based media, enhance vegetative growth in cucumber. Similar observations were reported by Siomos (2012), who noted that vegetable yields and growth parameters improved when organic media were supplemented with compost.

Number of Branches per Plant

The number of branches per plant is a key growth parameter influenced by both genetic and environmental factors and plays a crucial role in determining flower and fruit production (Khan et al., 2009). Significant differences in the number of branches per plant were observed among treatments eight weeks after planting (Table II). Treatment T3 (topsoil : Moringa leaf : compost, 1:1:1) recorded the highest number of branches per plant, indicating enhanced vegetative vigor. The increased branching observed in this treatment may be attributed to improved nutrient availability, particularly nitrogen, phosphorus, and potassium. Dried Moringa leaves are known to contain appreciable levels of potassium (1.9%), phosphorus (0.5%), and nitrogen (4.8%) (Yang & Chang, 2006), which may have promoted shoot development and branching. However, shoot branching is also regulated by environmental and developmental factors, as reported by Che et al. (2019).

Tables2 : Impact of various potting medium under shade net conditions on cucumber branch count and number of leaves.

Treatment	Leaf count							Number of branches			
	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP	5 WAP	6 WAP	7 WAP	8WAP
Treatment 1 (T_1)	7.17^{a}	11.00^{a}	15.00^{a}	33.80^{ab}	43.33^{ab}	51.00^{a}	58.50^{b}	1.00^{a}	4.16^{b}	5.50^{b}	06.00^{b}
Treatment 2 (T_2)	7.67^{a}	09.83^{a}	11.50^{a}	33.17^{b}	40.50^{b}	49.17^{a}	61.83^{b}	0.66^{a}	6.00^{ab}	7.00^{ab}	08.33^{ab}
Treatment 3 (T_3)	7.17^{a}	09.67^{a}	14.17^{a}	39.83^{ab}	51.17^{a}	60.17^{a}	77.33^{a}	0.83^{a}	6.00^{ab}	8.83^{a}	10.00^{a}
Treatment 4 (T_4)	7.17^{a}	10.17^{a}	13.17^{a}	42.67^{a}	51.67^{a}	58.67^{b}	70.17^{ab}	0.66^{a}	6.33^{ab}	7.80^{ab}	08.16^{b}
Treatment 5 (T_5)	7.17^{a}	10.50^{a}	13.50^{a}	42.50^{a}	49.00^{ab}	55.50^{b}	68.67^{ab}	0.50^{a}	7.16^{a}	7.50^{ab}	08.00^{ab}
Treatment 6 (T_6)	7.50^{a}	10.50^{a}	13.00^{a}	40.17^{ab}	49.67^{ab}	58.50^{b}	75.67^{a}	0.50^{a}	6.16^{ab}	8.00^{ab}	09.16^{a}

Within a given treatment, means with the same letter do not differ substantially at $p = 0.05$.

WAP indicates the Week After Planting.

T1 Control: Topsoil + Compost; Treatment 2: Topsoil + *Giliricidia* leaf + Compost; Treatment 3: Topsoil + *Moringa* leaf + Compost; Treatment 4: Topsoil + Peanut shell + Compost; Treatment 5: Topsoil + *Prosopis juliflora* leaf + Compost; Treatment 6: Topsoil + *Azolla* + Compost

Total Number of Female Flowers

The total number of female flowers per plant differed significantly among treatments (Table III). The treatment comprising topsoil, peanut shell, and compost in a 1:1:1 ratio (T4) produced the highest number of female flowers. The enhanced female flower production observed in this treatment may be attributed to improved nutrient availability, particularly phosphorus, which is known to promote above-ground biomass accumulation and reduce the time required for flower initiation. Nitrogen and phosphorus are among the most extensively studied macronutrients influencing vegetative growth and reproductive development, with increased availability of these nutrients resulting in accelerated plant growth and improved floral characteristics. Previous studies have demonstrated that both nitrogen and phosphorus positively affect flower initiation, flower number, and flower size in cucurbits (Vaudo et al., 2022).

Total Number of Male Flowers

The number of male flowers per plant also varied significantly among treatments (Table III). The highest number of male flowers was recorded in Treatment T3 (topsoil : Moringa leaf : compost, 1:1:1), while the lowest number was observed in Treatment T2 (topsoil : Gliricidia leaf : compost, 1:1:1). The increased production of male flowers in T3 may be associated with the higher nutrient content of Moringa leaves, particularly nitrogen and phosphorus, which are known to influence floral development. Vaudo et al. (2022) reported that increasing soil nutrient levels significantly enhanced the number and size of male cucumber flowers, with nitrogen concentration showing a positive correlation with pollen count, nectar concentration, and flower size. Additionally, phosphorus was positively correlated with male flower number, nectar volume, and pollen grain production per flower. These findings are consistent with earlier studies highlighting the critical role of nutrient composition—especially nitrogen and phosphorus—in regulating floral traits and reproductive development in cucurbit crops (Rubatzky & Yamaguchi, 2012; Pal et al., 2020).

Table3. Effect of various potting media under shadow net conditions on the quantity of cucumber flowers, both male and female.

Treatment	Total female flower	Total male flower
Treatment 1 (T_1)	08.83^{ab}	90.17^{bc}
Treatment 2 (T_2)	07.33^{b}	81.33^{c}
Treatment 3 (T_3)	09.00^{ab}	120.17^{a}
Treatment 4 (T_4)	10.50^{a}	101.00^{abc}
Treatment 5 (T_5)	08.00^{b}	101.33^{abc}
Treatment 6 (T_6)	10.33^{a}	117.83^{ab}

Within a given treatment, means with the same letter do not differ substantially at p = 0.05.

T1 Control: Topsoil + Compost; Treatment 2: Topsoil + *Giliricidia* leaf + Compost; Treatment 3: Topsoil + *Moringa* leaf + Compost; Treatment 4: Topsoil + Peanut shell + Compost; Treatment 5: Topsoil + *Prosopis juliflora* leaf + Compost; Treatment 6: Topsoil + *Azolla* + Compost

Fruit Length (cm)

Fruit length did not differ significantly among treatments, with the exception of the control (Table IV). The longest fruits were recorded in Treatment T5 (topsoil: Prosopis juliflora: compost, 1:1:1), whereas the shortest fruits were observed in the control treatment (topsoil : compost, 1:2). The improved fruit length in T5 may be attributed to enhanced nutrient availability and improved physical properties of the growing medium.

Fruit Circumference (cm)

Fruit circumference varied significantly among treatments (Table IV). The highest mean fruit circumference was recorded in Treatment T5 (topsoil : Prosopis juliflora : compost, 1:1:1). However, no significant differences were observed among Treatments T3, T4, T5, and T6, indicating that these organic amendments provided comparable conditions for fruit girth development.

Fruit Production (Number of Fruits per Plant)

The number of fruits produced per plant differed significantly among treatments (Table IV). Treatment T6 (topsoil: Azolla : compost, 1:1:1) produced the highest number of fruits per plant (seven fruits), while the control treatment recorded the lowest fruit number. The superior fruit production observed in T6 may be associated with the high potassium content of Azolla, which has been reported to contain approximately 23,800 mg kg^{-1} of available potassium (Mahboub et al., 2019). Potassium plays a critical role in fruit formation, translocation of photosynthates, and overall yield enhancement. Similar findings were reported by Eifediyi and Remison (2009), who observed that increased NPK levels significantly improved the number of fruits per plant, fruit weight, and total yield of cucumber. Potassium has also been reported to enhance fruit quality and yield in cucurbits (Lam, 2011). Furthermore, adequate mineral nutrition, particularly balanced levels of nitrogen, phosphorus, and potassium, is essential for optimal cucumber growth and fruit yield (Feleafel et al., 2014).

Average Fruit Weight per Plant (g)

Average fruit weight per plant did not differ significantly among treatments, except for the control, which recorded the lowest fruit weight (Table IV). This result suggests that organic amendments provided sufficient nutrient availability to support fruit development. An increase in NPK levels has been shown to significantly enhance fruit set, average fruit weight, and total fruit yield in cucumber (Grozinger, 2009).

Average Yield per Plant (kg)

Significant differences in average yield per plant were observed among treatments (Table IV). Treatment T6 (topsoil : Azolla : compost, 1:1:1) recorded the highest average yield per plant (2.7 kg), followed by Treatment T4 (topsoil : peanut shell : compost, 1:1:1), which produced 2.3 kg per plant. In contrast, Treatment T2 (topsoil : Gliricidia leaf : compost, 1:1:1) recorded the lowest yield. The lower yield in T2 may be attributed to the rapid decomposition of Gliricidia leaves, as reported by Grandgirard et al. (2002), who noted that 81% of carbon and 69% of dry matter in Gliricidia decomposed within 70 days. Given the short crop duration of cucumber (approximately two months), nutrient release from Gliricidia may not have synchronized effectively with crop demand. In contrast, Azolla is known to improve soil fertility rapidly by releasing nitrogen-rich compounds and increasing the availability of organic carbon, phosphorus, and potassium within 8–10 days of incorporation (Mishra & Dash, 2014), thereby enhancing cucumber yield. Notably, cucumber yields under conventional inorganic farming systems in Sri Lanka typically range from 15 to 20 t ha^{-1} (Department of Agriculture). In the present study, the Azolla-based treatment achieved a yield equivalent to approximately 27 t ha^{-1}, highlighting its potential as an effective organic amendment under shade net cultivation.

Table 4 *:* Impact of varying potting material under shade net conditions on the average length, circumference, weight, yield, and quantity of fruits produced by a cucumber plant.

Treatment	Average fruit length (cm)	Average fruits circumference(cm)	Fruit production	Average fruit weight per plant	Average yield per plants (Kg)
Treatment 1 (T_1)	20.683^{b}	17.366^{c}	4.50^{bc}	298.38^{b}	1.325
Treatment 2 (T_2)	22.116^{a}	18.433^{ac}	2.833^{c}	355.92^{a}	1.025
Treatment 3 (T_3)	22.766^{a}	19.233^{ab}	4.50^{bc}	377.13^{a}	1.673
Treatment 4 (T_4)	22.633^{a}	19.083^{ab}	6.166^{ab}	374.70^{a}	2.235
Treatment 5 (T_5)	23.20^{a}	19.783^{a}	4.833^{b}	395.58^{a}	1.910
Treatment 6 (T_6)	22.216^{a}	19.016^{ab}	7.166^{a}	368.35^{a}	2.694

Within a given treatment, means with the same letter do not differ substantially at $p = 0.05$.

T1 Control: Topsoil + Compost; Treatment 2: Topsoil + Gliricidia leaf + Compost; Treatment 3: Topsoil + *Moringa* leaf + Compost; Treatment 4: Topsoil + Peanut shell + Compost; Treatment 5: Topsoil + *Prosopis Juli flora* leaf + Compost; Treatment 6: Topsoil + Azolla + Compost

CONCLUSION

The results of this study demonstrate that potting media composition significantly influences the growth, flowering, fruit development, and yield of cucumber grown under shade net conditions. Organic amendments incorporated into the growing media improved vegetative growth and reproductive performance compared to the control. Among the treatments evaluated, the potting medium supplemented with dried Azolla (topsoil : Azolla : compost, 1:1:1) consistently produced the highest number of fruits per plant and the greatest yield, indicating superior overall performance. Media amended Moringa leaves and *Prosopis juliflora* also enhanced specific growth and fruit quality parameters. Despite minor limitations related to pollination and microclimatic variability under shade net conditions, the findings clearly indicate that the incorporation of Azolla as an organic amendment is an effective and sustainable strategy to enhance cucumber productivity under protected cultivation systems in Northern Sri Lanka.

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Synergistic effects of co-digesting food waste and rubber waste filter sludge on biogas production and waste valorisation

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ABSTRACT

Tire manufacturing industry generates large amounts of effluent treatment plant (ETP) filter sludge and organic food waste resulting in industrial processes, which are traditionally disposed using ecologically unfriendly approaches, like incineration and landfilling. This paper explores the synergetic potentials of co-digesting these wastes to increase the production of biogas and waste valorisation. There were four experimental reactor conditions (reactor A: food waste, reactor B: filter sludge, reactor C: food waste/filter sludge 1:2, reactor D: food waste/filter sludge 2:1) that were set up in the 18-day anaerobic digestion experiment. An in-depth characterization of the physicochemical parameters was done as follows: Lab experiments were used to determine the proportion of carbon to nitrogen in the sample, volatile solids, pH, and heavy metal profile. The kinetics of biogas production, volumetric yield, methane composition, and heating values were observed and analysed. Filter sludge displayed positive properties of anaerobic digestion having volatile solids content of 57.23%, optimal C/N ratio of 18.4:1 and pH of 6.8. The level of heavy metals was maintained at levels below the inhibitory levels and offered valuable trace elements (zinc: 194 mg/kg, nickel: 12.2 mg/kg). Cumulative biogas production was similar in Reactors A and D, with each producing approximately 50 mL of biogas. Reactor A yielded the highest ratio of methane (57.49%) and heating value (3376.2 kcal/m^3) whereas Reactor D (2:1 food waste: sludge ratio) exhibited a good balance with the maintenance of production kinetics and a content of 56.26 % of methane. Food waste and tire industry filter sludge co-digestion is a practical choice of circular economy strategy, with two streams of waste being converted into renewable energy to create a digestate rich in nutrients, which may be applied to the soil. The results justify the scalability of implementation of sustainable industrial waste management and energy recovery in the tire manufacturing industry.

Key words: *Anaerobic Co Digestion, Biogas Production, Effluent Treatment Plant Sludge, Methane Yield, Sustainable Waste Management*

INTRODUCTION

Effluent Treatment Plants (E.T.P) are the basic infrastructure in a modern industrial environment, which is primarily meant to treat the waste water before disposal to the environment. These buildings, by removing the contaminants from the industrial wastewaters, bring about minimum damage to the ecosystem and thus, play a crucial part in the environmental protection (Ahring, 2001). However, there are general difficulties associated with the management of filter sludge which is a side-product of the ETP in many industrial sectors (Ahmad, 2023). It consists of biomass and the solids that have settled, arising from filtration and biological treatment processes. The actual composition of this sludge may vary greatly from one industrial sector to another owing to differences in the treatment procedures applied and other operational conditions. Filter sludge contains organic matter, nutrients, heavy metals, and potentially pathogenic microorganisms in varying concentrations (Affes et al., 2017). Landfilling and incineration, historically disposal options, were developed to deal with this waste stream. Such techniques pose a danger to the environment, besides leading to loss of potential resources (Ajala, Odejobi, & Osuolale, 2021).

In addition to the challenges of management of filter sludge, food wastage worldwide is increasing at an alarming rate. Roughly 1.3 billion tonnes of food, or one-third of the food produced globally for human consumption, is wasted or lost each year-themed as a 1.3 billion-tonne problem (Chen & Hashimoto, 1980). Massive losses of otherwise valuable resources have been incurred by sending this huge flow of waste for disposal by landfill, with significant increases in greenhouse gas emissions also ensuing. The resource potential of food waste derives from it generally containing high concentrations of readily biodegradable organic matter, nutrients, and water, with the capacity to become hazardous when poorly managed (Baek, Kim, & Shin, 2020). The two major issues here regarding waste management are kitchen waste from diverse sources and filter sludge from ETP's and, therefore, have promise for a joined creative response (Franke-Whittl et al., 2014). Recent studies have indicated that instead of treating these waste streams separately, they would create major synergistic benefits through co-processing (Ferreira et al., 2021). Such synergies that could come about are derived from the complementary features of the two waste streams: kitchen waste provides easily degradable organic carbon for biological processes whereas filter sludges contain the microbial communities likely to degrade complex organic pollutants. Apart from landfilling, real concern surrounds the nonconventional disposal methods (Battimelli, Petrangeli Papini, & Majone, 2003). The commercial disposal of certain ETP waste is a daunting factor and is adding operational and financial costs to the global industries (El-Mashad & Zhang, 2004). All these traditional disposal methods, particularly landfilling, are facing stricter regulations in the light of the anticipated effects of leachate generation, GHG emissions, and land-use conflicts. Although incineration clearly reduces waste volume, it does raise very serious issues about energy efficiency and air emissions, particularly where sludge has a high moisture content (Christou et al., 2021). The cost of disposal methods is on the rise in reaction to stricter regulations, rising transport costs, and the reduction of disposal capacity. Occurring is the consequent stimulation of interests to alternative management strategies. The characteristics of filter sludge differ widely among industries; yet, they influence both their value and danger in management (Cheah, 1998). The dye and chemicals used in the textile industry may pose toxicity problems and opportunities for specialized processing due to their presence in filter sludge. Sludge from pharmaceuticals contains metabolites and active pharmaceutical ingredients, requiring proper attention for disposal to protect the surrounding environment (Cruz, Pino, Martínez, & Gómez, 2018). Compared with sludge generated from the food processing industry, there is less toxicological concern due to the large amount of organic matter and nutrients in it; still, they have to be undertaken so as not to create conditions that are annoying for a community and resource recovery (Dague & Riffat, 1995).

The search for alternative sources of energy, which are sustainable and renewable, beyond fossil fuels is mainly motivated by the worldwide energy crisis, as well as the environmental problems related to waste management. In conjunction with waste management solutions, a dual advantage of this biogas generation method by anaerobic digestion is the production of clean energy (Elbeshbishy & Nakhla, 2012, Dasith , Tatiana, & Jado, 2025). This approach has been quite successful in a number of different industrial sectors, such as the tire manufacturing sector, where the waste materials compose a big portion of the organic waste streams that could be used as feedstock to biogas plant (Dahunsi, 2020). Over the last few decades, we have been seeing accelerated growth in the tire production industry, usually regarded as an important part of the transportation production system, with approximately 2.5 billion tires released into the market every year. Just 10 years ago, environmental conservation threatened to be the subtext on the tip of a few tongues, today we have the rapid facilitation of industrialization and resultant waste production, which becomes common during eras of economic development, such as the organic food wastes from factory canteens, an area of concern on one mid-century (Elsayed, 2020). At the moment, the majority of waste-based resources are usually either incinerated or sent to landfills, which causes emission of greenhouse gases and eliminates further energy recovery from the waste resources (Daramy, Xie, & Sun, 2020). In spite of its lesser presence compared to other organic wastes, wastewater treatment is a significant source of organic matter and nutrients found in effluent treatment plant sludge, which provide optimum substrates for microbial actions under anaerobic conditions of digestion (Del Borghi, Converti, & Del Borghi, 1999). The food waste from industrial canteens has high calorific value with good biodegradability, thus adding to the mass of feedstock for biogas production. The careful co-digestion of different waste streams can achieve an optimal C:N ratio and thus contribute to the diversity in nutrient composition favoured by methanogenic bacteria, which ultimately supports increased biogas production and overall enhanced process stability (Deng, Huang, & Liu, 2014).

Aim and Objectives of the Study.

The primary aim of this study is to evaluate the technical feasibility and optimization potential of biogas production through the anaerobic co-digestion of food waste and effluent treatment plant (ETP) filter sludge generated by the tire manufacturing industry. Specifically, the study seeks to investigate substrate compatibility, biogas yield and quality, and the influence of ETP sludge composition on methanogenic performance.

Issue, Rationale, and Knowledge Gap.

Although biogas production systems utilizing industrial waste streams have been widely studied, the application of anaerobic digestion to tire industry ETP sludge remains inconclusive due to its complex and heterogeneous composition. This sludge typically contains rubber particles, processing chemicals, trace metals, and variable organic content, which can exert either inhibitory or stimulatory effects on anaerobic microorganisms. Existing literature lacks systematic experimental evidence on the antagonistic or synergistic interactions between tire industry ETP sludge and readily biodegradable substrates such as food waste. This represents a critical knowledge gap that limits the large-scale implementation of biogas systems in the tire manufacturing sector.

Brief Methodology.

To address this gap, the present study employed laboratory-scale anaerobic digesters operated with mono-digestion and co-digestion configurations using food waste and ETP filter sludge at different mixing ratios. Key physicochemical parameters, biogas production dynamics, methane content, and substrate stability indicators were monitored to identify optimal operational conditions and substrate combinations.

Contribution and Significance.

This study contributes novel insights by demonstrating the feasibility of valorizing tire industry ETP filter sludge as a co-substrate for anaerobic digestion, transforming a problematic industrial waste into a renewable energy resource. The findings support the application of circular economy principles by integrating waste management, renewable energy generation, and resource recovery within the tire manufacturing industry. From a practical perspective, the results provide a pathway for tire manufacturers to reduce disposal costs, comply with environmental regulations, lower carbon emissions, and enhance energy security through sustainable biogas production systems.

METHODOLOGY

Initial Sample Testing

Composition Testing

Table 1: Composition Analysis Test Results of E.T.P Filter Sludge

Test/unit	Method	Results
Organic carbon, percent by mass	Soil Chemical Analysis by ML Jackson	9.2
Total nitrogen (as nitrogen), percent by mass	SLS 645 Part I : 2009	0.5
Total phosphate (as P), percent by mass	SLS 645 Part 5 : 1985	1.8

Potassium (as K), percent by mass	SLS 645 Part 4 : 1989	0.03
pH at 25.0'C (1:10)	ISO 10390	6.8
Faecal colilorm counts, per g	SLS 1246 : 2003	0.92
Salmonella, per 25g		Absent
Cadmium (as Cd), mg/kg	Dry Ashing /AAS — Flame	0.15
Lead (as Pb), mg/kg		4.7
Zinc (as Zn), mg/kg		194
Nickel (as Ni), mg/kg	Microwave Digestion /AAS- Flame	12.2
Copper (as Cu), mg/kg		15.7
Chromium (as Cr), mg/kg		15
Magnesium (as Mg), mg/kg		67.8
Calcium (as Ca), percent by mass		0.13
Mercury (as Hg), mg/kg	Microwave Digestion /AASVGA	0.3

PH determination

A performance evaluation methodology was developed for anaerobic digestion using raw food waste and ETP filter sludge as substrates as described in section 2.3, and the initial pH of each reactor mixture was measured. The solution was left of its own before the pH was measured by a digital pH meter at 25°C within the calibration by the ISO 10390 method (Gaibor-Chávez et al., 2021). The pH value directly affects the presence of methanogens in anaerobic digestion. Process stability and efficient methane generation are secured by keeping a pH in the perfect range (Gelegenis et al., 1996).

Carbon Nitrogen ratio (The Conventional method)

The total nitrogen content of the samples was determined using the Kjeldahl method (Hamburger, 1987). One gram of the sample and six millilitres of concentrated H_2SO_4 were placed in a digestion test tube and thoroughly mixed. Subsequently, 3.5 millilitres of H_2O_2 were added incrementally. After an initial reaction period, the tube was manually shaken, three grams of catalyst mixture were added, and the sample was weighed to obtain the required mass. The test tube was then left for 5–15 minutes to allow proper mixing before being placed in the digestion chamber. The digestion rack was inserted into the digester and heated at 370 °C for approximately four hours until a clear solution was obtained (Hashimoto et al., 1982). The digestion rack was then cooled using a smoke fan. To prevent sulphate precipitation, approximately 50 millilitres of distilled water were added to the digest and mixed manually. The solution was then diluted, and 25 millilitres of 40% NaOH were added (Imeni, 2019). For the distillation step, a 250 mL conical flask containing an indicator solution, 25 mL of distilled water, and 25 mL of boric acid was placed at the outlet of the distillation condenser, with the flask tip immersed in the solution. Distillation was continued for approximately eight minutes, or until the total distillate volume reached 200–250 mL (Jensen & Sullivan, 2014). The collected solution was then titrated with 0.1 N HCl until a yellow endpoint was observed, and the nitrogen content was calculated using the standard Kjeldahl equation. This procedure was used to determine the percentage nitrogen (N%) content of the samples (Khoo, 2021).

$$\% N = \frac{V*0.1*14*100}{WO} \quad (1)$$

where,

V- HCl volume in liter consumed to end point of titration

WO - sample weight in g for basis of dry matter and 14 g/mol of the nitrogen molecular weight

0.1 – HCl concentration mol/L

Determine the feedstock's physiochemical characteristics for AD

The following crucial biological parameters are taken into account by the supply chain when assessing the efficacy and efficiency of the anaerobic digestion (AD) process (Kim et al., 2023):

- Moisture content
- Volatile and fixed solid
- Total Solid

Volatile solid

The samples heated for 15 to 20 minutes at 550 °C in the centre in a muffle oven. It was cooled in a dry container until it balanced. Following equation 2 used to to get the fraction of volatile solids (Kivaisi, 1998).

$$\%VS = \frac{WVS*100}{WDS} \quad (2)$$

Where, *%VS* – Percentage of volatile solid, *VS* - Weight of volatile solid, *WDS* -Weight of dry sample

Moisture content

The moisture content of the samples was measured by carefully weighing the fresh sample (before to drying). This weight was noted as W1. following the sample's placement in an oven that had been prepared to a certain temperature (about 105°C to 110°C) (Lee, Jang, & Kang, 2022). It was dried until its weight remains constant. Once it was possible to take the sample out of the oven and let it cool in a vacuum chamber. Weighed the dry sample once it was cooled. This load was recorded as W2 file (Maddigan, 2008).

$$\%MC = \frac{(W1 \quad W2)*100}{W1} \quad (3)$$

Where, W1 – Initial weight (g) of the fresh sample, W2 – weight (g) of the dried sample

Total Solids Determination of E.T.P. Sludge Sample,

A dry sample of known weight is considered for total solids (TS) determination. It is calculated by reference to the remaining residue after evaporation. First, weigh the empty container, followed by weighing the same container with a known mass of sludge. The sample was thereafter heated at 105 °C in an oven to constant weight (Nkuna, Roopnarain, & Adeleke, 2019). The sample is then cooled in a desiccator and weighed. express percentage TS using the below formula (Mendes & Orrico, 2016):

$$\%TS = \frac{WDS*100}{WWS} \qquad (4)$$

Where,

TS - Total solid %, WDS – Weight of dry sample, WWS- Weight of wet sample

Reactor Design and Biogas Production

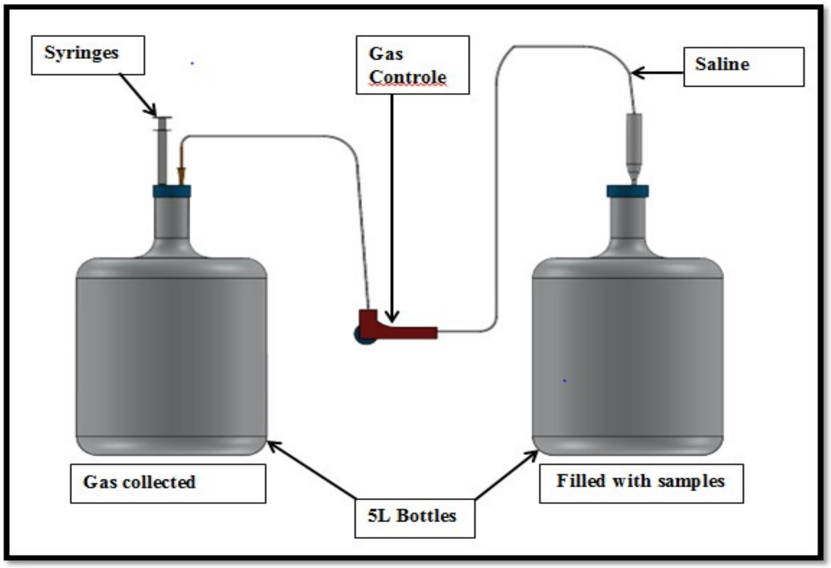

Figure 1: Reactor Design

This anaerobic multi-phase reactor has been designed to treat filter sludge and food waste for biogas generation. The system was designed to develop enhanced microbial activity for biogas generation. The structural components include the elements in this reactor's operations in their different roles gas collection systems, digesting chambers, and monitoring apparatus as shown in Figure 1. Reactor structure and components: digestion chamber, digestion chamber which is the most important part of the system, has been built from a strong airtight material, to stop the escape of gases (Schnürer & Nordberg, 2008).

- **Gas Collection System:**

Through a network of saline tubes, the generated gas enters the gas collection device from the digesting chamber. The gas measuring was done using the system of 50mL syringes contained in the setup. A gas controller was devised for controlling pressure and avoiding excessive accumulation inside the reactor (Panico, Ventola, & Pirozzi, 2014).

- **Operational Procedures.**

Sealing and incubation: The reactor was properly sealed to prevent any possible anaerobic conditions.

- **Gas Collection and Measurement:**

The biogas was progressively collected and channeled into the collection chamber using saline tubing. The gas was sampled at defined time intervals using a sampling syringe for compositional analysis. The reactor layout enhanced methane yield and anaerobic digestion performance by creating a stigmatic environment through controlled and repeatable settings for biogas production (Raposo, De la Rubia, Fernández-Cegrí, & Borja, 2011)

Sample Preparation

Table 2: Mixing ratio of substrates for each Sample

Sample Number	Food Waste (g)	Filter Sludge (g)	Inoculum (g)	water (ml)	Total volume (g)
A	200	-	180	2200	2580
B	-	200	200	2560	2960
C	100	200	300	3060	3660
D	200	100	300	2880	3480

Method of Sample Preparation

In the biogas generation experiment to evaluate the anaerobic digestion efficiency, different combinations of food waste and filter sludge inoculum with water are used.

- **Sample A Preparation:**

Weigh 200g of food waste and place in suitable container. Add to this 180g of inoculum to introduce the microbial community required for anaerobic digestion. The combination was then brought into an aqueous activity of 2200 ml to promote microbial activity and to homogenize the slurry. This prepared sample has a total volume of 2580 gram. Before anaerobic digestion, the mixture was well shaken to ensure that all ingredients were evenly distributed (Ulsido & Habtom, 2020).

- **Sample B Preparation:**

In the case of sample preparation, a working filter was used to collect sludge, approximately weighing 200 grams in a sterile container. Further activities regarding the composition of microbial action started with the initial inoculums of 200 grams. Six days after preparation, the moisture content is set up for action with microorganisms. An adjustment of the moisture includes adding up to 2560 mL in volume. The total weight of the adjusted sample is 2960 g. The sludge is then thoroughly mixed and poured into anaerobic digester (Uma & Sudhakar, 2018).

- **Sample C Preparation:**

Sample C is made up of the combination of food wastes with filter sludge. Hence the weighing of these parts is found to be 200 g filter sludge and 100 g food waste. Thus, those two make 300 g inoculum for this microbial action process. Employed herewith was an excess amount of 3060 ml. Weighing in total adds up to 3660 g of prepared sample. The entire mixture was then mixed entirely before pouring into a digester.

- **Sample D Preparation:**

Food waste, filter sludge, and inoculum were prepared in a weight ratio of 200:100:S 300 for the highest rate of biodegradation. Viscosity was brought about by adding 2880 mL water in which anaerobic respiration could take place. Hence, the weight of the sample becomes 3480 g. The entire mixture was blended very well before dumping for anaerobic digestion so that the constituents could properly interact as desired. So, each individual sample has undergone evaluations to provide qualitative evaluations in direct comparison for measuring success in biogas production. All measures have been performed in a manner stringent enough to be through link and calibration of weighing machines and instruments in the laboratory in order to have accuracy at each level of measurement in the research study.

Experimental Setup

- **Gas Collection:** The collection process should be done sometimes without any leak proving at later stages that biogas transfusion into an offline gas collection container was done well. Collected gas from anaerobic digestion should be kept in an airtight container after anaerobic digestion.

- **Tube Connection:** Flexible tubing connected with the gas storage provided an airtight connection to ensure a controlled flow of gases. The flow was ensured by directing it through the tube towards the combustion site.
- **Ignition Mechanism:** Normal lighter at the outlet of the tube was used for lighting the biogas. The process of ignition was done under whenever all necessary precautions were taken but, in a well-ventilated area for prevention of accidental ignition (Tufaner & Avşar, 2016).
- **Observation of Flame**: The flame color was then recorded; analyzed later. Differences in the features of the flame from different biogas samples were noted for further analysis.

Gas Burning and Flame Color Check

Figure 2: Gas Burning and Flame Colour Observation

Means of evaluating the quality of biogas. This was important in determining the role of methane and other combustible gases because they are prime determinants of biogas use efficiency (Dasith et al., 2025). The gas burning and flame color check was conducted as a qualitative assessment of biogas composition. Biogas samples were directed through a laboratory-scale burner and ignited under controlled ambient conditions. The flame was visually observed for color, stability, and soot formation. A stable blue flame was taken as an indication of higher methane content, while yellow or orange flames and unstable combustion suggested the presence of carbon dioxide, moisture, or other impurities (Tyagi et al., 2018).

Data collection and analysis

The assessment of the flames was complemented by photographic and video documentation to be able to monitor the good and bad interactions in real-time (Villamil, Delgado, & Garcia, 2018).

Gas Volume Analysis

The start of the anaerobic digestion experiment was defined as Day 0, corresponding to the initial loading and sealing of the reactors, Biogas generation was monitored daily from Day 18 until the end of the digestion period.

Methodology for Gas Volume Analysis in Biogas Production

Experimental Setup and Sample Preparation

This experiment was conceived for evaluating the volume of gas produced over an 18-day period in anaerobic digestion of food wastes and filter sludge. In this study, the Effluent Treatment Plant in the tire industry was employed. More quantities of food waste and filter sludge were also put out for biogas production. Four experimental setups were installed to measure the effect of mixed substrates on biogas production (Wang, 2016).

- **Food Waste Sample Alone (A):** The first setup included only food waste as the substrate.
- **Sludge Sample Alone (B):** The second setup contained only filter sludge as the feedstock.
- **Food Waste (100g) + Sludge (200g) (C):** The third setup included a mixture of food waste and sludge in a 1:2 ratio.
- **Food Waste (200g) + Sludge (100g) (D):** The fourth setup included food waste and sludge in a 2:1 ratio.

Experimental Conditions and Biogas Collection

Biogas formation was facilitated in closed, anaerobic digesters in which samples were placed. Regulated conditions in the digesters guaranteed maximum possible microbial activity. (Wang et al., n.d.)

Gas Collection System

1. The biogas produced in the digester was transmitted through a network of saline tubes into a gas-collecting apparatus.
2. In order to measure volume production, the setup was fitted with 50 mL syringes. A gas controller was used to release any pressure and prevent excessive gas build-up in the reactor.
3. To ensure consistency, every measurement was repeated at the same time each day.

Gas Composition Analysis

Figure 3: Gas Composition Analysis

It will calculate the quantity of biogas generated and its proportion of CH_4 once the anaerobic digestion process starts. A graduated syringe with a 50 ml capacity will be used to monitor the amount of biogas discharged into air pockets. A gas analyzer was used to determine the biogas's methane content (Xiao & Ren, 2015). The percentages of O_2, H_2S, CH_4, and CO_2 as well as the biogas balance can be determined using this gas analyzer (Yang

& Chen, 2019). The biogas from the four digesters will be syringed and fed straight into the gas analyzer for demonstration purposes. Finally, a Gas Analyzer was used to assess the heating value of biogas (Yapa, 2016). In addition to mapping various cycle processes with varying parameters, it understands thermodynamic processes. Partial load behaviour and system efficiency must be assessed. Understanding the economic, energy, and potential of these wastes for the global community may be aided by this research (Zhang, 2007).

RESULTS AND DISCUSSION

Composition Analysis of Feedstocks

C/N Ratio Analysis

The C/N is significant when one speaks of anaerobic digestion processes. The organic carbon content was 9.2% and the total nitrogen was 0.5%. An optimum C/N ratio from 15 to 30:1, towards anaerobic digestion processes, according to other researchers. The ideal C/N ratio means that methanogenic bacteria will, providing optimum nutritional availability; however, its excessive ammonia production will inhibit, lower C/N ratios, while higher ratios will inhibit by lack of nitrogen for metabolic activity. The filter sludge had a C/N ratio, signifying that without any added carbon or nitrogen, it would optimally serve as a substrate for biogas production. This is important in economic treatment evaluation because this simplified determination of nutritional requirements decreases operational cost.

Heavy Metals and Trace Elements

This filter sludge bore some heavy metals and trace elements like zinc (194 mg/kg), nickel (12.2 mg/kg), copper (15.7 mg/kg), and chromium (15 mg/kg). Though heavy metals at high concentrations can exert detrimental effects on this anaerobic digestion process, concentrations measured in the present study were, under the inhibitory levels against methanogenesis. In addition, certain trace elements especially Zn and Ni are essential cofactors of different enzymes of the methanogenesis pathway. The activity of carbon monoxide dehydrogenase, acetyl-CoA synthase, methyl coenzyme M reductase, and hydrogenases in Archie methanogenesis can be asserted with high degree of certainty that contamination, including zinc (194 mg/kg) and nickel (12.2 mg/kg) will enhance the activity of methanogenic pathways in the filter sludge by catalysing the key enzymatic processes in the biogas formation pathway. These metals may have had a stimulating effect on the growth and metabolic activities of methanogenic archaea, thereby increasing yield and production rates of methane. It has been reported that the addition of nickel led to an increase of methane production by as much as 25% in laboratory-scale digesters when it was added at a concentration of 5 to 20 mg/kg. Some heavy metals remained far below damaging concentrations-inhibitory ranges, including cadmium (0.15 mg/kg), lead (4.7 mg/kg), and mercury (0.3 mg/kg), leaving little to none opportunity for toxicity to the microbial communities.

pH Conditions

The pH was recorded at 6.8 at the filter sludge-to-chromatograph, which thus falls in the range as the optimal range for methanogenesis, 6.5 to 7.5. Methanogenic archaea and hydrolytic and acidogenic bacteria will thrive and maintain an anaerobic digestion process that is stable and balanced. This optimal pH will Favor the mediated activities of different microbial groups controlling different steps of the successive breakdown of the complex organic matter to methane. This happened at a pH of 6.8, which is more in the range that thrives optimal growth for many of the methanogenic archaea when slightly alkaline conditions prevail (pH 6.8-8.2). Hydrolysis is a process influenced and controlled by a set of exotic bacteria and a set of such groups acidogenic-which themselves manage best under a pH range of 5.5 to 6.5. Hence, during this pH measuring at 6.8 should also favor a great range and vigorous community of organisms that effectively oxidize organic matter into biogas. When considered as a co-substrate addition, the nearly neutral pH also signals buffering capacity, which is vital for process stability as any possible acidification during the rapid hydrolysis and acidogenesis of readily biodegradable organic matter in food waste.

Macro and Micronutrients

Filter sludge contains calcium, magnesium, potassium, and phosphorus. These components help in the organism's growth and metabolism during anaerobic digestion. Potassium is apt for setting osmotic pressure and enzyme activation, whereas phosphorus is very much concerned in nucleic acids, ATP, and membrane phospholipids. Calcium and magnesium may act as co-factors, imparting stability to the cell walls. Thus, due to the presence of macronutrients in filter sludge, there is no need to carry out external supplementation for biogas production, thus making its production economically viable.

Initial Test Results

Volatile Solids and Moisture Content Analysis

Table 3: Analysis of Feedstocks for Volatile Solids and Total Solids

Parameter	Filter Sludge	Cow dung	Food Waste	Digestate
Volatile Solids (VS)%	57.23	28	50	60
Total Solid (TS) %	71	-	60	70
Moisture Content %	22	-	40	30

- **Calculated from raw data: (35.9060-35.5600)/1.2369 = 0.28 or 28.0%**
- **Analysis of Volume of Biogas under Four Reactor Conditions**
- Reactor A: Food waste only (control)
- Reactor B: Filter sludge only (control)
- Reactor C: Food waste (100g) + filter sludge (200g) (1:2 ratio)
- Reactor D: Food waste (200g) + filter sludge (100g) (2:1 ratio)

Table 4: the total biogas produced from each reactor during the entire fermentation period of 18 days.

Date	Food waste gas volume (ml)(A)	Sludge gas volume (ml)(B)	Food waste(100g)+sludge(200g) gas volume (ml)(C)	food waste(200g)+sludge(100g) gas volume (ml)(D)
15	3			
16	3			2
17	5		1	2
18	5	1	2	3
19	6	2	3	3
20	7	2	3	3
21	8	3	4	4
22	8	6	5	7
23	12	7	6	7
24	18	8	9	10
25	25	12	14	16
26	28	20	22	23

27	35	25	28	28
28	41	29	33	39
29	46	35	37	44
30	50	42	44	48
31	50	45	46	50
32	50	47	48	50

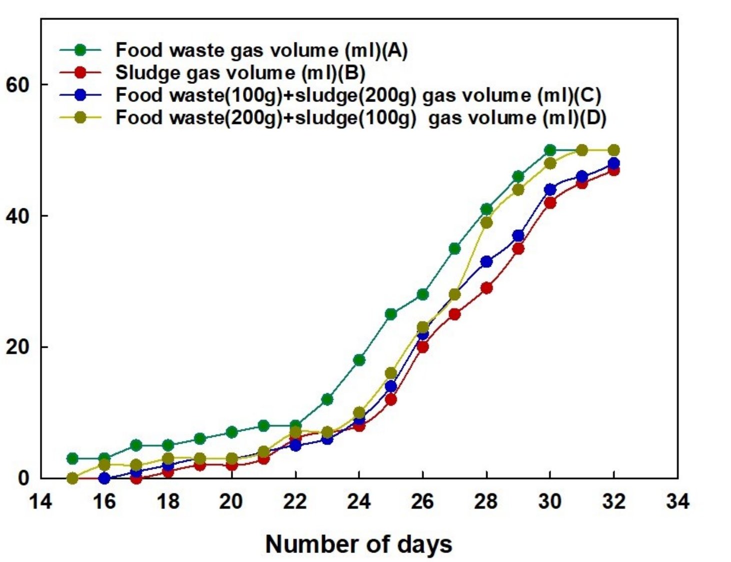

Figure 4: Cumulative Biogas Production (ml y axis) from Different Reactor Conditions, from day 14 to 32 (x axis)

Composition Analysis of four Reactor Condition

CH_4 Composition of Sample

Table 6. CH_4 Composition of Sample

Sample	CH_4 Percentage % (Composition)
A	57.48555
B	55.31328
C	51.82075
D	56.26158

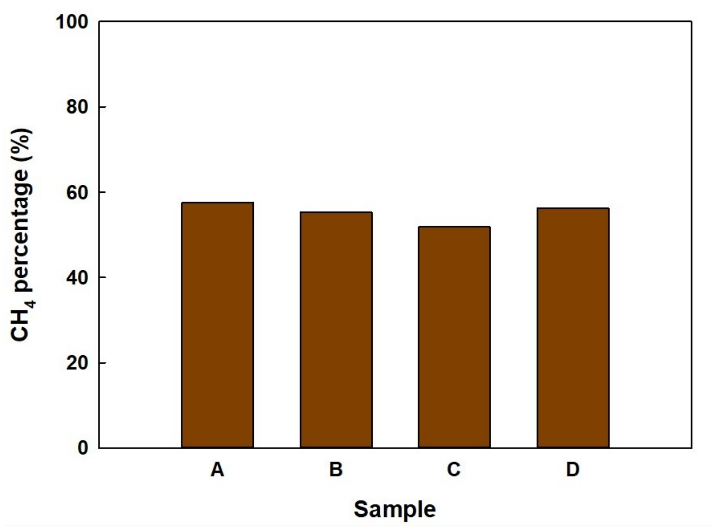

Figure 5: CH_4 Percentage % (Composition) of Sample Graph

CO_2 Composition of Sample

Table 7: CO_2 Composition

Sample	CO_2 Percentage % (Composition)
A	40.51445
B	42.68672
C	46.17925
D	41.73842

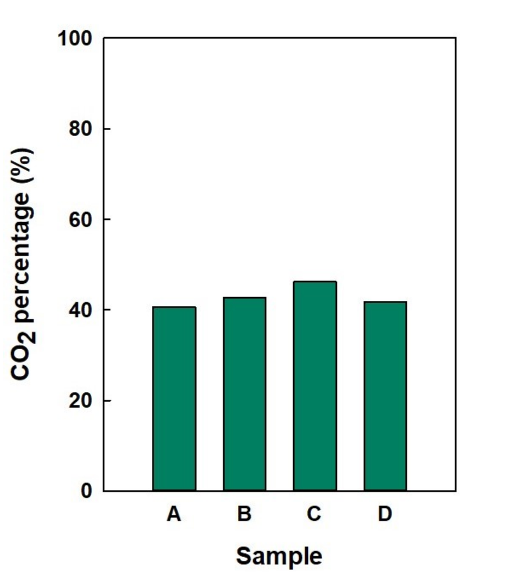

Figure 6: CO_2 Percentage % (Composition) graph

Heating value of sample

Table 8: Heating Value Of sample

Sample	CV Value of Sample (kcal/m^3)
A	3376.2
B	1852.1
C	1687.9
D	2336.4

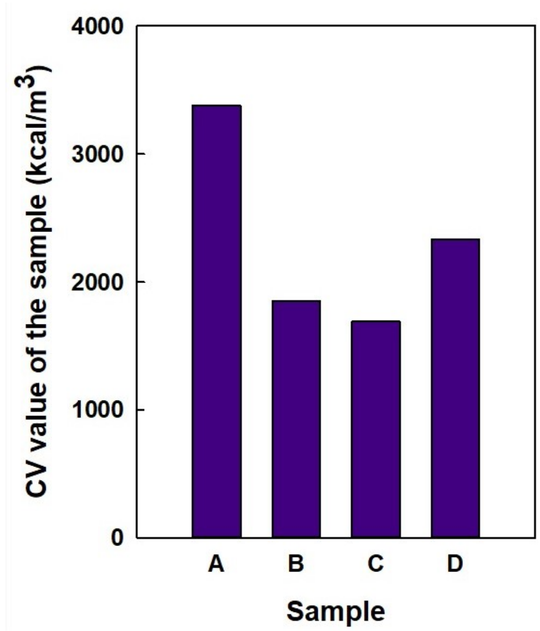

Figure 7: Heating Value of sample Graph

Digestate Management Analysis of Sample

Figure 8: Digestate Analysis with Crop Growth

DISCUSSION

The co-digestion of tire industry ETP filter sludge with food waste is a complex approach to bioconversion that takes advantage of the complementary nature of substrate properties to selectively optimize the methanogenic pathway and improve the overall thermodynamics of the process. Physicochemical characterization showed that filter sludge contains volatile solids 57.23% and VS /TS ratio 0.8062, the volatile content of filter sludge is biodegradable organic polymers that are prone to enzymatic depolymerization during anaerobic digestion under hydrolytic stages. This large proportion of readily mineralizable organic matter places filter sludge at the highest portion of the VS range of 40-70% of most effective substrate conversion and lowest proportion of recalcitrant residues that do not add any energy value to the digestate. A carbon-to-nitrogen ratio of 18.4:1 is thermodynamically optimum stoichiometry of syntrophic microbial consortia in sequential stages of anaerobic digestion. This ratio is close to what the theoretical best is with respect to methanogenic archea, which use carbon as cellular biosynthesis and energy metabolism but use nitrogen as protein synthesis and enzyme production. Excess or lack of the best C/N ratio of 15-30:1: Since the deaminated ammonia escapes into the archaeal membranes, thereby depleting proton motive force, a range of C/N values between 15-30:1 disrupts microbial homeostasis by either limiting nitrogen to proteins synthesis at prevailing ratios or due to ammonia toxicity, at the depression ratios. The naturally balanced stoichiometry of filter sludge makes the need to add external sources of carbon or nitrogen unnecessary, making the operational process more complex and eliminating the possibility of substrate inhibition effects with concentrated nutrient additions. The 6.8 pH gives the best environment of having redox potential gradients crucial in electron transfer between syntrophic bacterial partners as well as methanogenic archaea. Under anaerobic digestion, complex organic polymers are oxidized by hydrolytic and fermentative bacteria to volatile fatty acids, alcohols, and hydrogen to form reducing equivalents, which hydrogenotrophic methanogens must use to sustain thermodynamically favorable conditions to allow further oxidation of substrate. This interspecies electron transfer is pH sensitive and must be regulated to fine-tuning as methanogenic archea will have narrow pH optima of 6.5-7.5 in which carbonate buffering capacity is optimal and enzyme structures are intact. The system is in the optimal range of the two acetoclastic methanogens that utilize acetate to generate methane and carbon dioxide and hydrogenotrophic methanogens that utilize molecular hydrogen as the donor of electrons to reduce carbon dioxide at pH 6.8. In addition, this pH enables the activity of key methanogenic enzymes like methyl-coenzyme M reductase to reach an optimum activity as well as the enzyme is maximally active at 6.8-7.2. There is also inherent buffering capacity proposed by the constant pH, which offers stability on the fluctual accumulation of fatty acids during a rapid degradation of unstable organic matter, thus preventing a drop in the pH resulting in an inhibition of methanogenic activity and acidification of the system.

The trace metal analysis of filter sludge indicates levels that do not just stay below the cytotoxic levels, but are probably promoting kinetics of methanogenic activity by activating metalloproteins. The concentration of nickel of 12.2 mg/kg is within the range of concentrations that have been shown to promote the production of methane by up to 25 % by more actively involving nickel-dependent enzymes such as carbon monoxide dehydrogenase, acetyl-CoA synthase and methyl-coenzyme M reductase. These metalloenzymes play a significant role in acetoclastic and hydrogenotrophic methanogenic pathways and nickel is a prosthetic group of the active site which enables transfer of electrons and substrate binding. Zinc 194 mg/kg at the level supports carbonic anhydrase and other dehydrogenases that are involved in the intermediate metabolism, and copper 15.7 mg/kg may help to improve the cytochrome activity in electron transport chains. The synergistic interactions of various trace elements in sub-inhibitory concentrations may probably result in additive or synergistic effects on total activity of the methanogenic process since various metalloenzymes in one metabolic pathway function in a cascade manner, and sequential optimization of enzymatic activities in the whole pathway may result in disproportionate enhancement of overall flux. These were toxics such as cadmium at 0.15 mg/kg, lead at 4.7 mg/kg and mercury at 0.3mg/kg, which were infrequently toxic and did not exceed the thresholds that would cause membrane damage, enzyme active site disruption due to improper metal replacement, or produce reactive oxygen species in Fenton-type reactions. The comparative study of reactor designs through an experiment sheds light on general principles that dictate substrate biodegradation dynamics and the succession of microbial communities during anaerobic digestion. Reactor A that was solely food waste had a low level of lag phase and biogas was produced after day 1, as the food contained a high concentration of readily hydrolysable macromolecules (proteins, lipids, and carbohydrates) and low concentrations of recalcitrant structural elements. High kinetics of hydrolysis in this reactor were obtained, which resulted in vast the amount of volatile fatty acids that can be effectively converted into methane with 57.49% CH_4 content and 3376.2 Kcal/m^3 heating value. The high proportion of methane and low proportion of CO_2, 40.51 %, show that there is a high rate of carbon flux via acetogenic and methanogenic metabolism with few carbon wastes to carbon dioxide in the fermentative metabolism. This implies that complementation was contributed by acetoclastic methanogenesis that forms carbon dioxide and methane in a 1:1 ratio of acetate with hydrogenotrophic methanogenesis that lowers the amount of carbon dioxide to generate methane by using molecular hydrogen, which reduces the total emissions of carbon dioxide and enhances yield of methane. The blue steady flame seen at the time of testing combustion proves the little presence of higher hydrocarbons or sulfur compounds that would put out the fire or give colored emission. Complex cross-interactions between substrate characteristics and microbial ecology were found in the co-digestion systems to affect performance in the entire process. With the 1:2 ratio of food waste to filter sludge of 100:200g, reactor C generated the least quality of biogas that had 51.82% of methane, 46.18% of CO_2, and 1687.9 Kcal/m^3 heating value. Filter sludge prevalent in this mixture may also have imposed several performance constraints such as decreased access to readily hydrolyzable substrates, the possible presence of mass transfer constraints due to high solids concentration, and the possible presence of inhibitory intermediates due to incomplete oxidation of complex organic molecules. The high CO_2 percentage indicates that the carbon flux via fermentative routes generated large amounts of CO_2 which was not efficiently reduced to methane by hydrogenotrophic methanogens, possibly because of the limitation of the hydrogen mass transfer or unfavourable hydrogen partial pressures. Conversely, Reactor D which had 2:1 food waste to filter sludge ratio of 200g:100g showed the best performance with 56.26% methane, 41.74% CO_2 which was the lowest among all the reactor configurations and 2336.4 Kcal/m^3 heating value. This ratio of substrates apparently optimized several process variables simultaneously by offering a large amount of readily degradable organics in the form of food waste to support a high rate of microbial growth and metabolism and including sufficient levels of filter sludge to add trace elements, form microbial diversity and buffer against changes in pH conditions during volatile fatty acid production. The synergies underlying the improved co-digestion capacity include complicated biochemical and ecological interactions of the complementary properties of substrates. Food waste contains labile organic carbon with little recalcitrant matter, which allow the hydrolysis process to happen quickly and the abundant substrate of acidogenic and acetogenic bacteria that generate the direct products of the methanogenesis process. A large proportion of moisture (around 60-80 per cent) in food waste increases solubilization of the substrates and the mass transfer of soluble intermediates between microbial populations. Filter sludge brings adapted microbial consortia pre-acclimated to anaerobic conditions, a wide range of catabolic capability in degrading complex industrial organics, needed trace elements acting as enzymatic cofactors, and buffering compounds such as proteins and phosphates that stabilize pH in the rapid production of volatile fatty acids. These complementary properties were balanced in Reactor D by the 2:1 ratio which furnished adequate labile substrate to sustain high metabolic rates and sufficient filter sludge to optimize the trace element concentration, create sufficient microbial diversity to degrade a wide range of organic compounds and provide buffering capacity to avoid pH depression throughout the acidogenic period where the volatile fatty acid production rate may temporarily be greater than the methanogenic consumption rate.

Analysis of the metabolic pathway shows that the Reactor D is better due to the optimization of the electron flow by syntrophic interactions of fermentative bacteria and methanogenic archaea. In the first hydrolysis and acidogenesis stages, the complex organic polymers are undergone to depolymerization to monomers which are then oxidized to the volatile fatty acids, alcohols, carbon dioxide and molecular hydrogen. Low hydrogen partial pressures are required to ensure the thermodynamic viability of these oxidation reactions because increased hydrogen levels will make subsequent oxidation of substrates energetically inaccessible. Hydrogenotrophic methanogens like hydrogen sinks are oxidized by H_2 to lower the CO_2 to methane ratio, and keep the thermodynamic conditions conducive to further oxidation of the substrate by fermentative bacteria. The 2:1 food/filter sludge ratio of Reactor D apparently created optimal conditions that would sustain this syntrophic metabolism through the provision of high-energy electron donors or food waste oxidation and the provision of high concentrations of trace elements or filter sludge to support the activities of high concentrations of methanogenic enzymes to ensure efficient hydrogen turnover and avoid metabolic bottlenecks. The analysis of flame colour gave qualitative mechanistically informative validation of the composition and purity of biogas. The high, stable, blue flames of Reactors A and D are evidence of almost complete methane combustion without any significant luminous particle formation (carbon particles) and potentially high methane purity and low concentration of higher hydrocarbons, hydrogen sulphide or other impurities that would change flame properties. The blue flame colour is due to emission of light with wavelengths at the electronic transitions of excited CH and C_2 radicals in the combustion of methane at high temperatures. There is no yellow luminosity, which shows there was little soot generated because higher hydrocarbons were not completely burned or subjected to pyrolysis. Reactor B had occasional yellow flickering, indicating the occasional presence of substances that formed carbon particles during combustion, which could possibly be due to pyrolysis of trace levels of higher molecular weight hydrocarbons or aromatic compounds formed by industrial organics in filter sludge. The fact that the traits of the flame correlate with the measured contents of methane confirm the validity of the analysis measurements and the fact that differences in biogas quality across the configurations of the reactor are genuine compositional changes as opposed to artifacts of analysis.

Thermodynamic analysis shows that the values of biogas heating are directly correlated to the content of methane and the density of energy. Methane has a higher heating value of about 890 kJ/mol (essentially zero in the case of carbon dioxide) and hence the fraction of methane is the major determinant of volumetric energy content. Reactor A had the largest heating value of 3376.2 Kcal/m^3 and the lowest heating value of 1687.9 Kcal/m^3 respectively, with the highest and the lowest methane content of 57.49% and 51.82% respectively. A heating value of 2336.4 Kcal/m^3 of Reactor D corresponds to 69% of the theoretical maximum suggesting that methanogenesis pathways have been optimized significantly but not completely. Additional refinements could be possible by modifying the operation such as increasing the hydraulic retention time to enable greater conversion of substrates, optimization of temperature to increase enzymatic reaction rates, or addition of other trace elements to induce more methanogenic enzyme activities. These economic and environmental consequences of the findings are not limited to the waste valorisation, but they include core principles of the industrial ecology and the implementation of the circular economies. Turning filter sludge, which is a waste liability and must be disposed of at considerable expense, into a feedstock to generate renewable energy provides a variety of value streams such as eliminated disposal costs, generated renewable energy substituting fossil fuel use, lower greenhouse gas emissions through avoided land filling and fossil fuel displacement, and the production of renewable energy by-products in the form of fertile digestate which could be used as agricultural fertilizer. The strong physicochemical properties of filter sludge such as optimum C/N ratio of 18.4:1, good pH of 6.8, desirable trace elements and high volatile solids content of 57.23% make it a drop-in substrate that has a small amount of preprocessing or supplementation needed, capital costs and operation costs are minimized to implement it in industries. The proven usefulness of post-digestion digestate as agricultural efficacy indicated by the increase in seedling growth in terms of leaf surface area and plant height, is an added value, since it is able to replace synthetic fertilizers that require energy-intensive industrial processes. This multi-product biorefinery model is an illustration of the idea of a circular economy, as it is a closed loop system, the entire material is reused, and material that can be derived as waste is used to generate several sources of revenue.

However, as a considerable factor, when anaerobic digestion sludge or derived filter sludge is applied to agricultural land as a soil amendment, heavy metals and trace elements retained in the solid phase may be gradually released into the soil matrix through mineralization, leaching, and repeated land application. Over prolonged application periods, these metals can accumulate in soils and may enter the food chain via plant uptake, particularly in the case of zinc, nickel, copper, and chromium. Therefore, although the measured concentrations in the present study were below inhibitory levels for methanogenesis, appropriate management practices, application rate control, and periodic monitoring are essential to minimize the risk of long-term heavy metal accumulation in agricultural fields.

CONCLUTION

This overall research of the co-digestion of food waste and tire industry effluent treatment plant (ETP) filter sludge has shown a high potential in sustainable management of the waste and also in renewable energy production. The study has been successful in confirming that filter sludge which was a waste liability lesson attracting a cost that would have required to be disposed was successfully converted into a useful biogas production raw material through an anaerobic digestion process.Physicochemical characterization of filter sludge found out that the properties were very favorable to the anaerobic digestion. The solids content of the substrate is 57.23% volatiles (volatiles solids) and 71% total solids and, therefore, the substrate has an abundance of biodegradable organic material. The carbon to nitrogen ratio of 18.4:1 is in the optimal 15-30: 1 ratio suggested to support the process of methanogenesis, and the nutrient supplementation is not necessary and minimizes the cost of operation. The pH is nearly neutral (6.8), which gives the optimum environment to methanogenic archaea and acidogenic bacteria so that the processes remain stable during the entire digestion time. Most importantly, heavy metal analysis proved that zinc (194 mg/kg), nickel (12.2 mg/kg), copper (15.7 mg/kg) and chromium (15 mg/kg) were not present at levels that inhibited the performance of the methanogenic enzymes but acted as beneficial cofactors which could increase biogas production up to 25 % as confirmed in the past literature.The 18-day experimental analysis of four reactor systems was very convincing in terms of substrate optimization. Reactor A (food waste only) recorded the highest content of methane of 57.49 % with a heating value of 3376.2 Kcal/m^3 showing that food waste is more biodegradable. The reactor B (filter sludge only) generated 47 ml of cumulative biogas containing 55.31 % methane and 1852.1 Kcal/m^3 heating value, thus validating that filter sludge alone can be used as a viable substrate even though it has longer lag phases. The results of the co-digestion systems showed that the Reactor D, which employed a ratio of 2:1 of food waste to filter sludge (200g:100g) produced the best results of 50 ml biogas, 56.26% methane composition, 2336.4 Kcal/m^3 heating value, and the lowest concentration of carbon dioxide; 41.74%. Such a setup had faster biogas production dynamics as well as sustained yields, which were the most balanced system in terms of implementation on an industrial scale. The compositional data was supported by the flame colour analysis, with Reactor A and D generating stable blue flames that signified good quality, methane-rich biogas that could be used in direct energy production. The comparatively small difference in the cumulative biogas volumes end result, as was found in all reactors (4750 mL), indicates that ultimate biogas potential is not affected by substrate composition, but rather differentiation and quality vary greatly, depending on substrate ratios.

A key novelty of this study lies in demonstrating that tire industry ETP filter sludge, traditionally regarded as a disposal liability, can be valorized as a functional co-substrate in anaerobic digestion without the need for external nutrient or trace metal supplementation. Unlike previous studies that primarily treat heavy metals as inhibitory agents, this work provides experimental evidence that zinc and nickel present in the filter sludge act as beneficial catalytic cofactors for methanogenic enzymes, enhancing methane production while simultaneously enabling an effective industrial waste management solution.

In addition to energy recovery this study proves the agro-economic value of post-digestion digestate which is confirmed through the use of experimental seedling growth tests which showed better growth of the plant, especially with filter sludge digestate, which is exhibited by the increase in leaf surface area and plant height, in contrast to the control samples. It has several strategic benefits to the integration of filter sludge into anaerobic digestion systems: by-passing landfills, and thereby protecting the environment and greenhouse gases, renewable energy generation, which replaces the reliance on fossil fuels, eliminating the large disposal charges, and generating biofertilizer rich in nutrients, which contributes to the sustainability of agriculture. The results create a strong foundation of using the principles of a circular economy in the tire production industry and changing the two types of waste into useful energy and farm products. When the 2:1 ratio of food waste to filter sludge is optimized and the operation parameters are controlled, industrial-scale biogas plants may provide cost effective and sustainability considerate solutions to waste management, which will play a major role in energy security and sustainability processes in the tire industry and its associated industries.

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ISSN 1391-0256

Journal of the Sri Lanka Association for the Advancement of Science

Volume 7 Issue 2

Edited and Published by the Sri Lanka Association of for the Advancement of Science

ISSN 1391-0256

9771391025002