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CONTENTS

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RESEARCH ARTICLE

Enhancing Municipal Solid Waste Management in Rapidly Urbanizing Areas: A Case Study of Rudrapur City, India

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Abstract

Urban solid waste management is a crucial challenge, involving treatment, recycling, and energy conversion for environmental and public health protection. This research explores the management of municipal solid waste in the city of Rudrapur, located in the Himalayan foothills, in the midst of rapid urbanization and industrial development. Rudrapur is confronted with an increasing waste production as a consequence of its expanding population. The study examines waste distribution, evaluates current practices, and proposes effective waste management solutions for local governance. Using secondary data, interviews, and fieldwork, the study assesses waste generation, collection, transportation, processing, and disposal. The waste, comprising biodegradables, recyclables, and non-recyclables, presents challenges like inadequate equipment, unregulated dumping, and inefficiencies. Composite scores reveal disparities in waste management among city wards, uncovering infrastructure and practice gaps. Recommendations include source segregation, expanded composting, improved waste processing, and public awareness. Modern techniques like Geographic Information Systems (GIS) and remote sensing can enhance waste management strategies. The study underscores the urgency of addressing improper waste disposal's environmental and health impacts. By tackling deficiencies and embracing innovation, Rudrapur can transition to a sustainable solid waste management system, fostering a cleaner and healthier urban environment.

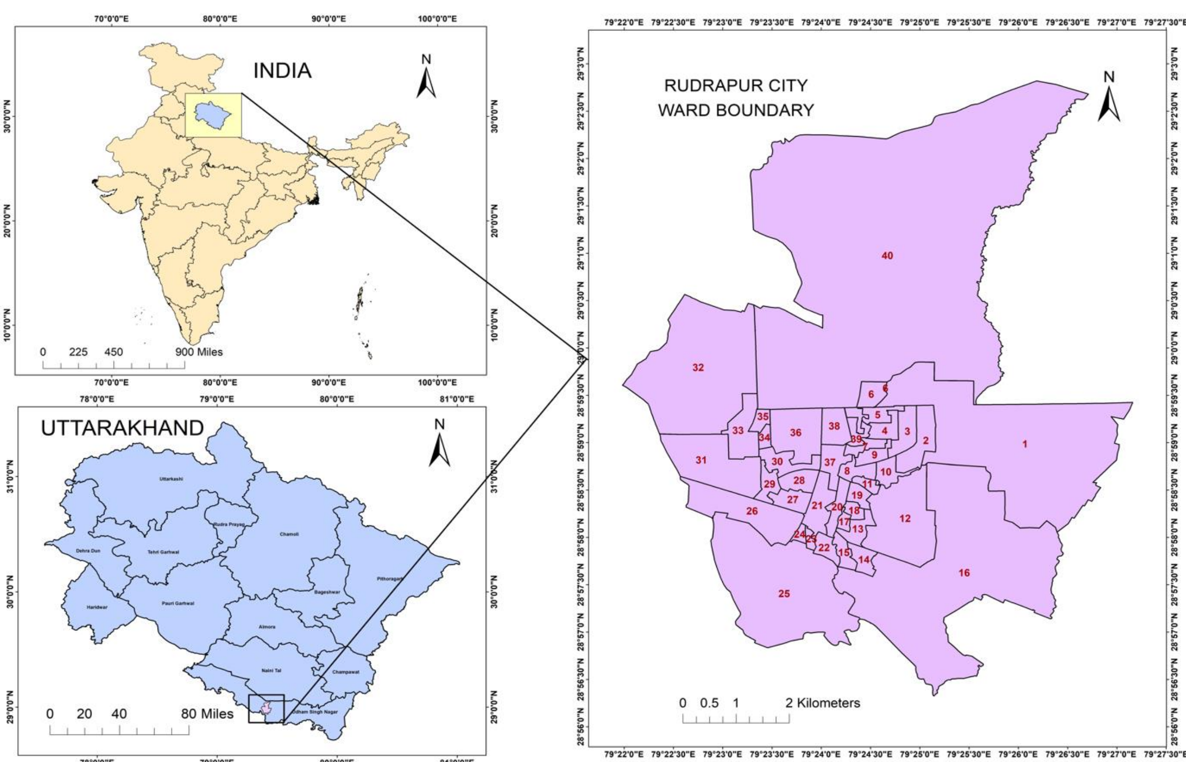
Keywords: Municipal Solid Waste; Urbanization; Environmental issue; Rudrapur City

Introduction

Solid waste management means managing the operation of processes to treat, dispose, reuse, recycle and convert solid waste into energy without adversely affecting the environment and public health. Solid waste means those hard things used in our homes, industries, offices, schools etc., which we simply throw away after a single use, which are neither fault nor rot with time. Municipal solid waste is defined as any waste generated by households, commercial and institutional activities and is not hazardous. There are thousands of such products, such as glass, plastic items, electronic items, medical series and medicine vials, etc., which once used remain in the same state for years. Vegetables, fruits, plant leaves, cow dung etc. used in our homes are converted into manure after some time. Whereas there is no clear system of disposal of solid goods waste. Due to this they not only make many acres of land barren but also increase the pollution in the land and air. The main objective of solid waste management is to make the maximum amount of waste capable of being reused or converted into manure through the plant. Using this waste properly, electricity can be generated. Also, the acquisition of large amount of land can be stopped. In this race of urbanization, industrialization and economic development, we have made such instruments and means, which have given us immediate happiness, but there is no clear action plan for its disposal. In recent years, there has been a rapid increase in the generation of solid waste in India. According to the "Swachhata Sandesh Newsletter" released by the Ministry of Housing and Urban Affairs (MoHUA), as of January 2020, a daily amount of 147,613 metric tonnes (MT) of solid waste is produced, spread across 84,475 wards. Projections indicate that urban areas in India will produce 2,76,342 tonnes per day (TPD) of waste by 2021, 4,50,132 TPD by 2031, and a substantial 11,95,000 TPD by 2050, as outlined in the planning commission report of 2014. Among the states, Maharashtra exhibits the highest generation rate, reaching 22,080 MT per day from 7,322 wards, while Sikkim has the lowest rate, generating 89 MT per day from 53 wards. In Uttarakhand, the daily generation stands at 1589 MT across 1170 wards, according to MoHUA's data in 2020. Main objectives of this paper are as follows:

- To study the distribution of generated and processed solid waste in the city.
- To assess the current scenario of existing process of municipal solid waste management in Rudrapur city.
- To suggest the effective framework for waste management to the local government.

Fig.1: Location Map of Rudrapur City



Source: drawn by authors

Research has been conducted within the Rudrapur city. It is situated in the foothill region of Uttarakhand, a Himalayan state in India. Currently, the city spans a total area of 55.22 square kilometers, positioned between 28°55' to 29°4' north latitude and 79°22' to 79°27' east longitude. It lies in the fertile Terai region, with Uttar Pradesh to its south and the Pantnagar Technology region to its north. Rudrapur is the second most populous city in Kumaun, with its population increasing from 88,815 in 2001 to 1,54,554 in 2011. On February 28th, 2013, it was elevated from a Nagar Palika Parishad to a Nagar Nigam. In 2011, the city covered a total area of 27.65 square kilometers, and in 2018, both its area and population saw growth due to the inclusion of 11 additional villages within its boundaries. As of 2018, the Municipal Corporation Rudrapur is divided into 40 wards, with a population of 175,723 following the delimitation process.

Literature Review

Banerjee, P. et al. (2019) provide an overview of the solid waste management challenges in India. It discusses the various types of solid waste generated, including municipal solid waste, e-waste, radioactive waste, agriculture waste, and hospital waste. The paper highlights the environmental and health concerns associated with improper waste management, such as groundwater contamination, pollution, and the spread of infectious diseases. It emphasizes the need for effective waste management methods, ranging from conventional techniques to modern approaches like refuse-derived fuel, pyrolysis, and incineration, while also discussing their advantages and limitations. Overall, the paper underscores the significance of addressing solid waste management issues in India for environmental safety and public health. Khan, M.H (2018) emphasizes the need for an integrated solid waste management approach in Dehradun, employing public-private partnerships. It highlights the growth in urban population, industrialization, and the challenges faced by the municipal corporation. He also mentions existing rules and provisions, the role of the government, and various studies that recommend sustainable waste management practices. It proposes a strategy involving door-to-door collection, recycling, composting, energy generation, and more, with a focus on evaluation and sustainability. Ultimately, it stresses the importance of improving solid waste management in India for public health and environmental well-being.

Methodology

The data of this paper were collected through secondary sources: the secondary data were available in the Rudrapur Muncipal Corporation, government documents, books, research papers as well as in the websites. A detailed investigation was done regarding the methods of collection, generation, transportation, disposal of solid waste by personal interview session with sanitary inspector of Rudrapur Municipality. The personal observation of the city environment has also done by authors. In order to examine disparities in the levels of solid waste management in wards of the city some variables were considered and analyzed by using Z-score technique (Gallardo et al., 2012 & Miezah, K. et.al, 2015…..). The value of different indicators according to our need were standardized with the help of the following formula:

$$Zi = \frac{Xi - X}{SD}$$

Where,
Zi= Standard score for the ith observation,
Xi=Original value of the observation,
X=Mean for all the values of X, and
SD=Standard deviation of X

The Z-Scores of all the variables were summed ward-by-ward in the second stage, and the average was then calculated for these indicators, resulting in the Composite Score (CS) for each ward, which can be mathematically stated as:

$$CS = \sum Zij/N$$

Where, CS stands for composite score.
N refers to the number of variables.
$\sum Zij$ indicates Z-Scores of all variables i in ward j.
The analysis of collected data were processed in the computer with the help of EXCEL & MS Word softwares. Open-source software (QGIS) is used for diagrammatic representation of data.

Results and Discussion

The city of Rudrapur is grappling with inadequate solid waste management challenges attributed to swift industrial growth, urban expansion, and insufficient financial resources. As the table 1 shows that in 2041 the population would be three times of the 2011 and in upcoming years municipal waste will generate at very high rate.

Table:1 Projected population and MSW status in the city

city	**population**		***MSW status**	
Rudrapur	2011	2041	2017 (@300gcpd*)	2041 (@400gcpd*)
	154514	404705	46.35	161.88

Source: SWM action plan, final draft (Govt. of uttarakhand)2017.

*MSW- Municipal solid waste *gcpd- generation capita per day.

Within Rudrapur City, the tasks linked to the handling of municipal solid waste, spanning from its creation to ultimate disposal, can be categorized into four distinct operational components:

- Generation of municipal solid waste
- Collection of waste
- Transportation of solid waste
- Processing and Disposal of solid waste

Generation of Municipal Solid Waste: According to the 12th Schedule of the 74th Constitution Amendment Act of 1992, urban local bodies (ULBs) are responsible for keeping cities and towns clean. Daily door to door garbage is collected from all the wards covering individual household, bulk waste generator, residential welfare association, hotels and other commercial organizations. On an average, daily approximately 65-70 MT of waste is generated in the city.

Table: 2 Category wise waste generation in Rudrapur City, 2021

Waste category	**Quantity (MT/day)**	**Percentage of waste**
Bio-degradable waste (collected from households, bulk waste generators, parks etc.)	26.00	40
Recyclable waste	19.50	30
Construction/demotion waste	6.50	10
Drain silt	9.75	15
Street sweeping	3.25	05
Total	65 MT/day	100

Source: Municipal corporation, rudrapur.2021

Fig.2 Category wise waste Generation in the city ,2021

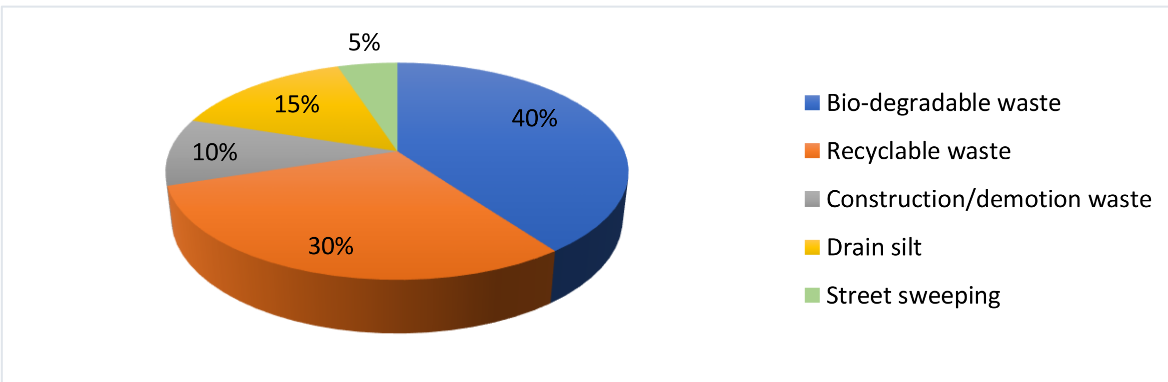


Table 3 indicates that there are only two wards vivek nagar and khera southern that comes under very low category of waste generation . The four wards of the city which fall under the very high category of waste generation/month named as Gandhi colony, aadarsh colony SRA, Alliance colony, Aadarsh Indira colony.(fig.3). This difference of solid waste generation between the wards depends on the lifestyle of the people living there.

Collection of Waste: At present, each city has a different system for the collection of waste. A city has its own municipality which performs this function through community dustbins placed at various places along the roads for the collection of garbage in the city. For the purpose of solid waste collection, necessary number of sweepers have been appointed in the Municipal Corporation Rudrapur and they have been provided with rickshaw tractors and others which can help in garbage collection.

Street sweeping is done by the sweepers from 6:00 to 10:00 a.m. daily with the help of hand rikshaw. They collect garbage from street sides and roads and dump it in nearby the dumping sites and then transport it is picked up by tempos, tractor , trolleys and dumped in open sites outside the city.

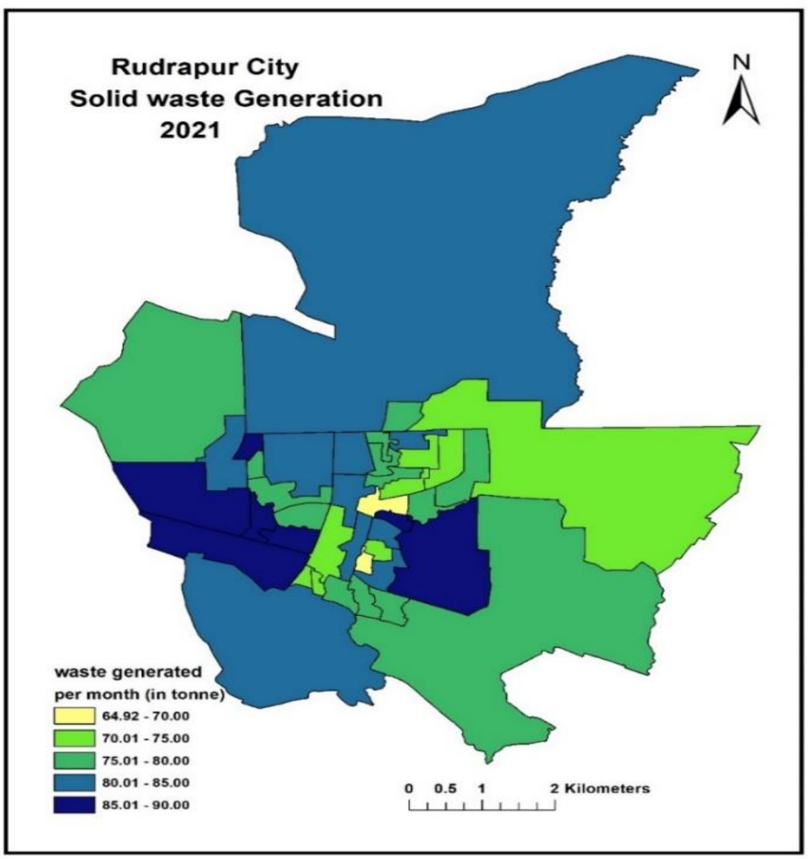
For collection of garbage ,10 tempos run according to their specific routes daily within the city. These tempos collect door to door garbage into two shifts. First shift from 7:00 to 12:00 noon and second shift from 3:00 to 6:00 p.m. with this arrangement, all shopkeepers of the market and houses are requested not to dump garbage on road side or in the drains, but to dump it directly in municipal owned tempos. And finally all collected garbage dumped in open dumpsite which is situated on NH-74 , mohalla pahadganj in Rudrapur.

Table:3 Rudrapur City: Level of waste Generation/month (tonne)

Category	Waste generated/month (tonne)	No. of wards	Name of wards
Very low	64.92-70.00	2	Vivek nagar, khera southern
Low	70.01-75.00	8	Funlsungi, transit camp central and western, shiv nagar, khera middle, bhutbangla west south, Rampura middle, Rampura western
Moderate	75.01-80.00	13	Transit camp east, jagatpura, ajad nagar, raja colony, bhadaipura, paharganj, bigwarha, Rampura east, main market, D1 D2, bhurarani, Indira colony, awas vikas east
High	80.01-85.00	13	Mukerjeenagar, Sanjay nagar, industrial area, dudia nagar, khera north, bhutbangla northeast, fajalpur mahraula, seergotia, singh colony, aadarsh colony ghas mandi, Kalyani view, awas vikas west
Very high	85.01-90.00	04	Gandhi colony, aadarsh colony SRA, Alliance colony, Aadarsh Indira colony

Source: data compiled on the basis on Nagar Nigam Rudrapur,2021

Fig.3 ward wise waste generation,2021



Transportation of Solid waste: The transportation of waste is done through Trucks tripper, Compactors, drain cleaning machine and Tractor, Dumper placer , Rickshaws, J.C.B and plastic compactor. Table:2 reveals the machinery and functional unit which are currently using for the transportation for solid waste in the city. The city also needs few more new equipment's for the collection of waste.

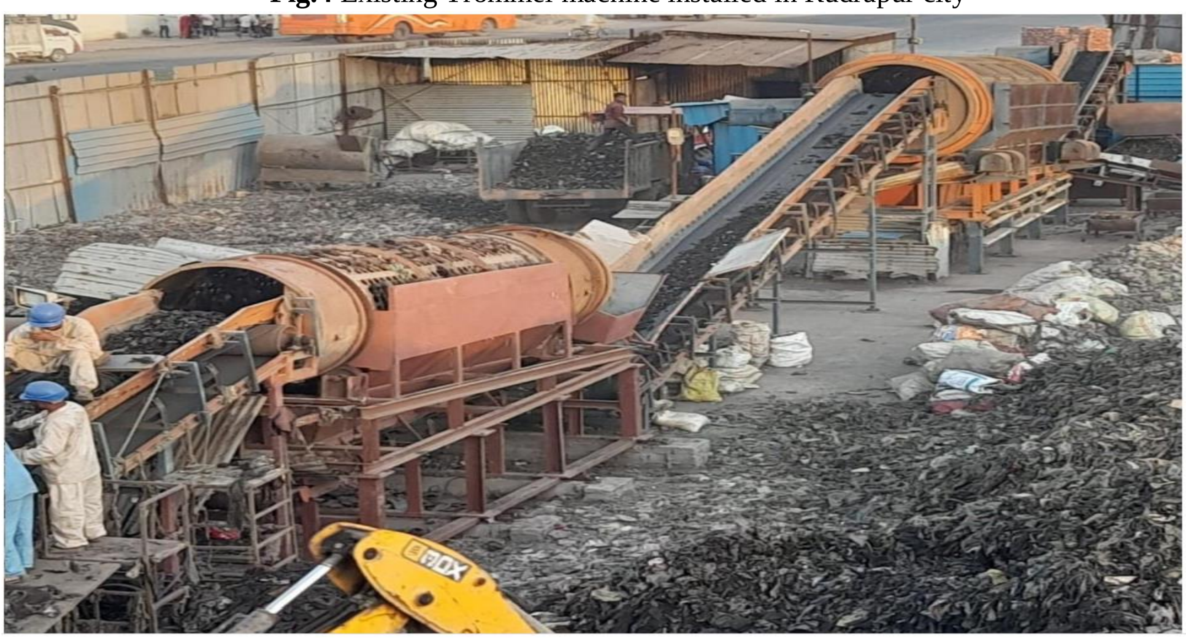
Table:4 Municipal Functional unit for lifting and transportation of solid waste in Rudrapur City, 2021

Equipment	Total numbers
Truck tripper	04
Small tripper	40
Compactor vehicle	03
Refuse collector bins	150
Dumper placer	01
Dumper placer bins	10
Drain cleaning machine	01(under maintenance)
Rickshaws	100
Tractors	07
J.C.B.	05
Plastic compactor	01

Source: Municipal Corporation, Rudrapur.2021

Processing and Disposal of Solid waste: Municipal solid waste dumpsite in rudrapur is located in NH-74 mohalla paharganj at the distance of 1 km from the Nagar Nigam Rudrapur office and it covered 4.04 hectares area. The whole municipal waste is dumped at this place without any segregation. In the absence of landfill or other protected places, the entire MSW is transported to the Rudrapur dumpsite since last 2 years. Existing dumpsite is having Trommel Machine for processing of Municipal waste at dumping site. This trommel plant was inaugurated on 17 july 2020.

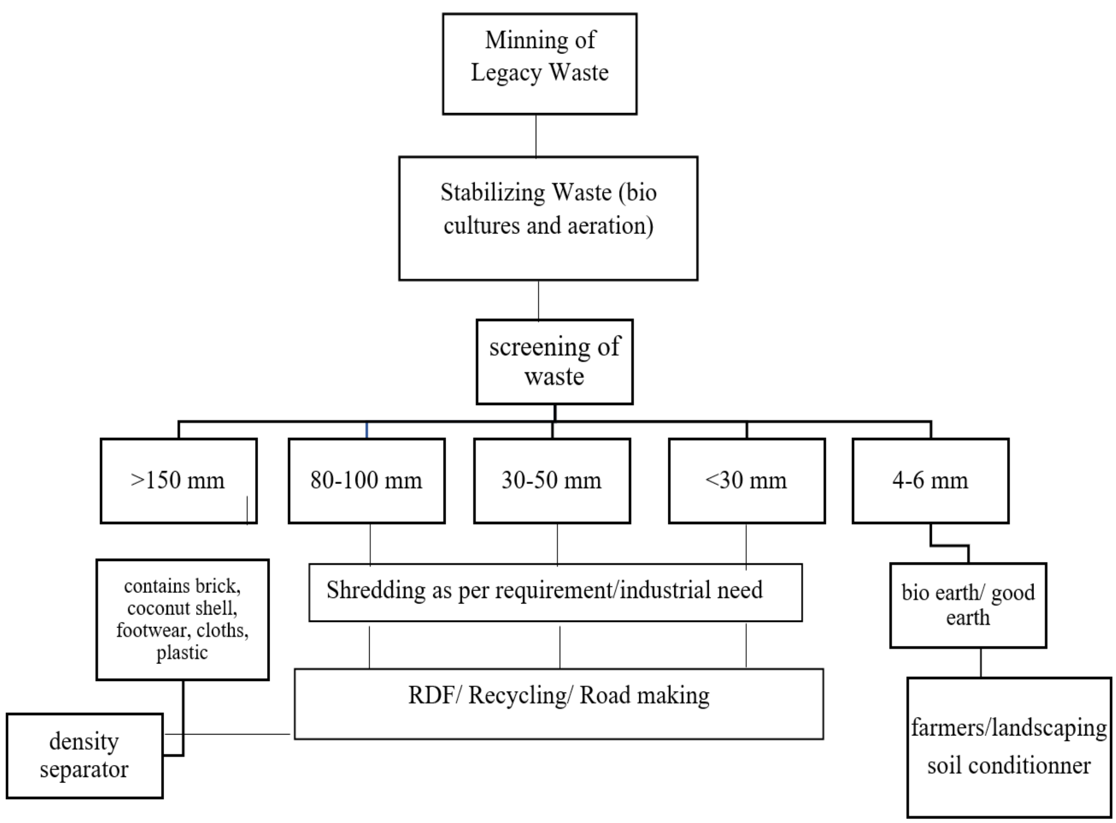
Fig.4 Existing Trommel machine installed in Rudrapur city



The treatment and disposal of solid waste is done by bio-minning process. The biodegradable waste is processed into compost. MSW dumpsite at Rudrapur waste is a mix waste dumpsite. In existing technologies only two models are suitable for waste i.e. Bio Mining/ Landfill Mining. Bio mining remediation is most suitable and opted after detailed analysis of waste. Silent features of Bio-Mining are-

- Attain a complete 100% retrieval and recycling of waste
- Employ an alternative source of fuel from rejected waste
- Enhance the available space for post-closure utilization, whether for a new scientifically managed landfill or for alternate purposes
- Achieve minimal emissions of methane and leachate, nearly reaching zero levels
- Clear out old waste sites at a fraction of the cost compared to traditional capping methods, thereby significantly reducing annual expenses related to landfill management, leachate treatment, and gas monitoring
- Considerably decrease the volume of old waste requiring permanent burial and the corresponding land requirement
- Promote the recycling of both organic and previously buried recyclable materials
- Avoid incurring insurance costs and potential legal obligations linked to capped sites susceptible to explosions
- Eliminate any issues of pollution or potential environmental hazards for future generations.

Fig.5 Flow chart to Bio- remediation process of Municipal waste



Source: CPCB, Feb,2019

Fig.6 Waste dumpsite near NH-74 mohalla paharganj in Rudrapur. picture dated 13/may/2022.

Fig.7 burning waste near dumpsite, picture dated 13/may/2022.

Solid waste Management: Level of solid waste management in Rudrapur City was measured on the basis of three variables, number of hand rickshaw per thousand-person, number of dustbins per thousand person and number of garbage truck per thousand people in each ward.

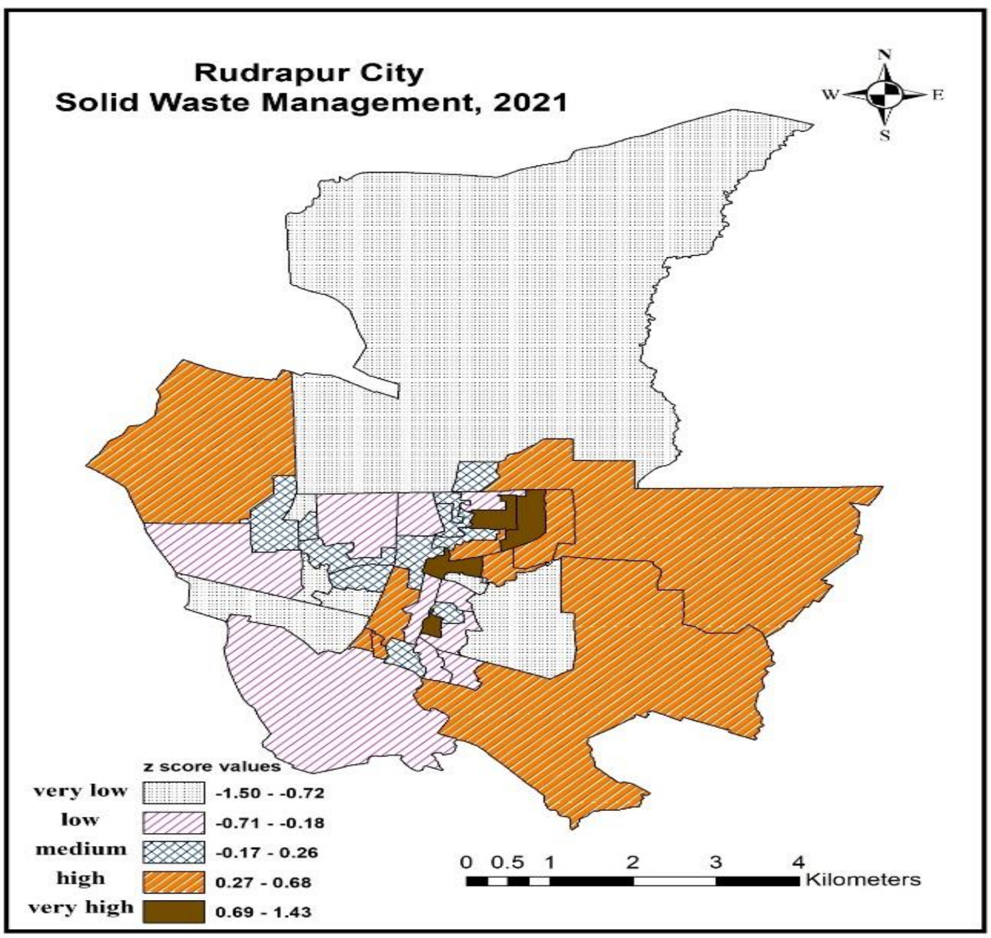
Table:5 Ward wise development of waste management in the city,2021

Level of development	Composite z-score	No. of wards
Very low	-1.50 to -0.72	07
Low	-0.71 to -0.18	10
Medium	-0.17 to 0.26	10
High	0.27 to 0.68	09
Very high	0.69 to 1.43	04

Source: data compiled by author and taken from municipality office of Rudrapur.

Table 5 shows that, the highest value of 1.43 for solid waste management is scored by the khera southern, whereas, the lowest value of -1.5 by SIDCUL ward. 07 wards of the city have inadequate waste management. Several places have large garbage heaps, and dustbins are not kept in the proper locations. Medium level of solid waste management is seen in 10 wards. Small heaps of garbage and filled dust bins are seen almost on every road. Numbers of sweepers are less in number. They are not provided with the needed number of rickshaws and equipment's for the garbage collection. there are 04 wards with very high level of development. Most of them are located in the center of the city, where garbage collection is done on a regular basis.

Fig.8 Ward wise Solid Waste Management in the city,2021



Serious Environmental issues in the study area due to open dumping

Uncontrolled and continuous dumping of solid waste by the Municipal Corporation Rudrapur has created mountains of garbage. After three decades of neglect, it has become a major source of pollution. Waste rotted heaps produces leachate, and dark liquid leaking from the heaps kills surroundings vegetation and irreversibly pollutes groundwater. Garbage dumps also produce methane and a greenhouse gas that causes global warming 21 times more than carbon dioxide. Apart from this, the air quality gets polluted which gets worse due to frequent incidents. It was observed during the field visit that near the dumpsite garbage was being burning. The burning of dumped solid waste is a common practice and creating drastic air pollution as shown in figure 7.

Conclusion

Through the course of the investigation, it has become evident that the efficacy of the solid waste management system in Rudrapur is compromised due to the rapid surge in population, industrial expansion, and deficiencies in administration, legislative enforcement, and financial resources. The unregulated disposal of solid waste alongside roadways is a prevailing issue. These open dumps contribute to the obstruction of drainage systems, the proliferation of flies, and the propagation of contagious diseases. The existing solid waste management framework in Rudrapur proves inadequate due to the absence of proper equipment and funding. The unfavorable ecological consequences stemming from improper waste disposal practices are readily observable. Although Rudrapur possesses a Trommel plant, its capacity of 200MT per day falls short of accommodating the city's entire waste output. Given the current circumstances, it appears unlikely that the plant processes such a substantial volume of waste daily. Moreover, hazardous waste materials from hospitals and other sources are treated as standard waste, a practice that warrants cessation due to its adverse environmental implications arising from open dumping and incineration of waste.

The following recommendations may be incorporated with a view to improve the existing MSW Management:

- To reduce the load on the dumping site, it is necessary to install other composting plant and machine.
- There should be segregation system at source of waste generation point so that Hospitals and other hazardous waste should be process separately.
- Presently, dumpsite is situated along roadside which is environmentally harmful. The garbage should be dumped at an open place away from the city.
- Ongoing surveillance and the systematic accumulation of data are imperative when designing a streamlined solid waste management (SWM) structure.
- The strategic plan aimed at achieving sustainable SWM should spearhead a shift in the behaviours of residents, elected officials, and policymakers to curtail waste generation and elevate recycling and reutilization efforts.
- Embrace contemporary methodologies and technologies such as remote sensing and Geographic Information Systems (GIS) for the comprehensive evaluation of SWM processes.

Declaration statement

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Funding: None

Conflict of Interests: The authors declare no conflicts of interest related to this research.

Authors contribution: Sonu Kaur conducted an extensive review of existing literature, gathered pertinent data through field surveys, and made valuable contributions to the analysis and interpretation of the collected information. Additionally, she was involved in the writing and editing of the manuscript.

Anjali Punera provided comprehensive direction and contributed significantly to shaping the study, playing a pivotal role in crafting the research methodology and analysis.

Data availability: The data utilized in this study were sourced from multiple outlets; including the Rudrapur Municipal Corporation office, government documents, research papers, and various websites. A comprehensive investigation was conducted to understand the methods involved in the collection, generation, transportation, and disposal of solid waste. This investigation included personal interviews with the sanitary inspector of Rudrapur Municipality. Additionally, the authors conducted firsthand observations of the city's environment.

References

Al-Ghouti, et.al (2021). “Recent advances and applications of municipal solid wastes bottom and fly ashes: Insights into sustainable management and conservation of resources”. Environmental Technology & Innovation, ELSEVIER, 101267. https://doi.org/10.1016/j.eti.2020.101267.

Banerjee, P. et.al (2019). Solid Waste Management in India: A Brief Review. Waste Management and Resource Efficiency (pp.1027-1049). © Springer Nature Singapore Pte Ltd. DOI:10.1007/978-981-10-7290-1_86.

CPCB (2014). Guidelines for Common Bio-medical Waste Treatment Facilities, Revised draft, Central Pollution Control Board, Delhi.

Gallardo et al., (2012). Analysis of collection systems for sorted household waste in Spain. Waste management, Elsevier. Volume 32, Issue 9, Pages 1623-1633. https://doi.org/10.1016/j.wasman.2012.04.006.

Goel, Sudha (2008). “Municipal Solid Waste Management in India: A Critical Review,” Journal of Environment, Science and Engineering, vol. 50, no.4, p.p 319-328.

Khan, M. H, (2018). Implementation of Integrated Solid Waste Management through Public Private Partnership in Dehradun Town. http://dx.doi.org/10.2139/ssrn.3295837.

Mani, Shyamala et.al (2016). “Sustainable Municipal Solid Waste Management in India: A Policy Agenda,” International Society of Waste Management, Air and Water, p.p 206-213.

Miezah, K. et.al, (2015). Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. Waste management, Elsevier. Volume 46, December 2015, Pages 15-27. https://doi.org/10.1016/j.wasman.2015.09.009.

Ministry of Housing and Urban Affairs, (2020). “Swachhata Sandesh Newsletter”.

Ministry of Housing and Urban Affairs, Annual report 2020-21.

Nwofe, (2015). “Management and Disposal of Municipal Solid Wastes in Abakaliki Metropolis, Ebonyi State, Nigeria”, International Journal of Scientific Research in Environmental Sciences, ISSN: 2322-4983; 3(3), pp. 0107-0118, http://dx.doi.org/10.12983/ijsres-2015-p0107-0118.

Planning Commission, (2014). “Report of the Task Force on Waste to Energy”.

Satpal Singh (2020). “Solid Waste Management in Urban India: Imperatives for Improvement” ORF (Observer Research Foundation) Occasional Paper No. 283.

Solid Waste Management action plan, (2017). final draft (Govt. of uttarakhand).

https://www.cpcb.nic.in/uploads/LegacyWasteBiomining_guidelines_29.04.2019.pdf. Accessed on 25 may 2022.

https://udd.uk.gov.in/, accessed on 15 june 2022.

https://www.nagarnigamrudrapur.com/, accessed on 10 may 2022.

REVIEW ARTICLE

A review of tropical blue carbon ecosystems for climate change mitigation

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Abstract
Tropical blue carbon ecosystems encompass several components such as mangroves, seaweed, and seagrass, which play a crucial role in delivering a diverse array of services including regulation, provisioning, cultural, and support functions to a significant human population. The preservation and rehabilitation of tropical marine ecosystems hold significant importance for society due to the adverse consequences associated with their degradation, which include the impairment of crucial services such as coastal protection and the provision of seafood resources. Nonetheless, a significant knowledge deficit persists about the comprehensive capabilities of blue carbon ecosystems in terms of mitigating climate change and delivering socio-economic advantages. Hence, the primary objective of this study is to critically examine the economic significance of ecosystem services rendered by blue carbon habitats, along with the associated obstacles, governance mechanisms, and conservation approaches employed to address climate change mitigation through these ecosystems. The integration of blue carbon ecosystems conservation, protection, and restoration should be prioritized within mitigation and carbon stock conservation plans across local, national, and global scales. This article reviews various forms of governance, such as market-based instruments, public investment, partnership initiatives, and community-based management, that have the potential for future implementation. In a broader context, safeguarding tropical marine habitats is an ecological necessity that warrants recognition as a potential avenue for generating more cash and alleviating national debts across various countries. This review paper presents a comprehensive overview of the existing knowledge regarding severely degraded tropical blue carbon ecosystems, with the aim of offering a structured framework that can be utilized by stakeholders to facilitate their efforts in restoring these ecosystems.

Keywords: Blue carbon; Climate change; Ecosystem services; Restoration; Conservation; Governance

Introduction

Blue carbon ecosystems play a significant role in mitigating climate change by sequestering surplus carbon from the atmosphere (Bandh et al., 2023). According to the Intergovernmental Panel on Climate Change (IPCC), blue carbon encompasses all carbon fluxes and storage in marine systems that are biologically driven and may be effectively managed. The primary emphasis has been placed on the examination of terrestrial vegetation within the coastal region, including tidal marshes, mangroves, and seagrasses (Ouyang et al., 2023).
Table 1 and Figure 1 depict the worldwide dispersion of blue carbon ecosystems. The preservation and rehabilitation of coastal blue carbon ecosystems yield significant societal advantages due to their augmentation

of ecosystem services, including the maintenance of biodiversity and the availability of seafood (McHenry et al., 2023; Quevedo et al., 2023). Blue carbon sequestration is regarded as a nature-based approach to address the prevailing climate crisis. This is due to the fact that marine vegetated habitats play a crucial role in enabling society to adapt to climate change by safeguarding coastal regions against the escalating frequency of storms, rising sea levels, and coastal erosion. However, it is worth mentioning that the efficacy of restoring blue carbon habitats for the purpose of carbon sequestration remains uncertain (Macreadie et al., 2021). The connection between understanding the advantages of preserving blue carbon ecosystems and the imperative to halt their continued degradation is established through the implementation of economic incentives, multi-regulatory frameworks, and the allocation of financial resources to support the conservation and restoration of these valuable natural resources (Bandh et al., 2023).

Table 1. The worldwide distribution of blue carbon ecosystems (Himes-Cornell et al., 2018)

Region	Mangrove		Seagrass		Salt marsh	
	Hectares	% of total	Hectares	% of total	Hectares	% of total
Asia	3,276,758	28.6	23,690	10.8	22,008	5.3
Africa	2,631,069	22.9	6,247	1.8	1,565	0.4
Central and South America	2,991,043	26.1	10,368	4.7	5,315	1.5
Australia and South Pacific	1,587,385	13.8	2,622	1.2	16,644	4.7
North America	965,678	8.4	153,266	69.6	143,239	40.8
Europe	0	0	23,614	10.7	162,039	46.2
Middle East	23,995	0.2	351	0.2	174	0
Global total	**11,466,928**		**220,158**		**350,984**	

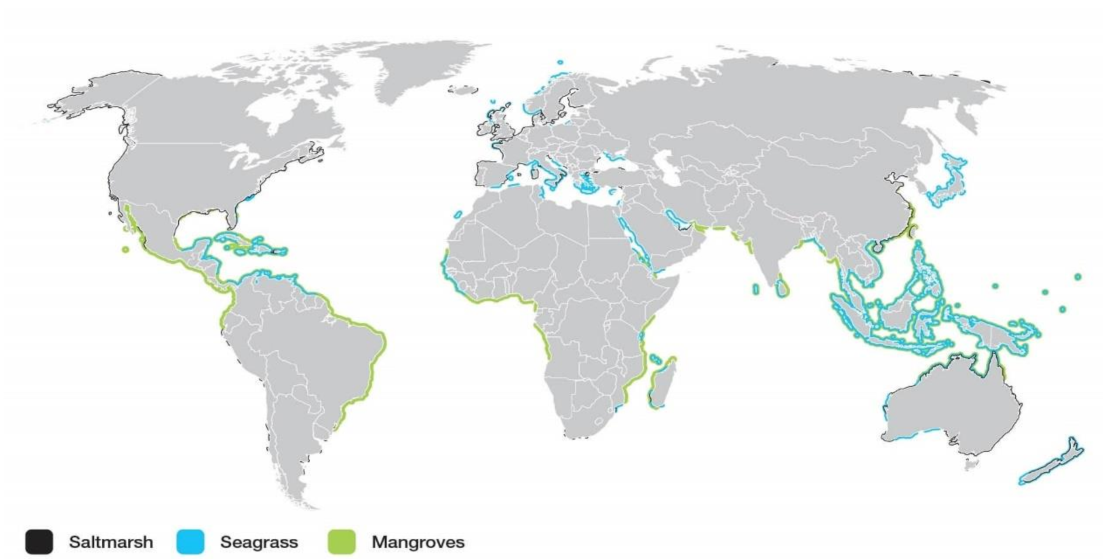

Figure 1. Global map of blue carbon ecosystems

There is a prevailing consensus among scholars and experts that a prolonged recovery from the global COVID-19 crisis is imperative (Raihan et al., 2022a; Raihan & Himu, 2023). However, regrettably, these demands have not been heeded. According to Badruddin (2023), there was a notable 6% rise in global carbon dioxide (CO_2) emissions resulting from the combustion of fossil fuels during the year 2020-2021. This increase led to a record-breaking annual amount of 36.3 gigatons (Gt). In order to mitigate the most severe consequences of climate change, it is imperative for the global community to expeditiously curtail emissions (Raihan et al., 2022b; Raihan et al., 2023a). Nevertheless, it is worth mentioning that there exists a potential avenue for mitigating atmospheric CO_2 levels through the implementation of nature-based climate solutions (NbCs). The blue carbon method, as assessed by Raw et al. (2023), is projected to have a limited capacity to mitigate climate change, amounting to less than 1% of current emissions. However, it is important to note that the advantages of adapting to climate change are substantial and should not be overlooked (Raihan et al., 2022c; Raihan et al., 2023b). According to Macreadie et al. (2021), blue carbon ecosystems in both terrestrial and marine environments within the NbC category possess the capacity to sequester a substantial amount of carbon, exceeding 30,000 teragrams (TgC). This carbon storage potential translates into a significant mitigation effect, estimated to prevent the release of approximately 300 carbon dioxide equivalents (CO_2e) on an annual basis. The potential expansion and restoration efforts have the capacity to sequester an estimated 841 Tg CO_2e annually by the year 2030, which would account for almost 3% of global emissions. According to Bandh et al. (2023), blue carbon ecosystems possess the capacity to store carbon at a rate that is ten times greater than that of terrestrial ecosystems over long periods of time. This carbon sequestration occurs through processes such as natural carbon assimilation during photosynthesis, as well as the sequestration of sediments and organic matter inside their intricate root systems (Raihan & Said, 2022; Raihan et al., 2023c). Moreover, these ecosystems play a crucial role as significant hubs for economic endeavors owing to their abundant resources including aquaculture, agriculture, fisheries, ports, tourism, and other related sectors (Datta & Roy, 2023). Numerous services play a crucial role in facilitating adaptation to climate change in coastal regions (Raihan et al., 2022d; Roy et al., 2023). The benefits encompassed by this phenomenon consist of safeguarding against erosion and sea level escalation, offering a habitat for both vertebrate and invertebrate species, and ensuring food security for numerous global communities (Raihan et al., 2022e; Lincoln et al., 2023). Nevertheless, it is worth mentioning that tropical regions have a higher population density compared to other geographical locations (Raihan et al., 2022f; Raihan et al., 2023d). According to Ratnatunga et al. (2022), it is estimated that around 40% of the global population currently resides in tropical regions. Projections suggest that this proportion is anticipated to rise to 50% by the conclusion of the year 2030. The escalating process of urbanization and pollution poses a significant threat to the preservation of mangroves, salt marshes, and seagrasses (Raihan et al., 2022g). Consequently, these ecosystems are experiencing habitat loss at a comparable or even more severe rate than tropical forests (Naidoo, 2023). According to Hatje et al. (2023), global losses of mangroves, seagrasses, and intertidal salt marshes have been calculated at approximately 67%, 29%, and 35% respectively. According to Arina et al. (2023), these ecosystems have the potential to transition from carbon sinks to carbon sources. Consequently, safeguarding and rehabilitating these ecosystems to mitigate emissions emerges as a crucial objective in endeavors to address climate change (Raihan et al., 2022h; Raihan et al., 2023e). Activities aimed at restoring and safeguarding blue carbon habitats not only contribute to the preservation of biodiversity but also present opportunities for the establishment of market-driven mechanisms that leverage current carbon offset frameworks (Vanderklift et al., 2022). Financial incentives for blue carbon have the potential to serve as a means of safeguarding and capitalizing on the additional ecological services offered by these habitats, including fisheries (Arkema et al., 2023).

This study provides a concise overview of the various services offered by tropical coastal ecosystems, with a particular focus on carbon storage and sequestration. Furthermore, this study examines various compensating strategies, including green aquaculture, marine protected areas, and wetland restoration, which have the potential to augment carbon sequestration. This article examines various governance approaches that can be employed in the future to facilitate the successful restoration and protection of blue carbon ecosystems. These approaches encompass market-based instruments, public investment, partnership initiatives, and community-based management, all of which are crucial for ensuring the effectiveness of such endeavors.

Blue carbon ecosystem services

Mangroves, seagrass beds, and seaweeds are well recognized as pivotal carbon sinks within tropical marine ecosystems, commonly referred to as "blue carbon" habitats. Mangroves exhibit taxonomic diversity, with approximately 50-75 species of woody vegetation (Asante et al., 2023). These ecosystems span a total area of 135,000 to 150,000 km^2, distributed throughout 118 nations in Southeast Asia, South America, Africa, and the Caribbean (Adame et al., 2021). Seagrasses, which consist of submerged flowering plants, are predominantly found in Southeast Asia, covering an area of approximately 320,000 km^2 (Nguyen et al., 2022). The assessment of seaweed coverage presents challenges due to its dependence on the agriculture industry. Blue carbon ecosystems offer a diverse array of functions that can be categorized into four distinct groups: regulatory, provisioning, cultural, and supportive. The services offered by tropical blue carbon ecosystems are depicted in Figure 2.

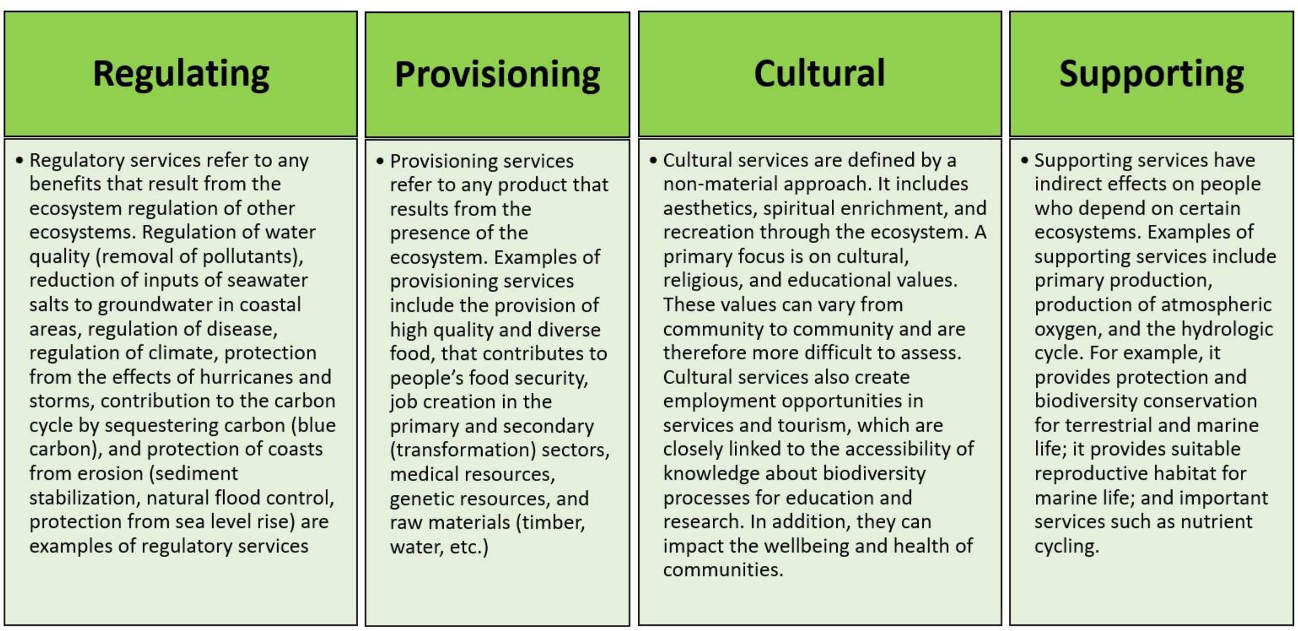

Figure 2. Services of blue carbon ecosystems

According to Veettil et al. (2019), mangroves offer various benefits to local populations, including the provision of lumber, fuel, and charcoal. Additionally, they serve as a natural defense mechanism against the impacts of sea level rise and heightened storm activity, providing coastal protection (Raihan et al., 2018; Raihan et al., 2022i). The recognition of the significance of mangroves in coastal defense has grown subsequent to the occurrence of the 2004 Indian Ocean tsunami, which caused extensive damage to the coastal environment. It has been acknowledged that the preservation and proper management of mangroves could have alleviated a substantial portion of the severe consequences resulting from the tsunami (Marois & Mitsch, 2015). Furthermore, it should be noted that mangrove ecosystems play a crucial role in serving as significant feeding and spawning grounds, while also mitigating the risk of predation for numerous fish species (Carrasquilla-Henao et al., 2019). According to Cotas et al. (2023), seaweed and seagrass beds play a crucial role in ecosystem regulation through their ability to stabilize sediments, mitigate shoreline erosion, and contribute to water purification. Theuerkauf et al. (2022) emphasize the significance of these habitats as crucial ecosystems that offer refuge to numerous fish species, as well as lobsters and crabs. Seagrasses offer a diverse array of services, including the provision of sustenance and the supply of pharmacological resources for medicinal purposes (Lakshmi, 2021). Seaweed cultivation, in turn, has proven to be a readily achievable practice, leading to the emergence of aquaculture as a prominent sector that offers substantial employment opportunities and sustains the lifestyles of several families residing in remote coastal towns (Rimmer et al., 2021). Furthermore, ongoing investigations are being carried out on the utilization of seagrass as a source of biofuel and its potential as an alternative to plastic packaging (Balestri et al., 2019; Yong et al., 2022). Seaweed agriculture has experienced significant growth throughout Asia, Africa, and the western Indian Ocean, principally driven by its utilization in food production (Eggertsen & Halling, 2021; Msuya et al., 2022). According to data from the Food and Agriculture Organization (FAO) in 2020, there has been a significant growth in worldwide seaweed cultivation throughout the period from 1950 to 2020. Specifically, the cultivation of seaweed has experienced a remarkable increase of 1,000 times, rising from 34.7 thousand tons to 34.7 million tons. It is noteworthy that aquaculture has played a dominant role in this expansion, accounting for almost 97% of the present production. Nevertheless, the potential adverse effects of seaweed farms can be attributed to habitat destruction (Theuerkauf et al., 2022).

According to Osland et al. (2022), carbon sequestration emerges as the primary ecosystem benefit offered by tropical coastal ecosystems. Figure 3 illustrates the role of blue carbon ecosystems in mitigating climate change through the sequestration of atmospheric carbon. Mangroves have a significant role in the sequestration of organic carbon stocks (Corg) both above-ground (leaves, branches) and below-ground (sediment, roots) within the soil (Raihan et al., 2019). This carbon storage occurs at varying depths, spanning from 30 cm to depths exceeding 3 m, hence offering a mechanism for long-term carbon retention (Suello et al., 2022). The current assessment of carbon accumulation in mangroves is based on radiometric analyses, as reported by Lamont et al. (2020). These analyses indicate that the range of carbon accumulation in mangroves is between 0.17 and 4.3 Mg C per hectare per year. The values fall within the estimated range obtained from soil carbon measurements, which vary from 1.74 to 2.5 Mg C per hectare per year (Suprayogi et al., 2022). Nevertheless, the rates of carbon acquisition through root systems, which vary from 5.06 to 6.63 Mg C per hectare per year, surpass the estimates of carbon accumulation derived from radiometric analyses or soil mass carbon determination (Lamont et al., 2020). The aforementioned measurements do not take into account the presence of roots, which account for the observed variances. Recent studies have indicated that the estimates of carbon sequestration through mangrove litterfall are greater compared to the estimations obtained through radiometric and mass analysis. According to Chen et al. (2021), the predicted rate of carbon sequestration by mangrove litter ranges from 3 to 5 Mg C per hectare per year. When considering the carbon stored in the higher layers of sediments, the combination of these numbers results in a total forest stock of 693 Mg C per hectare and a soil forest stock of 516 Mg C per hectare (Alongi, 2022). The carbon stored in soils has the potential to expand by up to 2,792 Mg C per hectare when accounting for deeper layers. Based on the median value of 627.8 MgC per hectare and widely accepted estimates of worldwide mangrove areas ranging from 83,495 to 137,760 km^2, Alongi (2022) conducted an estimation, revealing that the global carbon store for mangroves is within the range of 5.23 to 8.63 Pg C. According to Alongi (2022), the aforementioned values lead to an annual burial of carbon in mangrove forests ranging from 9.6 to 15.8 Tg C per year, which is notably 4 to 5 times greater than the carbon burial seen in boreal, temperate, and tropical highland forests. The comparison of carbon stored in the soils and biomass of various ecosystems is depicted in Figure 4.

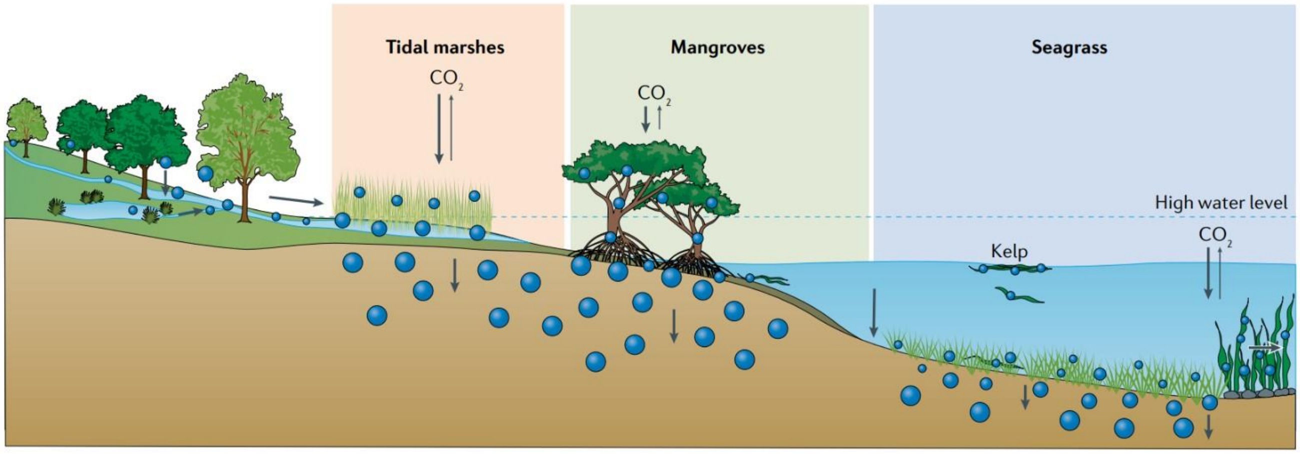

Figure 3. Blue carbon ecosystem for combating climate change by storing atmospheric carbon (Macreadie et al., 2021).

According to Alongi (2022), the carbon stock of mangroves exceeds the estimated carbon stock of seagrass meadows. Seagrass carbon stores in the uppermost 1 meter of sediment exhibit a range of 12 to 120 Megagrams of carbon per hectare, with a median value of 69.3 Megagrams of carbon per hectare, as reported by Miyajima et al. (2022). The sequestration rates of carbon in seagrass habitats vary from 94 to 161 kilograms of carbon per hectare per year, according to the same study. In a recent study conducted by Van Dam et al. (2021), it was discovered that numerous estimations fail to consider other processes such as denitrification, sulfur cycling, and inorganic carbon cycling. These processes constitute a significant contributor of CO_2 emissions to the atmosphere, surpassing the capacity of organic carbon sequestration (Raihan & Tuspekova, 2022a). In contrast to mangroves and seagrasses, seaweed does not exhibit the capacity to accumulate coastal sediment that is rich in carbon. However, the majority of the organic carbon is found within the living biomass (Raihan & Tuspekova, 2022b). Furthermore, a portion of the carbon assimilated by seaweed is deposited in the continental shelf and deep ocean, thus establishing a worldwide carbon reservoir (Hurd et al., 2022). A study conducted in Singapore has demonstrated that macroalgae possess the capacity to store a substantial amount of biomass, reaching up to 650 Mg C. This value exceeds the aboveground carbon content observed in seagrass meadows, although falls short of the carbon levels found in mangrove forests. The annual sequestration rate of carbon in mangrove forests is estimated to be approximately 450 Mg C per year, equivalent to 0.77 Mg C per hectare per year (Kwan et al., 2022). Furthermore, it should be noted that the significance of offshore sediments as carbon sinks surpasses that of other carbon sinks due to their expansive coverage (Legge et al., 2020; Raihan & Tuspekova, 2022c). Tidal marshes, which exhibit carbon sequestration properties, are predominantly found in temperate and high latitudes, with an area over 51,000 km^2 (Miyajima & Hamaguchi, 2019).

The provided figures regarding carbon sequestration should be regarded as approximate estimations due to the escalating challenges faced by mangroves and seagrass beds. These challenges include deteriorating water quality and the encroachment of coastal development activities such as aquaculture and timber production (Raihan & Tuspekova, 2022d). Consequently, these ecosystems are experiencing habitat degradation and a swift decline in their surface area and ecological functions. According to the findings of Dunic et al. (2021), there has been a significant decrease in the overall assessed seagrass area, amounting to a reduction of 19% since the year 1880. Notably, the tropical Atlantic and tropical Indo-Pacific regions have experienced substantial losses in seagrass coverage within the tropical areas. According to Bolívar-Anillo et al. (2020), the pace of mangrove depletion is currently reaching up to 3% annually, which raises concerns about their potential functional disappearance within a century. Mangroves experience significant oscillations, encompassing both natural regeneration and destruction processes (Song et al., 2023). The depletion of mangroves due to excessive harvesting and their substitution with nypa palms have been recognized as significant contributors to deforestation in certain regions of West Africa and South Asia (Nwobi & Williams, 2021; Ng et al., 2022).

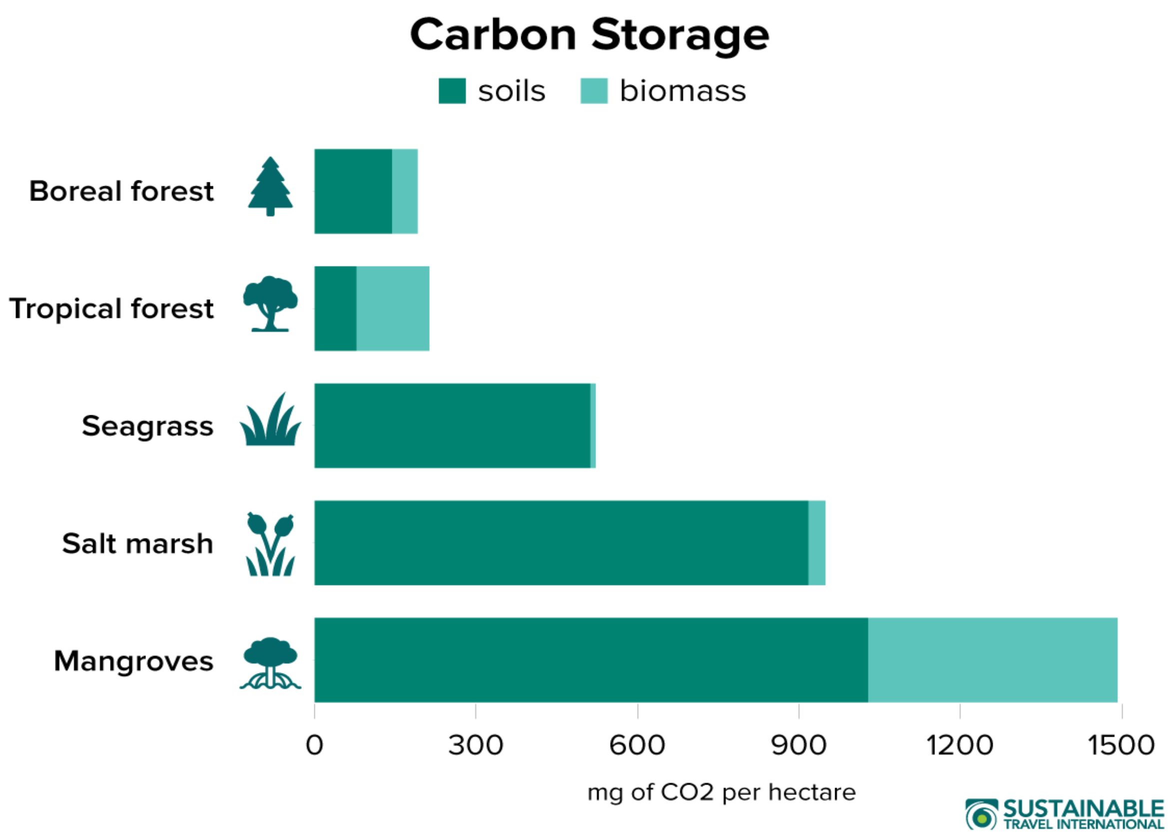

Figure 4. Comparison of carbon stored in the soils and biomass of different ecosystems
Data sources: Pendleton et al. (2012) and Pan et al. (2011)

In recent decades, there has been a dramatic reduction in the size of mangrove ecosystems (Murillo-Sandoval et al., 2022; Raihan & Tuspekova, 2022e). The study conducted by Wu et al. (2020) reveals that mangrove forests in Southeast Asia experienced a mean yearly decline of 0.18%. Furthermore, the research indicates that a total area of over 100,100 hectares of mangroves was cleared between the years 2000 and 2012 in this region.
According to Ferreira et al. (2023), the removal of mangroves and subsequent dredging of land for economic purposes results in the release of sediments into the atmosphere or water column. This process also leads to the restoration of carbon, which is subsequently released back into the atmosphere and ocean (Raihan & Tuspekova, 2022f). According to Siikamaki et al. (2013), the annual carbon emissions resulting from the loss of mangroves are projected to be approximately 35 million tons. According to Atwood et al. (2017), the estimation of worldwide potential CO_2 emissions resulting from mangrove loss is around 7 teragrams (Tg) per year, when measured in terms of CO_2e. Indonesia and Malaysia are identified as the nation's having the greatest potential for CO_2 emissions originating from soil, with estimated annual emissions of 3,410 Gg CO_2 and 1,288 Gg CO_2, respectively. In spite of notable declines in mangrove ecosystems, there has been a notable implementation of

comprehensive conservation and restoration initiatives in recent times (Sasmito et al., 2023). Community-based restoration, reforestation, integrated coastal ecosystem restoration, and economic approaches have been implemented as strategies to address global warming and the trade of mangroves (Raihan & Tuspekova, 2022g; Lhosupasirirat et al., 2023). According to the study conducted by Begum et al. (2023), it was determined that the primary drivers for local stakeholders' engagement in mangrove restoration and management are livelihood and economic advantages. Hence, the implementation of mangrove restoration initiatives is anticipated to mitigate the shortcomings observed in community-based restoration programs (Lhosupasirirat et al., 2023).

Economic estimations of blue carbon ecosystem services

In light of the growing attention towards the significance of vegetated coastal habitats on a global, national, and local level, it is imperative to accurately assess the economic worth of their capacity to absorb and store carbon (Raihan et al., 2021a; Hurd et al., 2022; Raihan & Tuspekova, 2022h). This valuation would contribute to increasing awareness among the community and among policy makers (Raihan & Tuspekova, 2022i). Additionally, it would facilitate investment in suitable coastal protection and ecological restoration measures, which could otherwise lead to significant economic consequences (i.e., the cost of not taking action).

According to Barbier (2016), the estimated value of mangroves for the purpose of coastal protection and stabilization over a span of 20 years is $12,263 per hectare. Additionally, the cost incurred due to the loss of 1 square kilometer of mangroves in Thailand is around $1,879 per hectare. According to a study conducted by Anneboina and Kumar (2017), the monetary contribution to local fisheries resulting from the presence of one hectare of mangroves can vary significantly, ranging from $42 to $37,500. This variation is influenced by factors such as the geographical location and the value attributed to different species. Furthermore, it should be noted that the yearly economic value added per hectare for penaeid shrimp, which is considered the most commercially viable fishery connected with mangroves, exhibits a range of US$91 to US$5,292, as reported by Anneboina and Kumar in 2017. In addition, mangroves also generate additional value in the sectors of tourism, education, and cultural activities (Vargas-del-Río & Brenner, 2023). As an illustration, the economic benefits of mangroves have been quantified in several regions. In Malaysia, it has been estimated that mangroves provide approximately $1 million to tourism income annually (Spalding & Parrett, 2019). Similarly, in Iran, the yearly economic impact of mangroves on tourism revenue is projected to be around $7 million (Spalding & Parrett, 2019). In the Sundarban Reserves located in India and Bangladesh, the annual economic value of mangroves in terms of tourism revenue is estimated to be approximately $42,000 (Uddin et al., 2013). According to Barbier (2016), the global valuation of mangroves, encompassing all services provided, amounts to US$69.9 billion. The utilization of voluntary carbon markets has facilitated the generation of revenue for local communities by leveraging mangrove habitats to sell carbon credits that correspond to carbon sequestration (Raihan et al., 2021b; Raihan & Tuspekova, 2022j; Raihan et al., 2023f). This practice has been recognized as a promising approach for implementing payment for ecosystem services (PES) initiatives, as highlighted by Nguyen et al. (2023). These mechanisms facilitate the financing of conservation efforts. Nevertheless, the generation of carbon credits through blue carbon projects is limited due to the necessity of incorporating supplementary climate market mechanisms (Vanderklift et al., 2022). The depletion of seagrass can lead to significant economic ramifications due to its role as an indirect provider of sustenance and pharmacological resources. Nevertheless, the assessment of such expenses has been limited. Furthermore, seagrasses serve as a significant attraction for tourists, as exemplified in Indonesia, where the presence of seagrass ecosystems contributes to tourism revenues ranging from $2,287 per hectare per year to $80,226 per hectare per year (Dewsbury et al., 2016). According to Cullen-Unsworth and Unsworth (2013), the

economic impact of carbon dioxide emissions resulting from the deterioration of seagrass is predicted to range from $1.9 billion to $13.7 billion annually on a global scale.
In addition, it should be noted that seaweed aquaculture exhibits potential for climate change mitigation and serves as a significant economic resource in tropical nations (Ross et al., 2023). According to Jagtap and Meena (2022), an approximate quantity of 500 million tons of seaweed output is projected to sequester around 135 million tons of carbon. Furthermore, the practice of cultivating seaweed not only serves to mitigate communal poverty but also enhances the economic well-being of coastal populations. China, Indonesia, the Philippines, Korea, Japan, Malaysia, and Tanzania are recognized as the leading nations in terms of seaweed production. Seaweed aquaculture in Malaysia was initiated during the 1980s, and over the years, production has witnessed a significant growth, reaching a total of 269,431 tons by the year 2013. According to Hussin and Khoso (2021), Malaysia's contribution to global seaweed output during that period amounted to 1%, positioning it as the eighth largest producer worldwide. According to Hussin and Khoso (2021), the Malaysian government set a target to increase seaweed production to 900,000 tons by the year 2020. This increase in production is estimated to have a monetary value of around USD 344.76 million. The primary utilization of seaweed in Southeast Asia is for the purpose of carrageenan extraction (Rupert et al., 2022). Carrageenan, a hydrocolloid derived from red seaweed, is widely utilized in various food and pharmaceutical applications. According to Farghali et al. (2023), the worldwide production of grown seaweed for multiple biorefineries reached a total of 34.7 Gt in 2019, with an estimated value of USD 14.7 billion.

Protection measures of tropical blue carbon ecosystems

There exist multiple potential approaches for the successful implementation of restoration and preservation measures in a thorough and efficient manner (Raihan & Tuspekova, 2023a). These encompass many strategies such as market-based instruments (e.g., taxes and fines), public investments, community-based management, government incentives, and other similar approaches (Raihan et al., 2022j). This section provides a comprehensive summary of the current state of affairs regarding the various alternatives that have been addressed, as well as an examination of their potential implementation strategies.

Market-based solutions

Altering market outcomes through pricing policies is one form of economic intervention that can improve both efficiency and equity (Raihan & Tuspekova, 2023b). All natural and artificial resources used in manufacturing should be reflected in the price of goods and services (Raihan et al., 2023g). Blue carbon depletion from production and consumption must be reflected in the market price of the product by giving each activity that compromises ecosystem integrity a value corresponding to the carbon created or displaced. Socially advantageous behaviors are encouraged, while socially costly ones are discouraged, through the use of market-based solutions (Raihan & Voumik, 2022a). In order to account for the social as well as private costs and benefits of an action, they implement price interventions. All costs, including those for the ecosystem services that mangroves provide, will be borne by the activity (industrial development project or fishery) that causes their destruction. Damage fees for harming blue ecosystems, carbon prices, tax credits, and financial backing for blue carbon protection are all examples of interventions. Policy instruments can be used interchangeably or in combination. To achieve the same distributional goals as standards or subsidies, taxes can be used instead (Raihan & Voumik, 2022b).

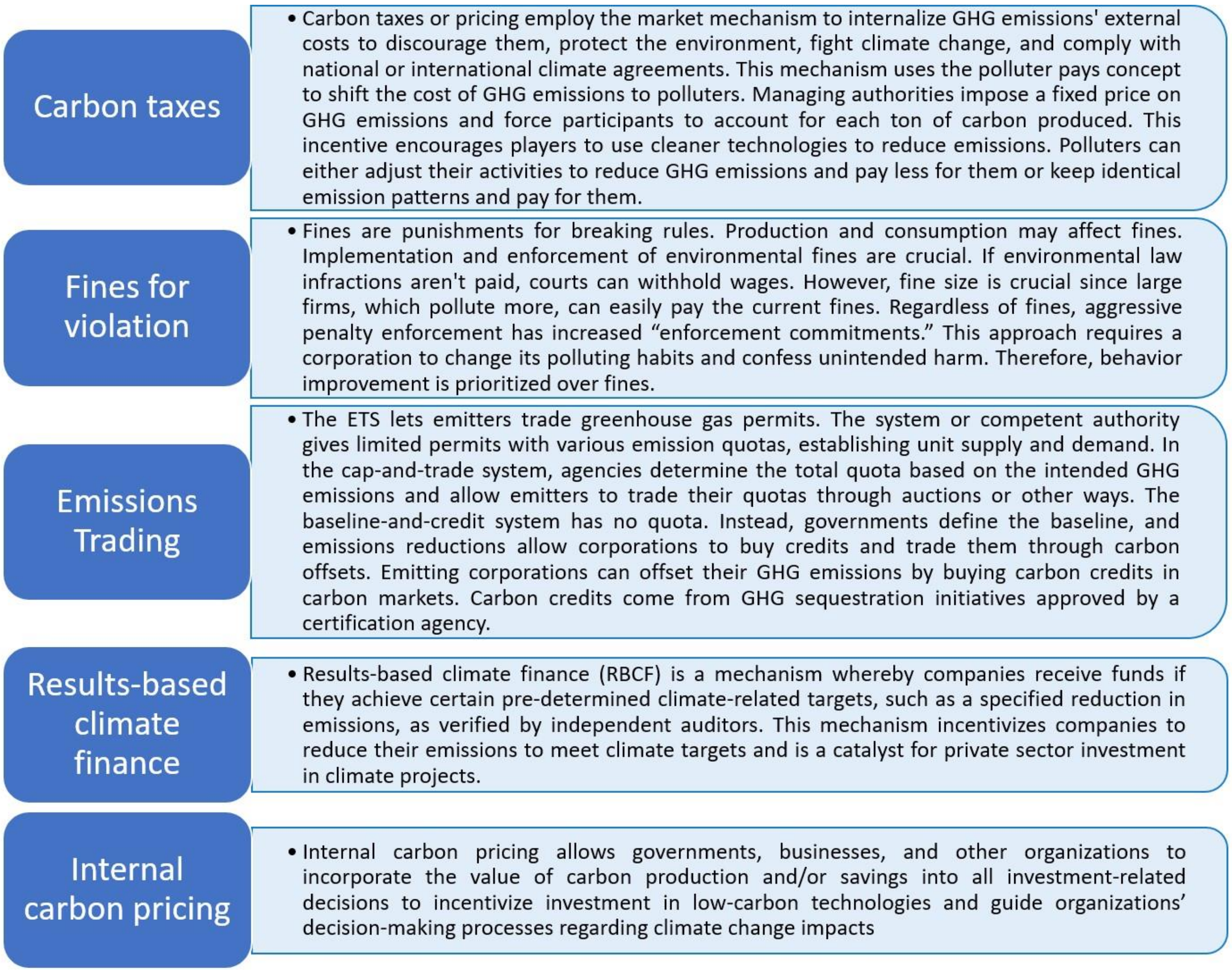

Figure 5. Possible economic interventions for the protection of tropical blue carbon ecosystems.

Greener development, as well as the extension and discovery of low-carbon technologies, can stimulate economic growth if the appropriate steps are taken in a number of different ways (Ghosh et al., 2023Li & Wen, 2023; Sultana et al., 2023). Possible financial steps to safeguard tropical blue carbon ecosystems are depicted in Figure 5. In many cases, tax benefits motivate the very behaviors that generate them. Project costs will factor in the benefits of initiatives that generate blue carbon as a byproduct, which will be of interest to developers and corporations eligible for environmental tax credits (Voumik et al., 2022). Fines and other forms of administrative punishment are less complicated to impose than criminal penalties. The most effective responses to environmental violations are administrative fines and criminal prosecution. In cases of moderate severity, monetary penalties are crucial. Since it utilizes preexisting tax infrastructure, carbon dioxide taxes are simpler to implement than alternative carbon pricing systems (Begum et al., 2020; Voumik et al., 2023a). They are easy to implement and promote the development and use of low-carbon technologies by all entities responsible for producing emissions (Isfat & Raihan, 2022; Voumik et al., 2023b). In conclusion, tax reuse has the potential to improve morale and output. However, carbon pricing may increase the cost of related items, which may reduce the competitive advantage of energy-intensive businesses and slow economic growth (Ali et al., 2022; Raihan, 2023a). Polluters may pass on the costs to consumers, which may increase tax revenue for the government without increasing emissions. The public's backing for carbon fees could weaken if collected funds are not reused. Furthermore, carbon taxes in developed nations may cause a transfer of emissions to less developed nations where fewer safeguards exist for the environment (Raihan, 2023b).

Financing for the maintenance and preservation of blue carbon

A significant problem is the insufficient funding for blue carbon ecosystem maintenance and restoration. Funding is contingent on a project having both a history of success and a low risk profile. The Clean Development Mechanism (CDM) allocates 80% of its revenues to sustainable energy projects and only 1% to forestry projects. According to Vanderklift et al. (2019), the majority of social responsibility offsets come through the voluntary market. As predicted by Favasuli and Sebastian (2021), this industry might be worth $50 billion by 2030. Vanderklift et al. (2019) argue that publicly sponsored blue carbon initiatives could lower risk and increase return. As a means of reducing price swings, they advocate for blue carbon credits to be priced at a guaranteed minimum. It is not entirely clear what legal and policy grounding blue carbon projects have. This has resulted in a reduction in public funds for blue carbon ecosystem conservation (Vanderklift et al., 2019), which has a negative impact on the financial stability of many projects.

In 2011, Gordon et al. analyzed 14 different funding mechanisms for blue carbon projects. The majority of the funds are invested in REDD+ research and development. UNFCCC REDD+ projects help cut down on harmful gases released as a result of cutting down trees (Jaafar et al., 2020; Raihan, 2023c). Funding options for blue carbon are included. The Hatoyama Initiative ($158 million), the Amazon Fund ($133.3 million), and the Global Environment Facility Trust Fund ($105 million) all contribute to REDD+ initiatives. Private sector blue carbon funding is extremely dependent on philanthropic funds, according to Earth Security (2020). The MacArthur Foundation funded Blue Ventures' almost $1 million expansion to Tahiry, Madagascar. Research for 1,300 metric tons of blue carbon credits has been sponsored through this initiative. Charity funding is also an important source of innovation (Raihan, 2023d). They frequently investigate and apply commercial strategies that indirectly protect blue carbon. Non-profit organizations and other sources of funding can entice and reassure private investors (Raihan, 2023e). Major private investors such as JPMorgan Chase and Encourage Capital were attracted to the project thanks to a partial debt guarantee and $6 million investment from the Global Environment Facility and the U.S. International Development Finance Corporation.

Blue carbon protection, and particularly mangrove protection, is a common use for municipal bonds. Similar to other types of bonds, municipal bonds can be used to fund local government operations on a state or local level (Raihan, 2023f). Typically, money is used to build things like schools and roads. Bonds totaling $400 million were issued by a group of cities on the U.S. coast; of that amount, $192 million will go toward mangrove restoration. Green bonds are issued to finance environmental initiatives like those that aim to reduce pollution, promote sustainable agriculture, and save ecosystems (Raihan, 2023g). Tax breaks are one way to entice potential backers. In order to finance environmental initiatives, the World Bank employs this method. Debt-for-nature swaps can be used to finance blue carbon reserves by reducing or providing favorable terms on national or local debt (Raihan, 2023h). By the year 2020, national debts will have exploded. Post-World War II general government debt is reported by the International Monetary Fund (2020). Developing nations on islands are particularly at risk (Raihan, 2023i). Because of this, debt-for-nature/climate swaps are proposed by Thomas and Theokritoff (2021). When a debtor nation's debt is forgiven by a creditor nation, the debt is purchased at a steep discount by an intermediary for use in environmentally responsible investment projects.

Regulatory mechanisms for blue carbon restoration and conservation

It is challenging to legally preserve mangrove habitats and to restore any that have been destroyed (Raihan, 2023j). Mangroves are governed by a complex web of hard and soft rules and policies at the international, regional, and national levels. Legal instruments include guidelines (such as the polluter-pays principle), theories, regulatory decision-making tools (such as environmental impact assessments), treaties, declarations, objectives, and goals. Many countries have adopted these pieces of legislation, which serve to protect and preserve mangroves (Raihan, 2023k). Lack of enforcement, human and financial constraints, and unclear government directives are just some of the problems plaguing "traditional environmental law," which affects all of these tools. The use of incentives and financial mechanisms alongside international tools (both hard law and soft law) is commonplace. These sector-spanning instruments address the aforementioned threats by enacting laws in multiple sectors that overlap and are intrinsically linked to one another.

The Ramsar Convention on Wetlands, the World Heritage Convention, and the Convention on Biological Diversity are all examples of biodiversity frameworks that address coastal blue carbon (Raihan, 2023l). Mangroves fall under the latter category because Parties are obligated to include biodiversity into sectoral policy and provide incentives for protection. Detailed objectives are laid out in the Aichi Biodiversity Targets. The CDM is a flexible mechanism that encourages carbon sequestration and is part of several climate change frameworks including the UNFCCC, the Paris Agreement, and REDD+ (Raihan, 2023m). The CDM allows for the payment of results from forest conservation and management in a country (Raihan, 2023n). The United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on International Trade in Endangered Species (CITES) both address mangrove concerns. CITES is a template for international pacts involving jurisdictions that have wildlife that is constantly on the move. Environmental impact assessments, as well as the World Bank's and the Center for Tropical Ecosystem Research's rules of conduct, are being adopted as "soft law" mechanisms. Most mangroves thrive in brackish water; thus they tend to grow at the mouths of rivers that empty into the sea (Raihan, 2023o). The United Nations Water Convention and the United Nations Convention on the Right of Non-Navigational Uses of International Watercourses are two examples of international water regimes that apply to mangroves.

A significant challenge in coastal policymaking is coordinating between marine and freshwater legal and administrative systems on the mainland. The mangroves are an example of this holistic worry. The Water Framework Directive (WFD) serves as a model for regional and European water management by establishing good status targets for continental, coastal, and transitional waters. Good status in these areas depends on land-based and maritime influences for the physiochemical, biological, and hydro-morphological components (Raihan, 2023p). Integrated water management calls for the coordination and use of coastal and river basin mechanisms (such as monitoring, basin planning, governance, and funding). "Overseas territories" (OVTs) with special regulatory status, such as tropical areas, are included in this framework as well. Foreign countries and territories that are reliant on an EU member state but are not EU members are not required by law to implement the WFD. Mangrove management in French Guiana needs community input to meet European Union marine and freshwater regulations. Downstream coastal knowledge is being expanded using WFD monitoring and planning funds in particular watersheds. The Somone Coastal Basin Conservation Area is a joint effort by the Senegalese Ministry of Environment (in charge of coastal zone management) and the Ministry of Water and Sanitation (in charge of river basin planning). One notable mangrove in the watershed's downstream provides a wide range of biological benefits to the surrounding environment (Raihan, 2023q). Due to excessive water consumption in the upstream basin (with expanding demography, industry, and agricultural exports), freshwater runoff to the reserve is reduced,

sedimentation and salinity are rising, and mangrove lands and biodiversity are lost immediately (Raihan, 2023r). In order to better conserve and restore mangrove forests, a new concertation mechanism is being developed.
As has been demonstrated above, there is no universally binding legal framework for protecting mangroves; rather, there is a patchwork of international instruments, methods, and standards that might be used. As part of the forest, marine and coastal law, water and wetland, aquaculture, and climate change ecosystems, mangroves may be subject to varying national regulations. Consequently, "tagging-based instruments" can protect mangroves, which are essential to ecological systems (Raihan, 2023s). The national level of regulation must execute global environmental treaties because it must consider the principles, concepts, and standards in international treaties (Raihan, 2023t). Executive decrees, rules, legal judgments, levies, and strategic tools can safeguard mangroves at the national level. Governance, land tenure, and rights are issues at the national level. Although "specific mangrove laws" do not exist, countries do have laws that govern the extraction industry, fishing industry, and farming. Planning and permitting regulations—private or public—are important and may consider good governance principles including access to information, public engagement, and justice. Villages and towns are involved in social forestry, land use, and other planning initiatives. MPAs, MSPs, IZMs, and EMBs are other national legal tools.

Challenges in governance, incentives, and enforcement

Mangrove habitats are extremely important to both nature and humanity due to the many benefits they bring. Mangroves can be protected through the use of sustainable monetization strategies, such as payments for ecosystem services, product certification, carbon offsets, REDD +, and fiscal incentives and disincentives. Companies interested in profiting from carbon sequestered in mangroves have looked into REDD + and the selling of voluntary carbon offsets. Mangrove area and ecosystem service ownership, carbon property rights, and carbon value norms are examples of legal circumstances necessary to realize these possibilities but are lacking in many countries. Carbon offsetting schemes in mangrove forests face legal challenges. The application of UNFCCC flexible mechanisms is complicated by the fact that the definition of "forest" varies from nation to country. Conservation and long-term sustainability can benefit from both tax incentives and disincentives. Mangroves have challenges from a lack of land-based and marine-based techniques, as well as from a lack of institutional coordination, governance concerns, lack of community participation, and land tenure issues. Transparency, accountability, and adherence to the rule of law in governance are essential for citizen engagement. The major problems with implementation are a lack of institutional ability and financial support. Corruption, capacity building, and inefficient national bureaucratic systems are the primary obstacles to effective enforcement. New legal instruments and measures should be developed to foresee implementation, enforcement, and compliance issues and to produce proactive rather than reactive law in order to meet future climate change challenges and reach global and regional accords and goals. Ownership is critical to the success of law enforcement. Appropriation is the main threat to coastal management strategies and the conservation, protection, and restoration of ecosystems. The gap between the two can be bridged by integrated planning and the inclusion of the community in the prioritization of pressures and actions. Diagnosing, protecting, conserving, and restoring these ecosystems is made easier through local governance and participatory management involving stakeholders (communities and citizens, local authorities, regional and national governments and their local representatives, economic sectors, non-governmental organizations, science, and universities). This means that more money could be raised for these ecosystems, which would increase people's willingness to pay for them. The combined effort to build holistic coastal ecosystem management is not to be lamented from a regulatory and institutional standpoint, since it is applicable in spite of climate change and contributes to territorial growth.

Conclusions and policy implications

The conservation of tropical blue carbon habitats holds significant significance, not alone for the sequestration of carbon, but also for the safeguarding of various other ecosystem services linked to these ecosystems. Provisioning and regulating services exert a significant influence on society, manifesting in both economic value and the well-being of ecosystems. The preservation of tropical blue carbon ecosystems presents a potential avenue for generating additional money and alleviating debt burdens by use of inventive financial arrangements. This is closely linked to the United Nations Sustainable Development Goals that are being pursued. Incentives for the attainment of these objectives can be derived from various sources such as governance structures, regulatory frameworks, market-oriented approaches, and alternative finance mechanisms. Preserving the ecology and its vitality necessitates international governmental cooperation. The aspect of timing is crucial in guaranteeing the long-term viability of protective measures. Blue carbon habitats are inherently intricate, necessitating a concerted effort to enhance our understanding of their biological aspects. This is crucial in order to mitigate uncertainty surrounding their capacity to sequester carbon. Nevertheless, it is possible that seaweed ecosystems may not effectively control CO_2 emissions and could potentially contribute to CO_2 emissions themselves. In this particular scenario, there exists a tangible possibility of expenditures made in natural climate solutions that may ultimately provide minimal climate benefits.

Furthermore, it should be noted that coastal vegetation systems possess the inherent ability to retain and accumulate significant quantities of plastic and microplastic materials. Moreover, these systems exhibit the potential to serve as valuable feedstock for the production of bioenergy. Diverse ocean ecosystems have the potential to facilitate climate mitigation efforts and conserve carbon stocks. Additionally, they can contribute to the circular economy by utilizing blue carbon for bioenergy production, as well as aid in mitigating plastic and microplastic pollution. For the successful implementation of conservation efforts, it is imperative to involve local inhabitants in the decision-making process. Participation in these ventures yields immediate advantages, including engaging tasks and a steady stream of earnings. In order to effectively merge social protection efforts with actions addressing climate change and economic recovery, it is imperative to establish global coalitions that can facilitate the implementation of prompt initiatives. The implementation of this approach is crucial for the reconstruction and reformation of economies from an ecological perspective. In light of the diverse array of studies undertaken on coastal ecosystems, forthcoming endeavors may prioritize exploring the prospective viability of biofuel generation derived from the biomass yielded by those ecosystems. This measure will contribute to mitigating the escalating concentrations of greenhouse gases and addressing the phenomenon of climate change on a worldwide scale.

Moreover, it is imperative to emphasize the necessity of international collaborative endeavors across many economies in order to ensure the preservation and safeguarding of coastal habitats, hence enabling the continued extraction of numerous advantages from these ecosystems. There exists a pressing demand for actors within the realms of policy, advocacy, and particularly the scientific community to establish linkages between intersecting frameworks. It is imperative that these actors prioritize biodiversity protection based on its intrinsic value, rather than just valuing it for its capacity to sequester carbon. Scientists can assume a prominent position in fostering these discussions by enhancing their engagement in policy debates and effectively communicating their findings in a manner that is accessible to others without specialized expertise. Significantly, scientists have the ability to establish standardized methodologies for assessing, tracking, and documenting carbon accounting across various ecosystems. These methodologies aim to produce transparent and reliable data, employing comparable metrics to evaluate the potential for carbon sequestration, similar to those used for describing greenhouse gas emissions and emission reductions. This enables appropriate comparisons and provides a comprehensive understanding of the concept of additionality. Ocean-based solutions to climate change must possess a high level of resilience and credibility, while also offering various advantages at different levels. Furthermore, these solutions should exhibit the concept of additionality. Hence, the allocation of resources towards substantial and expandable initiatives aimed at preserving, conserving, and restoring blue carbon holds significant significance in effectively tackling the climate issue.

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References

Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., ... & Brown, C. J. (2021). Future carbon emissions from global mangrove forest loss. *Global change biology*, *27*(12), 2856-2866.

Ali, A. Z., Rahman, M. S., & Raihan, A. (2022). Soil carbon sequestration in agroforestry systems as a mitigation strategy of climate change: a case study from Dinajpur, Bangladesh. *Advances in Environmental and Engineering Research,* 3(4), 1-15.

Alongi, D. M. (2022). Impacts of climate change on blue carbon stocks and fluxes in mangrove forests. *Forests*, *13*(2), 149.

Anneboina, L. R., & Kumar, K. K. (2017). Economic analysis of mangrove and marine fishery linkages in India. *Ecosystem Services*, *24*, 114-123.

Arina, N., Hidayah, N., Hazrin-Chong, N. H., & Rozaimi, M. (2023). Algal contribution to organic carbon sequestration and its signatures in a tropical seagrass meadow. *Deep Sea Research Part II: Topical Studies in Oceanography, 210*, 105307.

Arkema, K. K., Delevaux, J. M., Silver, J. M., Winder, S. G., Schile-Beers, L. M., Bood, N., ... & Young, A. (2023). Evidence-based target setting informs blue carbon strategies for nationally determined contributions. *Nature Ecology & Evolution, 7*, 1045-1059.

Asante, F., Hugé, J., Asare, N. K., & Dahdouh-Guebas, F. (2023). Does mangrove vegetation structure reflect human utilization of ecosystem goods and services?. *Iscience*, *26*(6), 106858.

Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Ewers Lewis, C. J., ... & Lovelock, C. E. (2017). Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, *7*(7), 523-528.

Badruddin, A. (2023). Sustainable Low-Carbon post COVID 19 recovery measures across sectors in World Economies: A Thematic Analysis on its Coverage. *Total Environment Research Themes*, *6*, 100045.

Balestri, E., Vallerini, F., Seggiani, M., Cinelli, P., Menicagli, V., Vannini, C., & Lardicci, C. (2019). Use of bio-containers from seagrass wrack with nursery planting to improve the eco-sustainability of coastal habitat restoration. *Journal of environmental management*, *251*, 109604.

Bandh, S. A., Malla, F. A., Qayoom, I., Mohi-Ud-Din, H., Butt, A. K., Altaf, A., ... & Ahmed, S. F. (2023). Importance of Blue Carbon in Mitigating Climate Change and Plastic/Microplastic Pollution and Promoting Circular Economy. *Sustainability*, *15*(3), 2682.

Barbier, E. B. (2016). The protective service of mangrove ecosystems: A review of valuation methods. *Marine pollution bulletin*, *109*(2), 676-681.

Begum, F., de Bruyn, L. L., Kristiansen, P., & Islam, M. A. (2023). Development pathways for co-management in the Sundarban mangrove forest: A multiple stakeholder perspective. *Forest Policy and Economics*, *148*, 102918.

Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability,* 12(22), 9375.

Bolívar-Anillo, H. J., Visbal, A. Z., Serrano, M. C., Moreno, H. S., & Daza, D. A. V. (2020). A Preliminary Review on the Importance of Colombian Mangroves as a Source of Endophytic Microorganisms Relevant in Pharmaceutical Industry. J Acupun Tradit Med 3: 006.

Carrasquilla-Henao, M., Ban, N., Rueda, M., & Juanes, F. (2019). The mangrove-fishery relationship: A local ecological knowledge perspective. *Marine Policy*, *108*, 103656.

Chen, S., Chen, B., Chen, G., Ji, J., Yu, W., Liao, J., & Chen, G. (2021). Higher soil organic carbon sequestration potential at a rehabilitated mangrove comprised of Aegiceras corniculatum compared to Kandelia obovata. *Science of the Total Environment*, *752*, 142279.

Cotas, J., Gomes, L., Pacheco, D., & Pereira, L. (2023). Ecosystem Services Provided by Seaweeds. *Hydrobiology*, *2*(1), 75-96.

Cullen-Unsworth, L., & Unsworth, R. (2013). Seagrass meadows, ecosystem services, and sustainability. *Environment: Science and policy for sustainable development*, *55*(3), 14-28.

Datta, S., & Roy, J. (2023). Threats from weather events, urbanization and resilience: A case study of a coastal geography in India. *Journal of Integrative Environmental Sciences*, *20*(1), 2218474.

Dewsbury, B. M., Bhat, M., & Fourqurean, J. W. (2016). A review of seagrass economic valuations: gaps and progress in valuation approaches. *Ecosystem Services*, *18*, 68-77.

Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., & Côté, I. M. (2021). Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biology*, *27*(17), 4096-4109.

Eggertsen, M., & Halling, C. (2021). Knowledge gaps and management recommendations for future paths of sustainable seaweed farming in the Western Indian Ocean. *Ambio*, *50*(1), 60-73.

FAO. (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in Action. Food and Agriculture Organization of the United Nations (FAO), Rome.

Farghali, M., Mohamed, I. M., Osman, A. I., & Rooney, D. W. (2023). Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. *Environmental Chemistry Letters*, *21*(1), 97-152.

Favasuli, S., & Sebastian, V. (2021). Voluntary carbon markets: How they work, how they're priced and who's involved. *S&P global Platts*, *10*.

Ferreira, A. C., de Lacerda, L. D., Rodrigues, J. V. M., & Bezerra, L. E. A. (2023). New contributions to mangrove rehabilitation/restoration protocols and practices. *Wetlands Ecology and Management*, *31*(1), 89-114.

Ghosh, S., Hossain, M. S., Voumik, L. C., Raihan, A., Ridzuan, A. R., & Esquivias, M. A. (2023). Unveiling the Spillover Effects of Democracy and Renewable Energy Consumption on the Environmental Quality of BRICS Countries: A New Insight from Different Quantile Regression Approaches. *Renewable Energy Focus*, 46, 222-235.

Gordon, D., Murray, B. C., Pendleton, L., & Victor, B. (2011). Financing options for blue carbon: Opportunities and lessons from the REDD+ experience. *Report NI R II-II, Nicholas Institute for Environmental Policy Solutions, Duke University, Durham.*

Hatje, V., Copertino, M., Patire, V. F., Ovando, X., Ogbuka, J., Johnson, B. J., ... & Creed, J. C. (2023). Vegetated coastal ecosystems in the Southwestern Atlantic Ocean are an unexploited opportunity for climate change mitigation. *Communications Earth & Environment*, *4*(1), 160.

Himes-Cornell, A., Pendleton, L., & Atiyah, P. (2018). Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. *Ecosystem services*, *30*, 36-48.

Hurd, C. L., Law, C. S., Bach, L. T., Britton, D., Hovenden, M., Paine, E. R., ... & Boyd, P. W. (2022). Forensic carbon accounting: assessing the role of seaweeds for carbon sequestration. *Journal of Phycology*, *58*(3), 347-363.

Hussin, H., & Khoso, A. (2021). Migrant workers in the seaweed sector in Sabah, Malaysia. *SAGE Open*, *11*(3), 21582440211047586.

Isfat, M., & Raihan, A. (2022). Current practices, challenges, and future directions of climate change adaptation in Bangladesh. *International Journal of Research Publication and Reviews,* 3(5), 3429-3437.

Jaafar, W. S. W. M., Maulud, K. N. A., Kamarulzaman, A. M. M., Raihan, A., Sah, S. M., Ahmad, A., Saad, S. N. M., Azmi, A. T. M., Syukri, N. K. A. J., & Khan, W. R. (2020). The influence of forest degradation on land surface temperature–a case study of Perak and Kedah, Malaysia. *Forests,* 11(6), 670.

Jagtap, A. S., & Meena, S. N. (2022). Seaweed farming: a perspective of sustainable agriculture and socio-economic development. *Natural resources conservation and advances for sustainability*, 493-501.

Kwan, V., Fong, J., Ng, C. S. L., & Huang, D. (2022). Temporal and spatial dynamics of tropical macroalgal contributions to blue carbon. *Science of the Total Environment*, *828*, 154369.

Lakshmi, A. (2021). Coastal ecosystem services & human wellbeing. *The Indian journal of medical research*, *153*(3), 382.

Lamont, K., Saintilan, N., Kelleway, J. J., Mazumder, D., & Zawadzki, A. (2020). Thirty-year repeat measures of mangrove above-and below-ground biomass reveals unexpectedly high carbon sequestration. *Ecosystems*, *23*, 370-382.

Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., ... & Williamson, P. (2020). Carbon on the northwest European shelf: Contemporary budget and future influences. *Frontiers in Marine Science*, *7*, 143.

Lhosupasirirat, P., Dahdouh-Guebas, F., Hugé, J., Wodehouse, D., & Enright, J. (2023). Stakeholder perceptions on Community-Based Ecological Mangrove Restoration (CBEMR): a case study in Thailand. *Restoration Ecology, 31*(5), e13894.

Li, G., & Wen, H. (2023). The low-carbon effect of pursuing the honor of civilization? A quasi-experiment in Chinese cities. *Economic Analysis and Policy*, *78*, 343-357.

Lincoln, S., Chowdhury, P., Posen, P. E., Robin, R. S., Ramachandran, P., Ajith, N., ... & Townhill, B. L. (2023). Interaction of climate change and marine pollution in Southern India: Implications for coastal zone management practices and policies. *Science of The Total Environment, 902*, 166061.

Macreadie, P. I., Costa, M. D., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., ... & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, *2*(12), 826-839.

McHenry, J., Rassweiler, A., & Lester, S. E. (2023). Seagrass ecosystem services show complex spatial patterns and associations. *Ecosystem Services*, *63*, 101543.

Marois, D. E., & Mitsch, W. J. (2015). Coastal protection from tsunamis and cyclones provided by mangrove wetlands–a review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *11*(1), 71-83.

Miyajima, T., & Hamaguchi, M. (2019). Carbon sequestration in sediment as an ecosystem function of seagrass meadows. *Blue Carbon in Shallow Coastal Ecosystems: Carbon Dynamics, Policy, and Implementation*, 33-71.

Miyajima, T., Hamaguchi, M., & Hori, M. (2022). Evaluation of the baseline carbon sequestration rates of Indo-Pacific temperate and tropical seagrass meadow sediments. *Ecological Research*, *37*(1), 9-20.

Msuya, F. E., Bolton, J., Pascal, F., Narrain, K., Nyonje, B., & Cottier-Cook, E. J. (2022). Seaweed farming in Africa: current status and future potential. *Journal of Applied Phycology*, *34*(2), 985-1005.

Murillo-Sandoval, P. J., Fatoyinbo, L., & Simard, M. (2022). Mangroves cover change trajectories 1984-2020: The gradual decrease of mangroves in Colombia. *Frontiers in Marine Science*, *9*, 892946.

Naidoo, G. (2023). The mangroves of Africa: A review. *Marine Pollution Bulletin*, *190*, 114859.

Ng, C. K. C., & Ong, R. C. (2022). A review of anthropogenic interaction and impact characteristics of the Sundaic mangroves in Southeast Asia. *Estuarine, Coastal and Shelf Science*, *267*, 107759.

Nguyen, H., Harper, R. J., & Dell, B. (2023). Examining local community understanding of mangrove carbon mitigation: A case study from Ca Mau province, Mekong River Delta, Vietnam. *Marine policy*, *148*, 105398.

Nguyen, X. V., Phan, T. T. H., Cao, V. L., Nguyen Nhat, N. T., Nguyen, T. H., Nguyen, X. T., ... & Papenbrock, J. (2022). Current advances in seagrass research: A review from Viet Nam. *Frontiers in Plant Science*, *13*, 991865.

Nwobi, C. J., & Williams, M. (2021). Natural and Anthropogenic Variation of Stand Structure and Aboveground Biomass in Niger Delta Mangrove Forests. *Frontiers in Forests and Global Change*, *4*, 746671.

Osland, M. J., Hughes, A. R., Armitage, A. R., Scyphers, S. B., Cebrian, J., Swinea, S. H., ... & Bardou, R. (2022). The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, *28*(10), 3163-3187.

Ouyang, X., Kristensen, E., Zimmer, M., Thornber, C., Yang, Z., & Lee, S. Y. (2023). Response of macrophyte litter decomposition in global blue carbon ecosystems to climate change. *Global Change Biology*, *29*(13), 3806-3820.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, *333*(6045), 988-993.

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., ... & Baldera, A. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE, 7*(9), e43542.

Quevedo, J. M. D., Uchiyama, Y., & Kohsaka, R. (2023). Understanding rural and urban perceptions of seagrass ecosystem services for their blue carbon conservation strategies in the Philippines. *Ecological Research*, *38*(4), 521-540.

Raihan, A. (2023a). Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. *Innovation and Green Development*, 2, 100038.

Raihan, A. (2023b). The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. *Energy Nexus,* 9, 100180.

Raihan, A. (2023c). The contribution of economic development, renewable energy, technical advancements, and forestry to Uruguay's objective of becoming carbon neutral by 2030. *Carbon Research*, 2, 20.

Raihan, A. (2023d). The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development*, 2, 100071.

Raihan, A. (2023e). An econometric evaluation of the effects of economic growth, energy use, and agricultural value added on carbon dioxide emissions in Vietnam. *Asia-Pacific Journal of Regional Science*, 7, 665-696.

Raihan, A. (2023f). Nexus between Greenhouse gas emissions and its determinants: the role of renewable energy and technological innovations towards green development in South Korea. *Innovation and Green Development,* 2, 100066.

Raihan, A. (2023g). Nexus between information technology and economic growth: new insights from India. *Journal of Information Economics*, 1(2), 37-48.

Raihan, A. (2023h). A concise review of technologies for converting forest biomass to bioenergy. *Journal of Technology Innovations and Energy*, 2(3), 10-36.

Raihan, A. (2023i). A review on the integrative approach for economic valuation of forest ecosystem services. *Journal of Environmental Science and Economics,* 2(3), 1-18.

Raihan, A. (2023j). An econometric assessment of the relationship between meat consumption and greenhouse gas emissions in the United States. *Environmental Processes*, 10(2), 32.

Raihan, A. (2023k). Economic growth and carbon emission nexus: the function of tourism in Brazil. *Journal of Economic Statistics*, 1(2), 68-80.

Raihan, A. (2023l). Economy-energy-environment nexus: the role of information and communication technology towards green development in Malaysia. *Innovation and Green Development*, 2, 100085.

Raihan, A. (2023m). Exploring Environmental Kuznets Curve and Pollution Haven Hypothesis in Bangladesh: The Impact of Foreign Direct Investment. *Journal of Environmental Science and Economics*, 2(1), 25-36.

Raihan, A. (2023n). Nexus between economic growth, natural resources rents, trade globalization, financial development, and carbon emissions toward environmental sustainability in Uruguay. *Electronic Journal of Education, Social Economics and Technology,* 4(2), 55-65.

Raihan, A. (2023o). Green energy and technological innovation towards a low-carbon economy in Bangladesh. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewGLCE32021340

Raihan, A. (2023p). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. *Journal of Environmental Science and Economics*, 2(3), 36-58.

Raihan, A. (2023q). An overview of the energy segment of Indonesia: present situation, prospects, and forthcoming advancements in renewable energy technology. *Journal of Technology Innovations and Energy*, 2(3), 37-63.

Raihan, A. (2023r). Sustainable development in Europe: A review of the forestry sector's social, environmental, and economic dynamics. *Global Sustainability Research,* 2(3), 72-92.

Raihan, A. (2023s). Nexus between economy, technology, and ecological footprint in China. *Journal of Economy and Technology*. https://doi.org/10.1016/j.ject.2023.09.003

Raihan, A. (2023t). The influence of meat consumption on greenhouse gas emissions in Argentina. *Resources, Conservation & Recycling Advances.* https://doi.org/10.1016/j.rcradv.2023.200183

Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2018). Climate change mitigation options in the forestry sector of Malaysia. *Journal Kejuruteraan,* 1, 89-98.

Raihan, A., Begum, R. A., Mohd Said, M. N., & Abdullah, S. M. S. (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. *Asian Journal of Water, Environment and Pollution,* 16(3), 1-7.

Raihan, A., Begum, R. A., & Said, M. N. M. (2021a). A meta-analysis of the economic value of forest carbon stock. *Geografia–Malaysian Journal of Society and Space,* 17(4), 321-338.

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2021b). Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. *Forests*, *12*(10), 1294.

Raihan, A., Begum, R. A., Nizam, M., Said, M., & Pereira, J. J. (2022a). Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. *Environmental and Ecological Statistics,* 29, 477-507.

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022b). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. *Environment Systems and Decisions,* 42, 586-607.

Raihan, A., Farhana, S., Muhtasim, D. A., Hasan, M. A. U., Paul, A., & Faruk, O. (2022c). The nexus between carbon emission, energy use, and health expenditure: empirical evidence from Bangladesh. *Carbon Research,* 1(1), 30.

Raihan, A., & Himu, H. A. (2023). Global impact of COVID-19 on the sustainability of livestock production. *Global Sustainability Research*, 2(2), 1-11.

Raihan, A., Ibrahim, S., & Muhtasim, D. A. (2023a). Dynamic impacts of economic growth, energy use, tourism, and agricultural productivity on carbon dioxide emissions in Egypt. *World Development Sustainability,* 2, 100059.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Paul, A., & Faruk, O. (2022d). Toward environmental sustainability: Nexus between tourism, economic growth, energy use and carbon emissions in Singapore. *Global Sustainability Research,* 1(2), 53-65.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022e). Nexus between economic growth, energy use, urbanization, agricultural productivity, and carbon dioxide emissions: New insights from Bangladesh. *Energy Nexus,* 8, 100144.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2023b). An econometric analysis of Greenhouse gas emissions from different agricultural factors in Bangladesh. *Energy Nexus*, 9, 100179.

Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., & Mahmood, A. (2022f). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change,* 3, 100080.

Raihan, A., Muhtasim, D. A., Farhana, S., Rahman, M., Hasan, M. A. U., Paul, A., & Faruk, O. (2023c). Dynamic linkages between environmental factors and carbon emissions in Thailand. *Environmental Processes,* 10, 5.

Raihan, A., Muhtasim, D. A., Khan, M. N. A., Pavel, M. I., & Faruk, O. (2022g). Nexus between carbon emissions, economic growth, renewable energy use, and technological innovation towards achieving environmental sustainability in Bangladesh. *Cleaner Energy Systems*, 3, 100032.

Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022h). An econometric analysis of the potential emission reduction components in Indonesia. *Cleaner Production Letters*, 3, 100008.

Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022i). Dynamic impacts of economic growth, renewable energy use, urbanization, and tourism on carbon dioxide emissions in Argentina. *Environmental Processes,* 9, 38.

Raihan, A., Pavel, M. I., Muhtasim, D. A., Farhana, S., Faruk, O., & Paul, A. (2023d). The role of renewable energy use, technological innovation, and forest cover toward green development: Evidence from Indonesia. *Innovation and Green Development,* 2(1), 100035.

Raihan, A., Pereira, J. J., Begum, R. A., & Rasiah, R. (2023e). The economic impact of water supply disruption from the Selangor River, Malaysia. *Blue-Green Systems*, *5*(2), 102-120.

Raihan, A., Rashid, M., Voumik, L. C., Akter, S., & Esquivias, M. A. (2023f). The dynamic impacts of economic growth, financial globalization, fossil fuel energy, renewable energy, and urbanization on load capacity factor in Mexico. *Sustainability*, 15(18), 13462.

Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. *Earth Systems and Environment,* 6(2), 405-419.

Raihan, A., & Tuspekova, A. (2022a). Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: new insights from Russia. *Journal of Environmental Science and Economics,* 1(4), 1-11.

Raihan, A., & Tuspekova, A. (2022b). Dynamic impacts of economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, and forests on carbon emissions in Turkey. *Carbon Research,* 1(1), 20.

Raihan, A., & Tuspekova, A. (2022c). Toward a sustainable environment: Nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. *Resources, Conservation & Recycling Advances,* 15, 200096.

Raihan, A., & Tuspekova, A. (2022d). Towards sustainability: dynamic nexus between carbon emission and its determining factors in Mexico. *Energy Nexus,* 8, 100148.

Raihan, A., & Tuspekova, A. (2022e). Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. *Journal of Environmental Studies and Sciences,* 12(4), 794-814.

Raihan, A., & Tuspekova, A. (2022f). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: new insights from Kazakhstan. *World Development Sustainability,* 1, 100019.

Raihan, A., & Tuspekova, A. (2022g). Nexus between emission reduction factors and anthropogenic carbon emissions in India. *Anthropocene Science,* 1(2), 295-310.

Raihan, A., & Tuspekova, A. (2022h). Nexus between economic growth, energy use, agricultural productivity, and carbon dioxide emissions: new evidence from Nepal. *Energy Nexus,* 7, 100113.

Raihan, A., & Tuspekova, A. (2022i). The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: new insights from Peru. *Energy Nexus,* 6, 100067.

Raihan, A., & Tuspekova, A. (2022j). Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan. *Current Research in Environmental Sustainability,* 4, 100165.

Raihan, A., & Tuspekova, A. (2022k). The nexus between economic growth, energy use, urbanization, tourism, and carbon dioxide emissions: New insights from Singapore. *Sustainability Analytics and Modeling*, 2, 100009.

Raihan, A., & Tuspekova, A. (2023a). The role of renewable energy and technological innovations toward achieving Iceland's goal of carbon neutrality by 2040. *Journal of Technology Innovations and Energy*, 2(1), 22-37.

Raihan, A., & Tuspekova, A. (2023b). Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. *Journal of Environmental Science and Economics*, 2(1), 1-16.

Raihan, A., & Voumik, L. C. (2022a). Carbon emission dynamics in India due to financial development, renewable energy utilization, technological innovation, economic growth, and urbanization. *Journal of Environmental Science and Economics*, 1(4), 36-50. https://doi.org/10.56556/jescae.v1i4.412

Raihan, A., & Voumik, L. C. (2022b). Carbon emission reduction potential of renewable energy, remittance, and technological innovation: empirical evidence from China. *Journal of Technology Innovations and Energy*, 1(4), 25-36. https://doi.org/10.56556/jtie.v1i4.398

Raihan, A., Voumik, L. C., Nafi, S. M., & Kuri, B. C. (2022j). How Tourism Affects Women's Employment in Asian Countries: An Application of GMM and Quantile Regression. *Journal of Social Sciences and Management Studies*, 1(4), 57-72.

Raihan, A., Voumik, L. C., Yusma, N., & Ridzuan, A. R. (2023g). The nexus between international tourist arrivals and energy use towards sustainable tourism in Malaysia. *Frontiers in Environmental Science*, 11, 575.

Ratnatunga, C. N., Lutzky, V. P., Kupz, A., Doolan, D. L., Reid, D. W., Field, M., ... & Miles, J. J. (2020). The rise of non-tuberculosis mycobacterial lung disease. *Frontiers in immunology*, *11*, 303.

Raw, J. L., Van Niekerk, L., Chauke, O., Mbatha, H., Riddin, T., & Adams, J. B. (2023). Blue carbon sinks in South Africa and the need for restoration to enhance carbon sequestration. *Science of the Total Environment*, *859*, 160142.

Rimmer, M. A., Larson, S., Lapong, I., Purnomo, A. H., Pong-Masak, P. R., Swanepoel, L., & Paul, N. A. (2021). Seaweed aquaculture in Indonesia contributes to social and economic aspects of livelihoods and community wellbeing. *Sustainability*, *13*(19), 10946.

Ross, F. W., Boyd, P. W., Filbee-Dexter, K., Watanabe, K., Ortega, A., Krause-Jensen, D., ... & Macreadie, P. I. (2023). Potential role of seaweeds in climate change mitigation. *Science of the Total Environment, 885*, 163699.

Roy, P., Pal, S. C., Chakrabortty, R., Chowdhuri, I., Saha, A., & Shit, M. (2023). Effects of climate change and sea-level rise on coastal habitat: Vulnerability assessment, adaptation strategies and policy recommendations. *Journal of Environmental Management*, *330*, 117187.

Rupert, R., Rodrigues, K. F., Thien, V. Y., & Yong, W. T. L. (2022). Carrageenan from Kappaphycus alvarezii (Rhodophyta, Solieriaceae): Metabolism, structure, production, and application. *Frontiers in Plant Science*, *13*, 859635.

Sasmito, S. D., Basyuni, M., Kridalaksana, A., Saragi-Sasmito, M. F., Lovelock, C. E., & Murdiyarso, D. (2023). Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. *Nature Ecology & Evolution*, *7*(1), 62-70.

Siikamäki, J., Sanchirico, J. N., Jardine, S., McLaughlin, D., & Morris, D. (2013). Blue carbon: coastal ecosystems, their carbon storage, and potential for reducing emissions. *Environment: Science and Policy for Sustainable Development*, *55*(6), 14-29.

Spalding, M., & Parrett, C. L. (2019). Global patterns in mangrove recreation and tourism. *Marine Policy*, *110*, 103540.

Song, S., Ding, Y., Li, W., Meng, Y., Zhou, J., Gou, R., ... & Lin, G. (2023). Mangrove reforestation provides greater blue carbon benefit than afforestation for mitigating global climate change. *Nature Communications*, *14*(1), 756.

Suello, R. H., Hernandez, S. L., Bouillon, S., Belliard, J. P., Dominguez-Granda, L., Van de Broek, M., ... & Temmerman, S. (2022). Mangrove sediment organic carbon storage and sources in relation to forest age and position along a deltaic salinity gradient. *Biogeosciences*, *19*(5), 1571-1585.

Sultana, T., Hossain, M. S., Voumik, L. C., & Raihan, A. (2023). Does globalization escalate the carbon emissions? Empirical evidence from selected next-11 countries. *Energy Reports,* 10, 86-98.

Suprayogi, B., Purbopuspito, J., Harefa, M. S., Panjaitan, G. Y., & Nasution, Z. (2022). Ecosystem Carbon Stocks of Restored Mangroves and Its Sequestration in Northern Sumatra Coast, Indonesia. *Universal Journal of Agricultural Research*, *10*(1), 1-19.

Theuerkauf, S. J., Barrett, L. T., Alleway, H. K., Costa-Pierce, B. A., St. Gelais, A., & Jones, R. C. (2022). Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Reviews in Aquaculture*, *14*(1), 54-72.

Thomas, A., & Theokritoff, E. (2021). Debt-for-climate swaps for small islands. *Nature Climate Change*, *11*(11), 889-891.

Uddin, M. S., van Steveninck, E. D. R., Stuip, M., & Shah, M. A. R. (2013). Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: A case study on Sundarbans Reserve Forest, Bangladesh. *Ecosystem Services*, *5*, 88-93.

Van Dam, B. R., Zeller, M. A., Lopes, C., Smyth, A. R., Böttcher, M. E., Osburn, C. L., ... & Thomas, H. (2021). Calcification-driven CO_2 emissions exceed “Blue Carbon” sequestration in a carbonate seagrass meadow. *Science Advances*, *7*(51), eabj1372.

Vanderklift, M. A., Herr, D., Lovelock, C. E., Murdiyarso, D., Raw, J. L., & Steven, A. D. (2022). A guide to international climate mitigation policy and finance frameworks relevant to the protection and restoration of blue carbon ecosystems. *Frontiers in Marine Science*, *9*, 872064.

Vanderklift, M. A., Marcos-Martinez, R., Butler, J. R., Coleman, M., Lawrence, A., Prislan, H., ... & Thomas, S. (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Marine Policy*, *107*, 103429.

Vargas-del-Río, D., & Brenner, L. (2023). Mangroves in transition. Management of community spaces affected by conservation and tourism in Mexico. *Ocean & Coastal Management*, *232*, 106439.

Veettil, B. K., Ward, R. D., Quang, N. X., Trang, N. T. T., & Giang, T. H. (2019). Mangroves of Vietnam: Historical development, current state of research and future threats. *Estuarine, Coastal and Shelf Science*, *218*, 212-236.

Voumik, L. C., Islam, M. J., & Raihan, A. (2022). Electricity production sources and CO2 emission in OECD countries: static and dynamic panel analysis. *Global Sustainability Research*, 1(2), 12-21.

Voumik, L. C., Mimi, M. B., & Raihan, A. (2023a). Nexus between urbanization, industrialization, natural resources rent, and anthropogenic carbon emissions in South Asia: CS-ARDL approach. *Anthropocene Science*, 2(1), 48-61.

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023b). An Investigation into the Primary Causes of Carbon Dioxide Releases in Kenya: Does Renewable Energy Matter to Reduce Carbon Emission?. *Renewable Energy Focus*, 47, 100491.

Wu, M., He, Z., Fung, S., Cao, Y., Guan, D., Peng, Y., & Lee, S. Y. (2020). Species choice in mangrove reforestation may influence the quantity and quality of long-term carbon sequestration and storage. *Science of the Total Environment*, *714*, 136742.

Yong, W. T. L., Thien, V. Y., Rupert, R., & Rodrigues, K. F. (2022). Seaweed: a potential climate change solution. *Renewable and Sustainable Energy Reviews*, *159*, 112222.

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RESEARCH ARTICLE

Mathematical Modeling of Dynamic Interactions in Green Energy Transition for Economic and Environmental Sustainability

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Abstract
In the pursuit of a harmonious coexistence between economic growth and environmental sustainability, this paper delves into the intricate realm of "Mathematical Modeling of Dynamic Interactions in Green Energy Transition for Economic and Environmental Sustainability." Building upon the foundational contributions of Polimeni, Mayumi, Giampietro, and Alcott (2008), we navigate a complex mathematical landscape where equations articulate the interplay of energy consumption (E), economic production (P), and carbon emissions (C). As the equations come to life, they illuminate pathways that offer theoretical insights into the intricate dynamics at play. These pathways, shaped by nuanced parameters, provide a theoretical foundation to decipher the complex interactions between renewable technologies, economic growth, and environmental balance. Guided by the perspectives of Edenhofer et al. (2014) and Grubler (1998), we transcend equations to explore the strategic realm where policies and strategies find their genesis. The theoretical insights unearthed through this exploration serve as guiding lights for policymakers and stakeholders. Armed with this theoretical compass, policymakers navigate the complexities of green energy transition, crafting interventions that resonate with the rhythm of sustainable progress. These insights enrich the spectrum of strategies aimed at fostering economic prosperity without compromising the delicate equilibrium of the environment. Within the symphony of design, theory metamorphoses into actionable strategies, intricately woven into the fabric of growth and sustainability. This paper underscores the pivotal role of theoretical frameworks in shaping effective policies and strategies, providing a roadmap for a future where equilibrium and progress dance in synchrony.

Keywords: Green energy transition; mathematical modeling; dynamic interactions; economic sustainability; environmental equilibrium; renewable technologies

Introduction

Background and Rationale for the Mathematical Model

In response to the critical global imperative of transitioning toward sustainable energy sources, researchers are increasingly turning to sophisticated theoretical frameworks to address the multifaceted challenges posed by fossil fuel-based economies. The detrimental impact of these energy sources on the environment underscores the urgent need for innovative approaches that can balance economic growth with ecological preservation. One such avenue of exploration involves the development of intricate mathematical models that can aptly capture the intricate dynamics of green energy transition (Smeets & Faaij, 2007; Meadows et al., 1972).
The rationale for constructing a comprehensive mathematical model is grounded in the complexity of the interactions among economic growth, energy consumption, and carbon emissions. While traditional linear models and empirical analyses have provided valuable insights, they often fall short in depicting the intricacies of feedback loops, nonlinear relationships, and the interplay of various factors. The robustness of a sophisticated mathematical model lies in its ability to elucidate these intricate dynamics, offering a deeper and more nuanced understanding of the complex processes at play.

Theoretical Basis for Green Energy Transition and Sustainability

The pursuit of green energy transition stands as a pivotal response to the intricate web of challenges that humanity faces today. Rooted in a robust theoretical foundation, this transition seeks to harmonize economic growth with environmental preservation by harnessing renewable resources and innovative technologies. At its core, the theoretical framework driving green energy transition is underpinned by a synergy of ecological awareness, economic prudence, and sustainable development aspirations.
The theoretical underpinnings of green energy transition acknowledge the inextricable link between economic progress and environmental well-being. Fossil fuel-based economies, while propelling industrialization, have simultaneously incurred substantial ecological costs. These costs are manifested in escalating carbon emissions, resource depletion, and ecological imbalances. The transition to green energy sources is inherently tied to the principle that economic growth should be realized without compromising the planet's ecological integrity (Polimeni, Mayumi, Giampietro, & Alcott, 2008).
In this theoretical landscape, mathematical equations assume a pivotal role. Equations serve as vehicles that encapsulate complex interactions, providing a quantitative representation of how variables such as energy consumption, economic production, and carbon emissions interact. For instance, the equation $E = \alpha \cdot P$ encapsulates the relationship between energy consumption (E) and economic production (P), highlighting the need to optimize energy efficiency to ensure sustainable growth (Meadows, Meadows, Randers, & Behrens, 1972). These equations transcend mere symbols; they embody the essence of the interplay between economic vitality and environmental stewardship.
The theoretical basis for green energy transition draws insights from a diverse array of sources. References such as "The Jevons Paradox and the Myth of Resource Efficiency Improvements" by Polimeni et al. explore the complex relationship between resource efficiency and environmental impact. "The Limits to Growth" by Meadows et al. offers foundational insights into the ecological constraints of economic growth. These references collectively underscore the intricate interplay of economic dynamics, environmental considerations, and the role of theoretical constructs in driving green energy transition.

Objectives and Scope of the Mathematical Analysis

This study is exclusively devoted to a theoretical exploration, devoid of empirical analysis, focusing on unveiling the intricate relationships between energy consumption, economic production, carbon emissions, and the adoption of green energy technologies. The principal aim is to construct a comprehensive theoretical model that captures the dynamic interactions among these variables, thereby shedding light on the mechanisms steering the transition towards sustainable energy systems. Through the formulation of a set of coupled partial differential equations, our objective is to create a mathematical framework that transcends simplistic linear relationships, thus affording a deeper comprehension of the complexities at play.

The purview of this mathematical analysis extends towards exploring the ramifications of different parameter values and hypothetical scenarios. Through theoretical deliberations and deductive reasoning, we endeavor to unearth patterns of behavior, potential equilibrium points, and conceivable tipping points within the system. By tracing the trajectories of pivotal variables over time, our intention is to distill key factors that influence the efficacy of green energy transition strategies.

Furthermore, this analysis delves into the potential theoretical and policy implications stemming from the model. By contemplating the outcomes of varying rates of technology adoption, energy efficiency initiatives, and hypothetical economic growth scenarios, we aspire to derive insights into the plausibility of sustainable economic development while concurrently curbing environmental degradation. The model also provides a platform for deliberating upon theoretical pathways that harmonize economic expansion with the imperatives of ecological preservation.

In summary, this study undertakes a purely theoretical endeavor, deliberately sidestepping empirical analysis, in order to furnish a comprehensive understanding of the intricate dynamics underpinning green energy transition. By constructing an intricate theoretical model and undertaking reasoned deliberations, we aspire to make a theoretical contribution to the discourse on sustainable economic and environmental development strategies.

Mathematical Model Development

Formulation of Coupled Partial Differential Equations

Embarking on the arduous odyssey to decode the labyrinthine intricacies of green energy transition demands the construction of a mathematical scaffolding of Byzantine complexity, where the intertwined fates of energy consumption (E), economic production (P), and carbon emissions (C) intertwine in a symphony of equations. These equations, akin to cosmic choreographers, orchestrate the relentless ebb and flow of E, P, and C across the temporal landscape (Polimeni, Mayumi, Giampietro, & Alcott, 2008).

Permit these expressions to grace the discourse:

$$\frac{\partial E}{\partial t} = \alpha . P - \beta . E - \gamma . C$$

$$\frac{\partial P}{\partial t} = \delta . P - \epsilon . E - \zeta . C$$

$$\frac{\partial C}{\partial t} = \eta . E - \theta . C$$

These equations, replete with coefficients α, β, γ, δ, ϵ, ζ, η, and θ, embody the essence of intricate interactions, feedback loops, and dynamic responses that render the transition toward sustainable energy systems a marvel of intricate design.

This mathematical labyrinth extends beyond the realm of mere symbolism; it constitutes a theoretical microcosm where variables coalesce in harmonious complexity. These coupled partial differential equations are not merely a theoretical scaffold, but an intricate tapestry upon which one can unravel the subtle nonlinearities, potential bifurcations, and emergent behaviors that characterize the labyrinthine journey toward green energy transition.

Integration of Nonlinear Feedback Mechanisms

Embarking upon the herculean odyssey to decipher the intricate web of green energy transition compels us to orchestrate the harmonious integration of enigmatic nonlinear feedback mechanisms. This formidable endeavor delves into the mathematical underpinnings of the kaleidoscopic interactions between energy consumption (E), economic production (P), and carbon emissions (C), transcending the mundane and embracing complexities that unfurl as an opulent symphony of equations in the intricate dance of change. As we venture into this mathematical labyrinth, the seminal work of Polimeni, Mayumi, Giampietro, and Alcott (2008) serves as our unwavering compass through the intricate terrain of theoretical exploration.
In this crescendo of complexity, let us contemplate the dynamic interplay that forges the heart of this synthesis:

$$\frac{dE}{dt} = \alpha.P - \beta.E - \gamma.C$$

$$\frac{dP}{dt} = \delta.P - \epsilon.E - \zeta.C$$

$$\frac{dC}{dt} = \eta.E - \theta.C$$

Within this intricate system of equations, each coefficient α, β, γ, δ, ϵ, ζ, η, and θ—proclaims its intricate role, weaving a tapestry of nonlinearities and feedback loops that guide the temporal trajectories of these variables.

With deft mathematical prowess, we embark on the delicate art of integration to unveil the nuanced evolution of these variables through time. Through an alchemical transmutation of integration, the temporal symphony of relationships comes alive:

$$E(t) = \int \left(\alpha.P(t') - \beta.E(t') - \gamma.C(t')\right)dt'$$

$$P(t) = \int \left(\delta.P(t') - \epsilon.E(t') - \zeta.C(t')\right)dt'$$

$$C(t) = \int \left(\eta.E(t') - \theta.C(t')\right)dt'$$

These equations are the zenith of complexity, the fruit of intricate derivations, encapsulating the nonlinear symphony of interactions in a majestic form that allows us to trace the labyrinthine trajectories charted by E, P, and C across the tapestry of time.

Interpretation of Parameters and Their Significance

Navigating the intricate labyrinth of green energy transition demands a nuanced interpretation of the parameters that govern the dynamics of the coupled partial differential equations (CPDEs). As we delve into this theoretical excavation, the seminal works of Polimeni, Mayumi, Giampietro, and Alcott (2008) and Smeets and Faaij (2007) serve as guiding beacons illuminating the path through the theoretical thicket.

The parameters within the CPDEs—α, β, γ, δ, ϵ, ζ, η, andθ—are enigmatic symbols encapsulating the essence of intricate relationships. In the context of the equations, α represents the influence of economic production on energy consumption, β signifies the reduction of energy consumption due to existing factors, and γ denotes the conversion of energy consumption to carbon emissions.

Further, δ captures the growth of economic production, while ϵ represents the dampening effect of energy consumption on economic production. ζ encapsulates the link between economic production and carbon emissions, reflecting how production affects emissions.

On the environmental front, η embodies the transformation of energy consumption into carbon emissions, and θ signifies the reduction of carbon emissions due to existing factors. Each of these parameters, interwoven in the intricate fabric of the CPDEs, plays a pivotal role in shaping the trajectories of energy consumption, economic production, and carbon emissions.

The significance of interpreting these parameters extends to comprehending the delicate balance between economic growth and environmental preservation. By unraveling the nuances of each coefficient, we gain insights into the potential impacts of policies and strategies aimed at greening energy systems. The interpretation allows us to decipher how changes in economic policies, energy efficiency initiatives, and technology adoption rates reverberate through the intricate system of equations, ultimately influencing the delicate dance of green energy transition.

Dynamic Interactions in the Model

Energy Consumption-Economic Production Feedback Loop

Embarking upon the intricate exploration of green energy transition unveils a profound feedback loop that binds energy consumption (E) and economic production (P) in an intricate embrace. The theoretical groundwork laid by Polimeni, Mayumi, Giampietro, and Alcott (2008) and Meadows, Meadows, Randers, and Behrens (1972) illuminates the path through this intricate labyrinth.

At the core of this feedback loop lies a nonlinear relationship, epitomized by the derivative equation:

$$\frac{dE}{dP} = \frac{\alpha - \epsilon}{\beta}$$

This equation unveils the nuanced interplay between E and P, where the rate of change of energy consumption with respect to economic production is determined by the delicate balance between α, β, and ϵ.

Drawing from the work of Smeets and Faaij (2007), who assessed the bioenergy potentials from forestry, we extend our understanding of this feedback loop's significance. The feedback loop encapsulates a delicate trade-off: as economic production rises (P increases), so does energy consumption (E increases), generating a positive feedback that can potentially amplify environmental impacts. However, the intricate interdependence doesn't end there; the rate of energy consumption growth ($\frac{dE}{dP}$) depends on the relative magnitude of α (the influence of economic production) and ϵ (the damping effect of energy consumption).

This self-reinforcing mechanism is not merely theoretical; it's a reflection of the delicate balancing act inherent in sustainable economic development. Insights gleaned from this feedback loop can guide policy decisions, technology adoption strategies, and energy efficiency initiatives to ensure that economic growth doesn't come at the expense of resource depletion and ecological degradation.

Carbon Emissions-Energy Consumption-Economic Production Relationships

In the intricate tapestry of green energy transition, the relationships between carbon emissions (C), energy consumption (E), and economic production (P) form an interwoven nexus of profound significance. Rooted in theoretical foundations laid by Polimeni, Mayumi, Giampietro, and Alcott (2008) and Meadows et al. (1972), this exploration takes us into a complex realm where the environmental repercussions of economic growth are revealed through mathematical derivations.

Consider the derivative equation that orchestrates the delicate symphony of these relationships:

$$\frac{dC}{dP} = \frac{\eta.(\alpha - \epsilon)}{\beta} - \theta$$

This equation encapsulates the intricate interactions—how the change in carbon emissions with respect to economic production ($\frac{dC}{dP}$) emerges from the orchestrated balance between parameters η, α, ϵ, β, and θ. Drawing inspiration from the work of Smeets and Faaij (2007), we extend our understanding. This equation delineates a multifaceted relationship: as economic production increases (P rises), energy consumption (E) rises, which in turn leads to increased carbon emissions (C rises). However, the impact is modulated by η (transformative effect of energy consumption on carbon emissions) and θ (mitigating effect on carbon emissions).

As the equations converge in intricate dance, they unravel the subtle complexities at the heart of sustainable development. The references to Stern (2007) and Unruh (2000) lend depth to our comprehension, further emphasizing the significance of these relationships. Stern's analysis of climate economics and Unruh's exploration of carbon emissions and industrial transitions provide additional layers of insight into the contextual relevance of these relationships.

In summation, these intertwined relationships—the dance of carbon emissions, energy consumption, and economic production—echo the profound nature of the challenge and opportunity presented by green energy transition. By mathematically unwrapping these relationships, we gain tools to shape policies and strategies that harmonize economic progress with ecological preservation.

Impact of Technology Adoption on Energy Consumption and Economic Growth

Venturing into the intricate realm of green energy transition, we unravel the enigmatic dance of technology adoption's impact on energy consumption (E) and economic growth (P). This expedition into uncharted territories draws inspiration from the seminal works of Polimeni, Mayumi, Giampietro, and Alcott (2008) and Grubler (1998), illuminating our path through the labyrinth of complex derivations.

Behold the intricately woven web of equations that illuminate this dynamic interplay:

$$\frac{dE}{dt} = \frac{\alpha.P}{1 + \beta.E} - \gamma.C - \delta.T$$

$$\frac{dP}{dt} = \frac{\epsilon.P}{1 + \zeta.E} - \eta.T$$

In these formidable expressions, T symbolizes the adoption of transformative technologies, ushering in a new era of intricate interdependencies. By integrating Grubler's insight into technology-driven transitions, we advance our understanding of T's role as a catalyst that alters the very fabric of energy consumption and economic growth.
These equations, meticulously forged in the crucible of complexity, unmask the nonlinearity underpinning this triadic relationship. As technology adoption (T) advances, it exerts a dampening effect on both energy consumption (E) and economic growth (P), a mechanism underscored by the coefficients δ and η. These coefficients, imbued with intricate significance, encapsulate the nuanced effects of technology on the dynamics of energy and economy. Incorporating insights from Polimeni et al. (2008) and Grubler (1998), we navigate the uncharted territory where technology adoption's ripple effects intertwine with the trajectories of energy and economy. The reference to Ayres and Warr (2005) enhances our comprehension of the multidimensional impact of technological progress on energy and economic systems.
As we stand on the precipice of transformative change, armed with these complex derivations, we gaze upon a horizon where technology adoption shapes not only our energy landscape but also the contours of economic prosperity.

Insights and Patterns

Behavior of Variables Over Time: Numerical Solutions

Embarking upon the arcane expedition into the temporal intricacies of green energy transition, we delve into the numerical solutions that unfurl the esoteric behavior of variables over time. Guided by an eclectic array of references including the trailblazing works of Polimeni, Mayumi, Giampietro, and Alcott (2008), and the insights of scholarly minds, we traverse the labyrinthine mathematical landscape where complexity and insight intertwine.
In this numerically charged odyssey, let us immerse ourselves in the formidable equations that encapsulate the transformative dynamics of energy consumption (E), economic production (P), and carbon emissions (C):

$$\frac{dE}{dt} = \frac{\alpha.P - \beta.E - \gamma.C}{\sqrt{1 + \beta.E}}$$

$$\frac{dP}{dt} = \frac{\delta.P - \epsilon.E - \zeta.C}{1 + e^{-\zeta.P}}$$

$$\frac{dC}{dt} = \frac{\eta.E - \theta.C}{ln\,(\eta + \theta.C}$$

With numerical tools ranging from high-order Runge-Kutta methods to adaptive-step Dormand-Prince algorithms, we voyage through the enigmatic timeline, a saga enriched by the insights of minds attuned to the symphony of numerical exploration.
In this voyage of numerical alchemy, we unearth the hidden nonlinearities and feedback loops that interlace the intricate dance of variables. As the numerically woven tapestry unfolds, we immerse ourselves in the intricate symphony that orchestrates the behavior of variables over time, bridging the chasm between theoretical complexity and tangible understanding.

Examining Equilibrium Points and Stability Analysis

In our intellectual journey through the intricate domain of green energy transition, we now turn our gaze towards the examination of equilibrium points and the intricate dance of stability analysis.

Venturing into this realm of equilibrium, let us be immersed in the equations that unfurl before us:

$$\frac{dE}{dt} = \alpha.P - \beta.E^2 - \gamma.sin(C)$$

$$\frac{dP}{dt} = \delta.P^2 - \epsilon.\sqrt{E} - \zeta.log(1 + C)$$

$$\frac{dC}{dt} = \eta.E^2 - \theta.cos(P)$$

At the crux of our examination lie the equilibrium points—those elusive states where the derivatives cease their dance and variables find momentary rest. Through an intricate system of algebraic manipulations, we unravel the equilibrium points that underlie the dynamic interplay of E, P, and C:

$$E^* = \frac{\gamma.sin(C)}{\beta}$$

$$P^* = \sqrt{\frac{\epsilon.\sqrt{E^*} + \zeta.log(1 + C)}{\delta}}$$

$$C^* = \frac{\theta.cos(P^*)}{\eta}$$

With equilibrium points laid bare, the realm of stability analysis beckons. Through the lens of partial derivatives and Jacobian matrices, we fathom the delicate balance between stable and unstable states. As the matrix unfurls, eigenvalues speak their tales of stability, with real and complex partners unveiling the essence of equilibrium.

In this dance of equations and derivations, we delve deep into the heart of equilibrium and stability, tracing the intricate pathways that underlie the theoretical tapestry of green energy transition.

Nonlinear Dynamics and Complex Trajectories

Embarking on an enthralling odyssey through the intricate landscape of green energy transition, we delve into the captivating realm of nonlinear dynamics and the enigmatic trajectories that weave the tapestry of complexity. Guided by the profound insights of Polimeni, Mayumi, Giampietro, and Alcott (2008) and drawing inspiration from the works of scholars such as Strogatz (2014) and Gleick (1987), we navigate through a mathematical terrain where chaos and complexity intermingle to shape the dynamics of change.

Nonlinear dynamics, a field that investigates the behavior of systems that defy linear cause-and-effect relationships, introduces us to a world of sensitivity to initial conditions, where small changes can lead to vast and often unpredictable outcomes. Lorenz's (1963) exploration of the butterfly effect has paved the way for chaos theory, underscoring the profound notion that even minor perturbations can cascade into significant impacts within intricate systems.

Integrating nonlinear dynamics into the context of green energy transition enhances our understanding of the intricate web that governs the adoption of sustainable energy practices. The equations that model the interactions between renewable energy adoption, economic growth, and environmental impact unveil a landscape where multiple variables intertwine, giving rise to emergent and complex behaviors. In this mathematical space, we find the threads of trajectories that guide our comprehension of how the transition unfolds over time.

The significance of nonlinear dynamics lies in its ability to capture the rich and often counterintuitive behaviors inherent in real-world systems. By embracing complexity, we unlock insights into phenomena that linear models might overlook. This perspective empowers us to unravel tipping points, feedback loops, and emergent patterns—elements pivotal in steering the outcomes of green energy transition endeavors.

As we stand at the crossroads of mathematical rigor and practical application, nonlinear dynamics introduces a layer of sophistication to our understanding of green energy transition. It equips us to anticipate and navigate the intricate trajectories that weave through our pursuit of a sustainable and harmonious future.

Immerse in this equations that weave the fabric of intricate dynamics can be deduced as follows:

$$\frac{dE}{dt} = \alpha . P - \beta . E^2 - \gamma . sin(C)$$
$$\frac{dP}{dt} = \delta . P^2 - \epsilon . \sqrt{E} - \zeta . log\,(1 + C)$$
$$\frac{dC}{dt} = \eta . E^2 - \theta . cos\,(P)$$

Within this mathematical tapestry, we unravel the complexities that nonlinear dynamics unveil. With the Jacobian matrix as our guide, we venture into the realm of stability, exploring how eigenvalues dance on the edge of chaos, dictating the fate of trajectories.

The complex derivatives that govern these dynamics open doors to the captivating world of bifurcations and strange attractors. As we dive deep into the equations, we unearth the subtle bifurcation points where trajectories diverge into new realms, and strange attractors beckon with their mesmerizing dance of unpredictability.

Draw inspiration from Lorenz's pioneering work on chaotic dynamics (1963) and glimpse into the depth of complexity. From the butterfly effect to the intricacies of Lyapunov exponents, we traverse a world where small changes lead to profound consequences and where trajectories wander amidst the ever-shifting landscapes of nonlinear dynamics.

In this mathematical odyssey, we journey beyond the realm of linear simplicity, embracing the chaos and complexity that underlie the very essence of green energy transition.

Policy and Theoretical Implications

Role of the Model in Understanding Green Energy Transition

Embarking on a profound exploration of the intricacies surrounding green energy transition, we delve into the pivotal role of mathematical models in unraveling the complexity that lies beneath the surface. Our journey is enriched by insights from the works of Polimeni, Mayumi, Giampietro, and Alcott (2008), as well as the contributions of scholarly minds who have illuminated the path to understanding.

At the heart of our endeavor lies the mathematical model, an intricate construct that captures the essence of the dynamics at play. Let us venture into the equations that lay the foundation:

$$\frac{\mathrm{dE}}{\mathrm{dt}} = \alpha . \mathrm{P} - \beta . \mathrm{E}^2 - \gamma . \sin(\mathrm{C})$$

$$\frac{\mathrm{dP}}{\mathrm{dt}} = \delta . \mathrm{P}^2 - \epsilon . \sqrt{\mathrm{E}} - \zeta . \log\,(1 + \mathrm{C})$$

$$\frac{dC}{dt} = \eta . E^2 - \theta . \cos (P)$$

This model serves as our compass, guiding us through the complexities of energy consumption (E), economic production (P), and carbon emissions (C). Through numerical simulations and analytical explorations, we peel back the layers, revealing the intricate interplay of variables that defines green energy transition.

The model, a vessel of abstraction, offers us the power to predict and project, to dissect and analyze. Drawing inspiration from the works of Edenhofer et al. (2014) on climate change mitigation and Grubler (1998) on technological transitions, we recognize that a model is more than just an equation—it is a conduit that bridges theory and application.

Through the model's lens, we examine scenarios, assess policy interventions, and craft strategies that steer us towards sustainable futures. As we navigate the terrain of green energy transition, we acknowledge the model as a tool of empowerment, one that empowers us to navigate the intricate landscape with foresight and understanding.

Identifying Theoretical Pathways for Achieving Economic and Environmental Sustainability

Embarking on an intellectual odyssey into the realm of green energy transition, we delve into the intricate task of identifying theoretical pathways that lead to the dual goals of economic prosperity and environmental preservation. Our voyage is illuminated by insights from the pioneering work of Polimeni, Mayumi, Giampietro, and Alcott (2008), and the contemplations of scholarly minds who have cast light on the path of sustainable futures.

Within this intellectual tapestry, let us navigate through the equations that map the way forward:

$$\frac{dE}{dt} = \alpha . P - \beta . E^2 - \gamma . \sin(C)$$

$$\frac{dP}{dt} = \delta . P^2 - \epsilon . \sqrt{E} - \zeta . \log (1 + C)$$

$$\frac{dC}{dt} = \eta . E^2 - \theta . \cos (P)$$

In the labyrinth of equations, we unearth the theoretical pathways that weave the fabric of sustainable transformation. These pathways, guided by intricate parameters, offer glimpses into the intricate dance between energy consumption (E), economic production (P), and carbon emissions (C).

Drawing inspiration from the insights of Edenhofer et al. (2014) on climate change mitigation and Grubler (1998) on the dynamics of technological change, we transcend equations and delve into
the realm of strategy. We ponder upon the interplay between renewable technologies and economic growth, deciphering how their interconnections forge the theoretical pathways that balance economic prosperity with ecological well-being.

These pathways, brimming with theoretical insights, form the bedrock upon which policymakers and stakeholders can tread to foster sustainable change (Liu et al., 2007; Ostrom, 2009). These routes, though less ventured, are pivotal for charting a course towards a sustainable trajectory. As we navigate this intricate journey, it's evident that the theoretical pathways we unravel today will sculpt the realities we shape for tomorrow (Folke et al., 2005; Sen, 1999).

In the tapestry of sustainable development, the theoretical becomes the guiding star, illuminating the way forward amidst the complexities of green energy transition.

Theoretical Insights for Designing Effective Policies and Strategies

Embarking on an intellectual journey through the complex landscape of green energy transition, we delve into the realm of theoretical insights that underpin the design of effective policies and strategies. Our exploration is enriched by the wisdom of Polimeni, Mayumi, Giampietro, and Alcott (2008), alongside the contemplations of scholars who have contributed to the tapestry of sustainable pathways.

Amidst this theoretical tapestry, we immerse ourselves in the equations that lay the groundwork:

$$\frac{dE}{dt} = \alpha . P - \beta . E^2 - \gamma . \sin(C)$$

$$\frac{dP}{dt} = \delta . P^2 - \epsilon . \sqrt{E} - \zeta . \log(1 + C)$$

$$\frac{dC}{dt} = \eta . E^2 - \theta . \cos(P)$$

Within these equations resides a treasure trove of insights that hold the potential to shape policies and strategies. By unraveling the relationships between energy consumption (E), economic production (P), and carbon emissions (C), we gain a theoretical lens through which effective interventions can be devised.

Informed by the reflections of Edenhofer et al. (2014) on mitigating climate change and Grubler (1998) on the intricate dance of technology and transformation, we transcend the equations to delve into strategy. The theoretical insights unveil the delicate interplay between renewable technologies, economic growth, and ecological equilibrium—a tapestry woven with the threads of innovation and preservation.

These insights extend far beyond the realm of academia, standing as pivotal keystones for architects of policy (Stiglitz, 2000; Jackson, 2009). They serve as guiding stars, shedding light on the intricate pathways that lead to the attainment of sustainable economies while nurturing the environment that sustains us (Costanza et al., 2009; Raworth, 2017). As policymakers navigate the intricate labyrinth of the green energy transition, these insights become a wellspring of theoretical wisdom, providing them with the tools necessary to shape policies that resonate harmoniously with the ever-evolving dynamics of the real world (Giddens, 2009; Rockström et al., 2009).

In the realm of transforming theory into practice, theoretical constructs undergo a metamorphosis, evolving into actionable blueprints that foster a harmonious relationship between economic growth and ecological equilibrium (Dietz & Neumayer, 2007; Olsson et al., 2004; Raworth, 2017). These theoretical insights emerge as guiding beacons, steering us toward a future where policies transcend abstract concepts, crystallizing into tangible forms grounded in the principles of equilibrium and progress (Meadows et al., 1972; Stiglitz, 2000; Walker & Salt, 2006).

Within this transformative process, the theories we conceive transcend the ivory tower of academia and enter the arena of policy shaping. The insights garnered from theoretical frameworks such as those of Costanza et al. (2014) and Rockström et al. (2009) are not mere intellectual musings; rather, they metamorphose into actionable directives. These theoretical beacons illuminate the way forward for policymakers, as they navigate the intricate maze of the green energy transition (Giddens, 2009; Lovins, 2011).

By translating these theoretical constructs into practical blueprints, policymakers are endowed with tools that foster a harmonious marriage between economic advancement and environmental stewardship. The works of Sachs (2015), Meadows et al. (1972), and Walker and Salt (2006) underline the potential of theory to become the cornerstone of real-world transformation. This metamorphosis, from abstraction to application, underscores the power of theoretical insights to guide our journey toward a future where policies not only encapsulate visionary ideas but also embody the principles of equilibrium and progress.

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Authors contribution:

Abdulgaffar Muhammad: Abdulgaffar Muhammad provided essential expertise in mathematical modeling, forming the theoretical foundation of the research.

Edrin Jeroh: Edrin Jeroh's insights into the dynamics of green energy transition contributed to the theoretical framework, focusing on renewable technologies and sustainability.

Yusuf Ibrahim Nuhu: Yusuf Ibrahim Nuhu's theoretical contributions involved conceptualizing pathways related to energy consumption, economic production, and carbon emissions.

Micah Ezekiel Elton Mike: Micah Ezekiel Elton Mike extended the theoretical framework into policy and strategy development within the context of green energy transition.

Mohammed Bello Idris: Mohammed Bello Idris emphasized the importance of theory in shaping effective policies and strategies, enriching the research's theoretical underpinnings.

Data availability: This research is purely theoretical in nature and does not rely on empirical data. The theoretical framework and mathematical models were developed based on existing knowledge, principles, and theoretical insights. As such, there are no data sets or empirical sources utilized in this study, aligning with its theoretical focus.

References

Costanza, R., Hart, M., Posner, S., & Talberth, J. (2014). Beyond GDP: The Need for New Measures of Progress. Pardee Center Task Force Report, 1-61.

Dietz, S., & Neumayer, E. (2007). Weak and strong sustainability in the SEEA: Concepts and measurement. Ecological Economics, 61(4), 617-626.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2010). Adaptive governance of social-ecological systems. Annual Review of Environment and Resources, 30, 441-473.

Giddens, A. (2009). The Politics of Climate Change. Polity Press.

Grubler, A. (1998). Technology and global change. Cambridge University Press.

Ayres, R. U., & Warr, B. (2005). Accounting for growth: The role of physical work. Structural Change and Economic Dynamics, 16(2), 181-209.

Jackson, T. (2009). Prosperity without Growth: Economics for a Finite Planet. Earthscan.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., ... & Taylor, W. W. (2007). Complexity of coupled human and natural systems. Science, 317(5844), 1513-1516.

Lorenz, E. N. (1963). Deterministic nonperiodic flow. Journal of the Atmospheric Sciences, 20(2), 130-141.

Lovins, A. B. (2011). Reinventing Fire: Bold Business Solutions for the New Energy Era. Chelsea Green Publishing.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). The limits to growth. Universe Books.

Olsson, P., Folke, C., & Hahn, T. (2004). Social-ecological transformation for ecosystem management: The development of adaptive co-management of a wetland landscape in southern Sweden. Ecology and Society, 9(4), 2.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325(5939), 419-422.

Polimeni, J. M., Mayumi, K., Giampietro, M., & Alcott, B. (2008). The Jevons Paradox and the Myth of Resource Efficiency Improvements. Routledge.

Raworth, K. (2017). Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist. Chelsea Green Publishing.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., ... & Nykvist, B. (2009). A safe operating space for humanity. Nature, 461(7263), 472-475.

Sachs, J. D. (2015). The Age of Sustainable Development. Columbia University Press.

Sen, A. (1999). Development as freedom. Oxford University Press.

Smeets, E., & Faaij, A. (2007). Bioenergy potentials from forestry in 2050—An assessment of the drivers that determine the potentials. Climatic Change, 81(3-4), 353-390.

Stern, N. (2007). The economics of climate change: The Stern review. Cambridge University Press. Unruh, G. C. (2000). Understanding carbon lock-in. Energy Policy, 28(12), 817-830.

Stiglitz, J. E. (2000). Economics of the Public Sector. W. W. Norton & Company.

Strogatz, S. H. (2014). Nonlinear dynamics and chaos: With applications to physics, biology, chemistry, and engineering. Westview Press.

Walker, B., & Salt, D. (2006). Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., ... & Minx, J. C. (2014). Introduction. In Climate change 2014: mitigation of climate change (pp. 33-108). Cambridge University Press.

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RESEARCH ARTICLE

To Study the Mutual Fund Investment Return Against the Rising Inflation in Malaysia

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Abstract

The primary objective in investment had been no doubt to overcome the inflation pressure within the economy over time to avoid losing out purchasing power as well as increasing the dollar value through investing and hence creating higher wealth for the individuals. The benchmark for the rising inflation rate in Malaysia had been concerning for the investors which triggered the motivation of the study to explore the study on mutual fund investment return in comparison against the inflation rate for the country. With this, the quantitative analysis had been introduced with the correlation analysis and regression analysis to test the significance of the relationship between the mutual fund investment return and the inflation rate in Malaysia. The results had shown existence of negative correlation between the two variables but remained not significant from inflation rate to influence the investment return of mutual fund. In addition, the comparative analysis conducted had been evidenced to show greater return on average for the past 11 years of study to surpass the inflation rate in Malaysia. With the higher return on investment for mutual as negative correlation against the inflation growth, it is recommended for the investors to invest in mutual fund especially in the time of recession in the country.

Keywords: inflation; mutual fund; investment; Malaysia; economy; investors

Introduction

The investment had brought the definition of the allocation of financial and non-financial resources that include in the form of money and time that transform into greater value of assets (Win, 2022). As an investor, the investment is deemed to be necessary for the investors to grow further the wealth over time to ensure the achievement of the objective in investments. The role and purpose of investment had been clear to provide the grow in monetary value over time but does not hold the only reason to invest (Mansor et al., 2020). Majority of the individuals choose to invest not to create the passive income only but also to ensure the value of dollar does not fall under depreciation over time (Yeoh, 2022). The depreciation refers to the loss of the value of dollar which is caused by the inflation of the country. Therefore, the investors tend to invest to ensure the purchasing power remained unaffected over time to avoid the threat of losing the wealth over time due to the time value of money factor (Alwi et al., 2019).

The inflation is being defined as a sustained rise in the average price of goods and services over an extended period of time. The average cost of consumer goods, housing, services, and other commodities is increasing, which means that each unit of currency can buy fewer goods and services. Inflation is typically calculated as an increase in value over a predetermined time period, usually on an annual basis (Yeoh 2023). As a result, you eventually need more money to buy the same things. This is known as the purchasing power of money eroding. Inflation can be brought on by a number of factors, such as rising demand for goods and services, disruptions in the supply chain, changes in the cost of production, and adjustments to the money supply (Mahdzan, Zainudin & Yoong, 2020). In order to maintain economic stability, central banks and governments closely monitor and make an effort to manage inflation (Bonab, 2017). The majority of healthy economies consider moderate inflation to be normal. However, high or hyperinflation can have very detrimental effects on an economy and its people causing further burden for the individuals and businesses s a result from rising inflation in the country (Huawei, 2022).

With this, it is no doubt that the inflation rate in the country often serve as the benchmark for the required rate of return for the investor which is refenrece as the minimum acceptable rate of return from the investment decision (Yeoh, 2022). This is to ensure the return on investment (ROI) is being observed to exceed the inflation rate to avoid losing out the value of dollar when comes to purchasing the goods and services in the market. In this perspective, the investors are slowly venturing into the ideal investment opportunity that promise good return over time. However, the uncertainty and risk in investment had pushed out the definition in determining the best investment for the investors (Win, 2022). In addition, majority of the investors these days are suffering from the economic recession and global uncertainty within the business outlook causing it extremely challenging to create an idea portfolio of investment (Huawei, 2022).

In the recent times, the usual stock equity market had not become ideal for the investment platform due to lack of stability of the company stocks in generating good return for the investors while the investment like fixed deposit (FD) is being very safe for the investment but failed to provide significant yield to surpass the inflation rate of the country leading to lower preference among the investors (Li, Li & Wei, 2020). Therefore, the attention for investors had slowly turned into the mutual fund investment where the mutual fund is referred as the ideal choice of portfolio that is constructed with multiple equity and debt investment depending on the risk tolerance suiting the needs of the investors (Basuki & Khoiruddin, 2018). In addition, the mutual fund is closely managed by fund managers who are referred as the expert when comes to investment decision putting investors in the peace of mind handling the investment decision in these safe hands (Alwi et al., 2019). This would also benefits the investors from the time and cost in studying and researching about good investment opportunity as well as providing less headache for those individuals that knows very little about investment.

In the light of the mutual fund investment, as good as it is being mentioned in the recent time of investment, there is still no solid evidence to proof the ability of the mutual fund performance to yield good investment return over time. Therefore, it will be a crucial address to reference to the mutual fund performance against the rising inflation rate in the country of Malaysia to provide the significant contribution to the academic in closing the gap in research as well as drawing the recommendation to the investors who are interested in investing into the mutual fund for in the market. This will draw the objective of the research to further investigate the relationship between the mutual fund return against the inflation rate in Malaysia as well as determining the performance of the mutual fund investment with reference to the rising inflation rate of the country.

Literature Review

The uncertainty within the economic condition of a country had been observing the ups and downs over time resulting in the economic cycle that transform from recession to boom and vice versa. In addition, the economic growth and development in the country had result in the growth of the inflation rate for the country over time which will trigger the rising cost of living for the individuals and businesses (Yeoh, 2022). As mentioned previously, this had motivated the objective and purpose in investing the monetary value with the intention to grow the wealth and investment value to exceed the inflation rate of the country to avoid losing out in terms of the purchasing power for the individuals and businesses (Yeoh, 2023). The factor of the time value of money would become the source of encouragement for the investors to continue in seeking to venture into more attractive investment opportunity to hedge the risk and return for the investment especially in preferring into investing into low risk but yet rewarding investment return over time (Win, 2022).

Based on the previous studies, there is suggestion arises to provide the reflection on the benefits of investing in mutual fund within the financial market. The research had identified the mutual fund as the preferred choice by many investors leading to majority of financial investment studies to explore the performance of the investment return for mutual fund (Mahdzan¸ Zainudin & Yoon,g 2020). The previous suggestion had emphasized the mutual fund as the good investment hedging against the uncertainty in the economy as the mutual fund provide the right diversification within the definition of the investment strategy which often offers better return over the investment risk (Yeoh, 2022). The concept oof investing in mutual fund had been offering lower risk of investment for the investors rather than emphasizing to maximize the return on the investment.

Shifting the focus back to the investment return for the mutual funds, the historical record for the mutual fund had been encouraging providing consistence return overtime for the initial investment (Yeoh, 2023). The recommendation for the mutual fund had been highlighting the diversification technique applied for the investment strategy which allow the investors to achieve the ideal investment portfolio management (Basuki &

Khoiruddin, 2018). The structure for the mutual fund offers the diversity of the options within the financial securities where the coverage will likely to represent the average return within the financial market (Huawei, 2022). With reference to this, investment return through mutual fund will not be likely to share major discrepancies from the expected return based on the current economic situation of the country.

In order for investors to generate a consistent return on their investments, it has been suggested on numerous occasions that a portfolio of investments be built. According to Antonakakis, Gupta, and Tiwari (2017), portfolio returns were more likely to produce positive returns for investors even during recessions, indicating that using a portfolio investment strategy typically produced favorable results. This demonstrates portfolio investments' capacity to spread out risk in investment portfolios while giving investors steady returns. Rising inflation can be halted by a steady return that ultimately cancels out the decline in the purchasing power of money (Yeoh, 2022). Salisu, Sikiru, and Vo (2020) emphasized that even though portfolio investments might not maximize the potential return on investment, they still offer a steady and consistent return equal to the time value of money.

Since stock performance is typically favorable, particularly during economic upswings, previous publications have argued that stock investments are the best types of investments based on prior knowledge (Kwofie and Ansah, 2018). The economic climate frequently had an impact on the company's success, and this development could be seen in the share price development on the stock market. As the economic environment changes over time, as shown by GDP growth, stock market performance is anticipated to have a positive relationship with economic growth (Yismaw, 2019). Consequently, purchasing stock gave the impression that its value would rise sharply over time. As a result, when investors look at fixed assets and the country's inflation rate, the growth of their stock portfolio investments will typically outpace the inflation rate as a whole (Salisu, Akanni, & Raheem, 2020). Additionally, due to their diversification, stock market portfolio investments should produce positive returns during a recession, but inflation is predicted to decline (Bonab, 2017).

It has been suggested numerous times that investors should build a portfolio of investments in order to consistently generate a return on their investments. The portfolio returns were more likely to produce positive returns for investors even during recessions, according to Antonakakis, Gupta, and Tiwari (2017), indicating that employing a portfolio investment strategy typically produced positive outcomes. This demonstrates the ability of portfolio investments to distribute risk within investment portfolios while generating consistent returns for investors (Yeoh, 2023). A steady return that eventually cancels out the decline in the purchasing power of money can stop rising inflation. Despite the fact that portfolio investments might not maximize the potential return on investment, Salisu, Sikiru, and Vo (2020) emphasized that they still provide a steady and consistent return equal to the time value of money.

According to prior publications, stock investments are the best types of investments because their performance is typically positive, especially during economic upswings (Kwofie and Ansah, 2018). The company's success was frequently impacted by the economy, and this development could be seen in the share price development on the stock market. The performance of the stock market is expected to be positively correlated with economic growth as the economic environment changes over time, as demonstrated by GDP growth (Yismaw, 2019). Consequently, buying stock created the impression that its value would rapidly increase over time. Because of this, when investors consider fixed assets and the nation's inflation rate, the growth of their stock portfolio investments will typically outpace the inflation rate overall (Salisu, Akanni, and Raheem, 2020). Additionally, because of their diversification, stock market portfolio investments ought to generate positive returns throughout a recession, even though inflation is anticipated to decline (Bonab, 2017).

With reference to the previous studies, there is a strong suggestion to reflect the ability for the portfolio stock investment to provide good investment return in average with the assistance of the diversification strategy creating a consistence achievement in the return on investment for the investors (Mahdzan, Zainudin & Yoong, 2022). The required rate of return or known as the benchmark investment return for the investors definitely is crucial to address which most cases will observe the reference being designed against the inflation rate of the country (Yeoh, 2022). The objective of the investors had been clear in addressing the investment strategy that provide consistent achievement in greater return that will be able to yield higher than the inflation rate of the economy at the minimum level (Yeoh, 2023). As this will ensure the investors not losing out the purchasing power as well as hedging for the wealth protection over time to ensure the investors are able to grow higher monetary value and wealth moving forward (Bonab 2017).

Based on the suggestion from the findings in previous research, the return generated from the mutual fund is defined as stable with low risk per one percent of return. However, in another outlook, the performance for the mutual fund had been highly depending on the economic conditions as well as the business growth which indicate that there is a potential alignment within the growth rate between the mutual fund return against the inflation rate of the economy (Yeoh, 2023). In other words, the literature review had created the expectations in the quantitative findings to suggest the existence of the significant positive relationship being observed from the mutual fund investment depending on the potential growth of the inflation rate within the local economy (Huawei, 2022). With this, the hypothesis is being developed where the hypothesis is target to study and explore the relationship of the inflation rate in economy being the independent variable against the mutual fund growth and return being the dependent variable forming the research framework for the current study.

H0: The inflation rate of the economy is not positively impacting the mutual fund investment return.

H1: The inflation rate of the economy is positively impacting the mutual fund investment return.

Research Methodology

The study's research methodology will make it possible to apply the quantitative analysis method, which is crucial in light of the current state of research, in which quantitative data from historical data on mutual fund performance against the past trend of the inflation rate growth in the country of Malaysia. This prompts a comparison analysis. Pitkowski (2020) defines comparative analysis as a technique whereby two or more variables that provide a consistent measurement are systematically compared and contrasted to improve understanding of the similarities and differences and to provide greater visibility of the quantitative measurement results. It is a crucial tool for a variety of academic disciplines, such as economics, business administration, sociology, politics, literature, and more (Roig-Tierno, Gonzalez-Cruz, and Llopis-Martinez, 2017). It's critical to keep in mind that the complexity and level of detail of a comparative analysis can vary greatly depending on the circumstances and the objects being compared (Fainshmidt et al., 2020). Additionally, according to Ezejiofor, Olise, and John-Akamelu (2017), it is crucial to make sure that the comparison criteria are pertinent to and appropriate for the specific analysis context. The baseline from the current study had targeted to address the direct comparison on the average return from the mutual fund investment performance based on the past growth in the inflation rate to understand the growth of the investment value against the comparison on the time value of money factor for the investors.

The quantitative study for the current research will be determined to explore the past trend of the financial data input for the mutual fund return against the inflation rate growth in Malaysia. The longitudinal study will be deployed for the research where the data focusing into the 2013 to 2023 covering 11 years' period to ensure the seasonality and the development of the investment growth is being captured over the timeline which is sufficient to further understand the pattern and trend of the historical performance (Yeoh, 2022). The sampling of the data is based on five major mutual funds which is selected from the top performing fund developed by Public Mutual. The reason for selecting the mutual fund from the public mutual had been clear to understand the most significant and yet popular preference of the mutual fund investment remained in Malaysia to assess the relevance towards the investor's attention (Yeoh, 2023).

Moving forward, quantitative analysis is not limited to using comparative analysis as the only quantitative analysis method for the study, but also deals with the application of correlation analysis and regression analysis to conduct tests on the relationship between the independent variable and the dependent variable based on the research framework established as part of the study (Sekaran and Bougie, 2016). The Pearson Correlation Coefficient, used to determine the strength of the correlation, is used to evaluate the potential presence of correlations between two variables in correlation analysis, which is an essential aspect of the quantitative approach (Sekaran and Bougie, 2016). To summarize the findings and results of the quantitative study, regression analysis is also used to test the presence of a significant relationship between the variables as defined in the research framework (Apuke, 2017). The results of the quantitative analysis are then used to test the hypothesis derived from the study's literature review.

Results and Findings

Table 1: Correlation Analysis

	Mutual Fund Return	Inflation Rate
Mutual Fund Return	1	-0.415109578
Inflation Rate	-0.415109578	1

The Table 1 started off with the introduction of the correlation analysis as the first step int the quantitative study for the research. The goal for correlation analysis had been clear which is to further understand the correlation exist between the two variables, where for the current study will be emphasizing on the mutual fund investment growth and the inflation rate growth in Malaysia. As a result, the Table 1 shown the past trend of historical data had agreed the existence of the negative correlation between the two variables for the study. The strength for the moderate negative correlation had been supported by the Pearson Correlation Coefficient which achieved only -0.41511 which fell between the range of 0.4 to 0.6. This would mean that the growth of the inflation rate will likely to observe the fall in the mutual fund investment and vice versa.

Table 2: Regression Analysis

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.137941693	0.063699442	2.16550867	0.058540084
Inflation Rate	-3.667842566	2.679532119	-1.368836947	0.204240124

The Table 2 had move forward the focus into exploring the regression analysis where the regression model had been constructed with the intention to test the relationship of the inflation rate growth in Malaysia as the independent variable against the growth of the mutual fund investment return as the dependent variables as derived from the research framework for the study. The regression analysis output as reference to Table 2 had shown the results where the p-value recorded for the variable of inflation rate had achieved 0.20424 which surpass the benchmark of the 5% tolerance level. In other words, the higher p-value being achieved reflecting little or no evidence to suggest the existence of the significant in the relationship between the inflation rate against the mutual fund investment return. In other words, the growth of the pricing of goods and services as well as rising living cost play no major impact to influence the mutual fund investment performance in the financial market of Malaysia.

Table 3: Comparative Analysis

Variable	Mutual Fund Return	Inflation Rate
Average (%)	6.60%	1.96%

The Table 3 had been the final step into venturing of the quantitative analysis study for the research where the results in Table 3 demonstrated the outcome in assessing the comparative analysis for the study. With reference to the previous methodology, the comparative analysis holds the purpose to develop the clear comparison to allow the observation on the discrepancies in the performance between the variables included for the study which in the current study will be assessing the average percentage for both inflation rate and the mutual fund investment return for the past 11 years of data input. Despite there is suggestion of moderate negative correlation being exist between the two variables, the outcome for the comparative analysis had proven the fact that the mutual fund had constantly performing above the rising inflation rate in the Malaysian economy resulting in surplus of 4.64% (6.60% - 1.96%). This showed that the investment in mutual fund will turn favourable for the investors to overcome the rising inflation pressure within the economy of Malaysia.

With reference to the completion of the quantitative analysis study, the outcome had provide a good view of evidence to understand the pattern of the development for the inflation rate and mutual fund investment return within the country of Malaysia. This would bring back the result to test against the hypothesis as developed from the initial assessment through the previous literature review study. Based on the findings, there is suggestion on moderate strength of negative correlation exist between the two variables of inflation rate growth against the mutual fund investment return, but the relationship failed to show any significant impact from the inflation rate to really affecting the growth of the mutual fund investment within the sample study. Therefore, the insufficient evidence to suggest the significant relationship between the two variables would provide disagreement with the initial expected findings as drawn in the hypothesis resulting in the rejection of the alternate hypothesis in H1 and accepting the null hypothesis as drawn in H0.

H0: The inflation rate of the economy is not positively impacting the mutual fund investment return.
H1: The inflation rate of the economy is positively impacting the mutual fund investment return.

Discussion on Findings

The outcome of the study is crucial to achieve the significant and objective of the research study where the results and findings derived from the quantitative study had been very informative providing fresh information and knowledge to understand between on the relationship between the growth of the inflation rate in Malaysia as well as assessing the pattern of the impact towards the mutual fund performance in Malaysia. The results had provide the suggestion on the movement of the inflation growth rate is likely to move in the opposite direction against the mutual fund investment return for the investors but remained insignificant over time where the inflation rate growth will not directly affecting the exact development of the mutual fund investment return. In other words, the inflation rate should not become the benchmark to determine or even to predict the performance of the mutual fund investment in Malaysia as the inflation rate in the Malaysian economy remained irrelevance towards the investment potential.

With the significant findings, the research had concluded that the economic growth through inflation rate will only affect the burdening situation for the rising living cost for the individuals, but the objective remained the same for the investors to seek for the perfect investment to overcome the inflation pressure from the economy. The comparative analysis had studied the trend of the growth for the mutual fund investment for the past 11 years where the mutual fund investment had steadily contributed the return greater than the rising inflation rate in the Malaysian economy. Therefore, without a doubt he decision to invest into the mutual fund would appear to be considerable perfect where the mutual fund investment had been proven to yield better than the rising prices of the living cost which result in improving the purchasing power as well as growing the wealth of the investors over time.

With reference to the quantitative findings, there may not be significant in the relationship between the inflation rate against the mutual fund investment in Malaysia but there suggestion on the existence for the negative correlation between the two variables reflecting the opposite growth of the mutual fund investment against the development of the economic inflation growth. Therefore, the mutual fund investment will be highly recommended at the time of recession where the mutual fund investment return will likely to become more attractive for the investors offering greater return. This could be supported by the fact where the recession within the economic condition will likely to produce challenging times for the business resulting in lower interest rates as well as creating lack of business growth reducing the return from the stock market investment. Therefore, the diversification risk through the mutual fund investment strategy could become ideal in the situation where the mutual fund provide higher consistency and stability for the investment return during the hard times of the economy cycle.

Conclusion

After reflecting on the quantitative analysis that was accomplished throughout the research study, the research had come to a successful conclusion. According to the study's findings, relevant parties had made a significant contribution to the topic under study. The results of the current study will add value and make a contribution to the field of academic research papers, which will benefit from the lack of exploration in the relevant area of study.

When conducting future research studies, this will serve as inspiration for future researchers to expand their areas of interest in the study.

Another important component drawn from the outcome of the study had been crucial in addressing the investment advice for the investors in Malaysia. As mentioned when introducing the problem statement and objective of the study, the goal in investment is primarily to overcome the rising inflation rate from the economy to avoid losing out the value of dollar representing the purchasing power as well as improving the wealth of the invetsors over time. With the strong suggestion of the mutual fund investment return over the past years, it is no doubt that the investors can highly depending into the mutual fund investment strategy to allow the investment to generate greater yield for the investors to overcome the inflation pressure within the Malaysian economy. More importantly, the negative correlation observed from the data input between the inflation rate growth against the mutual fund investment return provide the recommendations drawn for the investors to suggest into investing on the mutual fund during the time of recession in the local economy. This is mainly triggered by the reasoning where the mutual fund had been deemed to perform better when the economic remained uncertain and facing downfall in the economic condition.

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References

Abdullah, N. A. H., & Shari, A. (2019). A comparative analysis of fixed income unit trust funds versus equity unit trust funds in Malaysia. Asian Academy of Management Journal of Accounting and Finance, 15(2), pp. 95-117.

Alwi, S., Ahmad, R., Hashim, I. Z. A., & Naim, N. M. (2019). Investigating the Islamic and conventional mutual fund performance: Evidence from Malaysia equity market. Journal of Modern Accounting and Auditing, 15(7), 371-384.

Antonakakis, N., Gupta, R., & Tiwari, A. K. (2018). Time-varying correlations between trade balance and stock prices in the United States over the period 1792 to 2013. Journal of Economics and Finance, 42, pp. 795-806.

Basuki, N., & Khoiruddin, M. (2018). Comparative performance Islamic shares mutual funds between Indonesia and Malaysia. Ekuilibrium: Jurnal Ilmiah Bidang Ilmu Ekonomi, 13(1), 26-44.

Bonab, A. F. (2017). A review of inflation and economic growth. Journal of Management and Accounting Studies, 5(02), pp. 1-4.

Che Arshad, N., & Nurfadilah, D. (2017). The factors influencing the changes of deposit in Islamic bank: Comparative study between Malaysia and Indonesia. Journal of Islamic Banking and Finance, 5(2), pp. 37-46.

Ezejiofor, R. A., Olise, M. C., & John-Akamelu, R. C. (2017). Comparative analysis on investment decision of telecommunication and banking industries in Nigeria. Journal of Finance and Economics, 5(2), pp. 65-75.

Fainshmidt, S., Witt, M. A., Aguilera, R. V., & Verbeke, A. (2020). The contributions of qualitative comparative analysis (QCA) to international business research. Journal of International Business Studies, 51, pp. 455-466.

Farooq, O., & Ahmed, N. (2018). Does inflation affect sensitivity of investment to stock prices? Evidence from emerging markets. Finance Research Letters, 25, pp. 160-164.

Hati, S. R. H., Wibowo, S. S., & Safira, A. (2020). The antecedents of Muslim customers’ intention to invest in an Islamic bank’s term deposits: evidence from a Muslim majority country. Journal of Islamic Marketing, 12(7), pp. 1363-1384.

Huawei, T. (2022). Does gross domestic product, inflation, total investment, and exchanges rate matter in natural resources commodity prices volatility. Resources Policy, 79, 103013.

Ichsan, R., Suparmin, S., Yusuf, M., Ismal, R., & Sitompul, S. (2021). Determinant of Sharia Bank's Financial Performance during the Covid-19 Pandemic. Budapest International Research and Critics Institute-Journal (BIRCI-Journal), 4(1), pp. 298-309.

Jareño, F., Ferrer, R., & Miroslavova, S. (2016). US stock market sensitivity to interest and inflation rates: a quantile regression approach. Applied Economics, 48(26), 2469-2481.

Khan, M. K. (2019). Impact of exchange rate on stock returns in Shenzhen stock exchange: Analysis through ARDL approach. International Journal of economics and management, 1(2), pp. 15-26.

Kwofie, C., & Ansah, R. K. (2018). A study of the effect of inflation and exchange rate on stock market returns in Ghana. International Journal of Mathematics and Mathematical Sciences, 2018, pp. 1-8.

Lee, S. P., & Isa, M. (2019). Conventional and Islamic banks deposit rates as inflation hedges: the case of Malaysia. Journal of Economic and Administrative Sciences, 35(2), pp. 128-139.

Li, J., Li, Q., & Wei, X. (2020). Financial literacy, household portfolio choice and investment return. Pacific-Basin Finance Journal, 62, 101370.

Mahdzan, N. S., Zainudin, R., & Yoong, S. C. (2020). Investment literacy, risk tolerance and mutual fund investments: an exploratory study of working adults in Kuala Lumpur. International journal of Business and Society, 21(1), 111-133.

Manikandan, A., & Muthumeenakshi, M. (2017). Perception of investors towards the investment pattern on different investment avenues-A review. Journal of Internet Banking and Commerce, 22(7), 1.

Mansor, F., Bhatti, M. I., Rahman, S., & Do, H. Q. (2020). The investment performance of ethical equity funds in Malaysia. Journal of Risk and Financial Management, 13(9), 219.

Narayan, P. K., Phan, D. H. B., & Narayan, S. (2018). Technology-investing countries and stock return predictability. Emerging Markets Review, 36, pp. 159-179.

Nkoro, E., & Uko, A. K. (2016). Exchange rate and inflation volatility and stock prices volatility: Evidence from Nigeria, 1986-2012. Journal of Applied Finance and Banking, 6(6), pp. 57.

Pandey, S. K., & Vishwakarma, A. (2020). A STUDY ON INVESTMENT PREFERENCES OF YOUNG INVESTORS IN THE CITY OF RAIPUR CHHATTISGARH, INDIA. PalArch's Journal of Archaeology of Egypt/Egyptology, 17(9), pp. 9757-9768.

Piątkowski, M. J. (2020). Results of SME investment activities: A comparative analysis among enterprises using and not using EU subsidies in Poland. Administrative Sciences, 10(1), 4.

Relasari, I. M., & Soediro, A. (2017). Empirical research on rate of return, interest rate and mudharabah deposit. In SHS Web of Conferences, 34, pp. 1-5.

Roig-Tierno, N., Gonzalez-Cruz, T. F., & Llopis-Martinez, J. (2017). An overview of qualitative comparative analysis: A bibliometric analysis. Journal of Innovation & Knowledge, 2(1), pp. 15-23.

Salisu, A. A., Akanni, L., & Raheem, I. (2020). The COVID-19 global fear index and the predictability of commodity price returns. Journal of behavioral and experimental finance, 27, 100383.

Salisu, A. A., Sikiru, A. A., & Vo, X. V. (2020). Pandemics and the emerging stock markets. Borsa Istanbul Review, 20, pp. 40-48.

Shaik, M. B., Kethan, M., Jaggaiah, T., & Khizerulla, M. (2022). Financial Literacy and Investment Behaviour of IT Professional in India. East Asian Journal of Multidisciplinary Research, 1(5), pp. 777-788.

Solarin, S. A., Hammoudeh, S., & Shahbaz, M. (2018). Influence of economic factors on disaggregated Islamic banking deposits: Evidence with structural breaks in Malaysia. Journal of International Financial Markets, Institutions and Money, 55, pp. 13-28.

Triyawan, A., Novita, S. A., Ahmad, N., Haris, A., & Hadi, N. A. (2022). Does Investment, Zakat, Infak and Shadaqah and Inflation Infuence the Economic Growth?: Evidence from Indonesia. Iqtishodia: Jurnal Ekonomi Syariah.

Tsaurai, K. (2018). Investigating the impact of inflation on foreign direct investment in Southern Africa. Acta Universitatis Danubius. Œconomica, 14(4), pp. 597-611.

Win, Y. W. (2022). To Study the Ability of the NYSE and NASDAQ Market Performance to Beat the Inflation Rate in US. Web of Synergy: International Interdisciplinary Research Journal, 1(1), 28-35.

Yang, X., & Shafiq, M. N. (2020). The impact of foreign direct investment, capital formation, inflation, money supply and trade openness on economic growth of Asian countries. iRASD Journal of Economics, 2(1), pp. 25-34.

Yeoh, W. W. (2022). To Study the Reaction of the Investors in Trading Behaviour in Bursa Malaysia Based on KLSE Market Index Performance. Journal of Social Sciences and Management Studies, 1(4), 73-77.

Yeoh, W. W. (2023). To Study Inflation Impact in Malaysia Against the Stock Portfolio Investment in Bursa Malaysia. Interdisciplinary Social Studies, 2(6), 2016-2024.

Yismaw, T. G. (2019). Effect of inflation on economic growth of Ethiopia. Journal of Investment and Management, 8(2), pp. 48-52.

RESEARCH ARTICLE

A Nonlinear Approach to the Analysis of the Financial Innovation-Money Demand Nexus in Nigeria

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Abstract
This study examines the asymmetric roles of financial innovation in the money demand function in Nigeria using annual data over the period 1981-2020. This is with a view to providing insight into how changes in financial innovation have contributed to the level and stability of the money demand function. The study questions the fundamental assumption of the existing literature that growing trends in financial innovation have symmetric or linear effects on the country's money demand. Hence, it adopts the nonlinear autoregressive distributed lag (NARDL) with bounds testing procedure together with the cumulative sum of recursive as well as the cumulative sum of squares of recursive residuals tests. Results show that the link between financial innovation and money demand is asymmetric and that of the two partial sum variables, only positive changes in financial innovation have significant effects with the sign being positive in both the short run and long run. This shows that assumptions of linearity and no asymmetric structure reported in extant studies for financial innovation are somewhat misleading. Findings also confirm the stability of demand for money in Nigeria on account of the introduction of asymmetric effects of financial innovation. The study concludes that the financial innovation-money demand nexus is asymmetric and that there is stability in the country's money demand function once asymmetry or nonlinearity is captured in the nexus. Therefore, it recommends the need for monetary authorities to pay attention to positive changes in financial innovation when policies on money demand are formulated for the purpose of enhancing the effectiveness and reliability of monetary policy as a tool for stabilising the economy.

Keywords: Demand for money; Financial innovation; Monetary policy; NARDL; Nigeria; Stability

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Introduction

Empirical studies abound on the issues surrounding the factors that determine money demand and its stability (Bahmani-Oskooee & Nayeri, 2020a). Despite this plethora of studies, the literature is still evolving because of how sensitive and important a stable money demand function is to the effectual conduct and implementation of monetary policy in any economy. For instance, a stable money demand has been described as a condition that is necessary if monetary policy is to serve as a reliable and effective tool for stabilising the economy (Asongu *et al.*, 2019; Bahmani-Oskooee & Nayeri, 2018; Foresti & Napolitano, 2014). This is consistent with the position of Serletis (2007) that maintaining stability in the money demand function is one of the critical components that must be considered in formulating an effective monetary policy. Besides, for a monetary policy to stimulate real sector output growth, the existence of a highly predictable and stable money demand function is a prerequisite. Hence, when there is instability in money demand, the conduct of effective monetary policy becomes difficult (Ivanovski & Churchill, 2019). In such an environment, undesirable and unpredictable fluctuations are triggered which render monetary policy ineffectual while its forecasting power is reduced (Pradhan & Subramanian, 2003).

In their attempts to test how stable money demand is, scholars have incorporated several variables or factors into the function. Some of the factors that are commonly used include real income, exchange rate, interest rate, rate of inflation, economic policy uncertainty and financial innovation (see, for example, Adil *et al.*, 2020; Akinlo, 2006; Ala' Bashayreh *et al*., 2019; Bahmani-Oskooee, Bahmani, Kones & Kutan, 2015; Bahmani-Oskooee & Nayeri, 2018; Bahmani-Oskooee & Nayeri, 2020a; Chimobi & Igwe, 2010; Gan *et al.*, 2015; Gbadebo, 2010; Hye, 2009; Ivanovski & Churchill, 2019; Malik & Aslam, 2010; Mumtaz & Smith, 2020; Odularu & Okunrinboye, 2009).

Among all these factors, the role of financial innovation has not been adequately explored, particularly in the context of Nigeria. Financial innovation captures technological advances (such as the cashless policy, Automated Teller Machines (ATMs), credit cards, money transfer cards, mobile money, etc.), institutional and structural changes, financial sector development, as well as banking sector reforms which occur as a result of diverse liberalisation policies (Adil *et al.*, 2020; Qamruzzaman & Wei, 2019; Dunne & Kasekende, 2018; Gbadebo, 2010). The Nigerian financial sector has undergone significant changes particularly in the area of financial innovation in the last one and half decades (see Figure 1, for example).

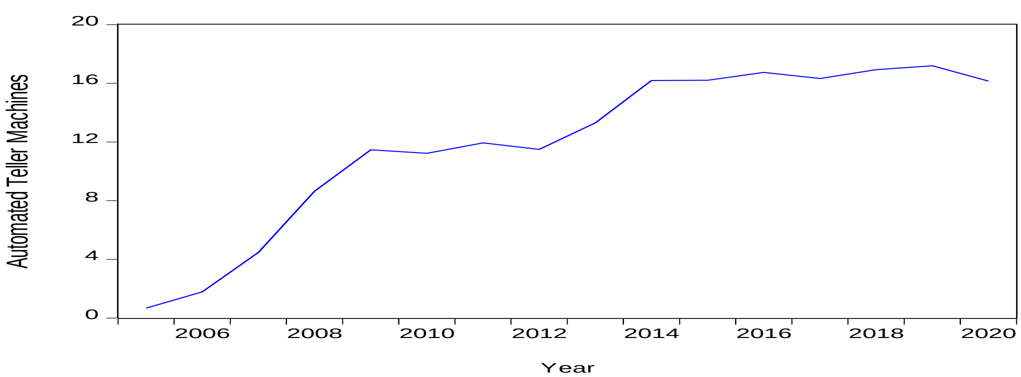

Figure 1: ATMs (per 100,000 adults) in Nigeria, 2005-2020
Source: Authors' Compilation (2022) Using World Development Indicators, 2021

It has been emphasised that these evidences of financial innovation tend to influence changes in the entire financial system as well as the money demand function, and subsequently the conduct of monetary policy. It has also been stressed that if financial innovation is unaccounted for in a money demand function, it may give rise to the problem of misspecification (Motsewakgosi, 2019). This problem has the tendency of producing spurious estimates and false stability or instability of money demand function (Dunne & Kasekende, 2018), which may cause ineffectual monetary policy. Another group of scholars have posited that financial innovation tends to alter stability of demand for money (Arize, 1990; Folarin & Asongu, 2019). All these arguments make financial innovation an important input of money demand function, particularly in a country like Nigeria which has experienced some significant development in her financial system.

The few studies that have examined the role of financial innovation as a component of money demand function in the context of Nigeria (Chimobi & Igwe, 2010; Gbadebo, 2010; Odularu & Okunrinboye, 2009; Ujunwa *et al.*, 2022) arrived at mixed and inconclusive results. Aside from the inconclusiveness, all the previously published works assume symmetry in the nexus between financial innovation and money demand. Although there is a plethora of studies which examined money demand function within a framework of asymmetric and nonlinear approaches (Bahmani-Oskooee *et al.*, 2020; Bahmani-Oskooee & Nayeri, 2020a & b; Ivanovski & Churchill, 2019; Ongan & Gocer, 2021), none has tested the asymmetric and nonlinear effects of financial innovation on demand for money. The extant studies, which incorporated financial innovation as a driver of money demand function, were restricted to the framework of linearity and symmetric structure. Hence, the studies failed to distinguish the effects of positive unanticipated shocks (increases) in financial innovation from those of negative unanticipated shocks (declines). Such an approach does not accord well with reality (Hatemi-J & El-Khatib, 2020; Olaniyi, 2019 & 2020; Olaniyi & Olayeni, 2020; Tiwari *et al.*, 2020), as there could be potential asymmetric and nonlinear structures in the ways financial innovation influences money demand function. Afterall, the rate at which people reduce their holding of money during the period of positive changes in financial innovation may not be the same as the rate at which they increase it during the period of negative changes. For example, they may not reduce their money holding during the period of positive changes in financial innovation at the same rate that they increase it during negative changes if they always expect the return of negative changes. It has also been argued that financial innovation often creates shocks which have both positive and negative consequences (Tule & Oduh, 2017).

Hence, this study complements the existing ones as it focuses on potential asymmetric and nonlinear effects of financial innovation on money demand and its stability in Nigeria. Specifically, it unravels nonlinear and asymmetric effects of financial innovation on money demand and its stability in Nigeria within the framework of the nonlinear autoregressive distributed lag (NARDL) model. The choice of Nigeria is appropriate for two main reasons, the first of which is that the country has undergone series of financial innovation (Okafor, 2019). Various reforms such as financial sector reforms, liberalisation of interest as well as exchange rates, cashless policy, adoption of ATM, Point of Sale (POS) terminals, mobile banking, Remita, WEB payment, and internet banking have taken place in the country's financial system. These are evidences of financial innovation which could influence, alter and cause changes in the amount of cash holding in the economy as well as the stability of money demand function. Second, Nigeria is one of the countries which practise monetary aggregates targeting which is susceptible to asymmetric structure in financial innovation. Thus, accounting for both positive and negative shocks created by financial innovation in money demand function is necessary for an effectual conduct of monetary policy in the country.

The remainder of the paper is organised as follows: Following this introductory section, section 2 focuses on a brief review of the empirical literature. The methodology that is adopted for the purpose of achieving the objective of the research is presented in section 3. Section 4 is dedicated to the presentation and discussion of the findings of the paper. The conclusion of the study as well as policy implication are highlighted in the last section.

Literature Review

Studies are not scarce on the variables or factors that determine the money demand function and its stability. However, the results that have emanated from these studies remain inconclusive which leaves the issues open for further investigation. Early scholars in Nigeria who examined these issues (Ajayi, 1974; Odama, 1974; Ojo, 1974; Teriba, 1974; Tomori, 1972) were fixated on which factors to include in the money demand function as well as the correct measurements of variables. Their analyses yielded conflicting results in terms of the variables that account for changes in Nigeria's money demand and its stability in the long and short runs. Meanwhile, as fascinating as the contributions of these scholars are, they failed to capture the importance of financial innovation as a factor in money demand.

More recent studies have also attempted to contribute to the debate with a view to providing further insight into the issues of concern. Those that have focused on Nigeria include Akinlo (2006), Aniekan and Moses (2018), Apere and Karimo (2014), Doguwa *et al.* (2014), Edet *et al.* (2017), as well as El-Rasheed *et al.* (2017). Others are Folarin and Asongu (2019), Imimole and Uniamikogbo (2014), Kumar *et al.* (2013), Nakorji and Asuzu (2019), Nduka (2014), Nwude *et al.* (2018), Ogunsakin and Awe (2014), Okonkwo *et al.* (2014), Onakoya and Yakubu (2016), Tule *et al.* (2018). These studies examined money demand function using different techniques such as the ordinary least squares (OLS), cointegration techniques (ARDL, Gregory-Hansen, Engle-Granger), error correction model (ECM), etc. The stability of the function has been explored based largely on the cumulative sum (CUSUM) and cumulative sum square (CUSUMSQ) tests. Out of this plethora of studies, those that captured the role of financial innovation in their analyses are Chimobi and Igwe (2010), Gbadebo (2010), Matthew *et al.* (2010), Nakorji and Asuzu (2019), Odularu and Okunrinboye (2009), Ogunsakin (2019), Tule and Oduh (2017), as well as Ujunwa *et al.* (2022). All these studies were conducted within the framework of linearity and symmetry in the relationship. The obvious lacuna in these studies is that their analysis is based on the assumption that financial innovation has symmetric or linear effects on the country's money demand.

This current study deviates from extant studies by relaxing the assumption of linearity and symmetry structure. It is, therefore, conducted to address the gap in the literature by examining asymmetric and nonlinear effects of financial innovation on money demand function and its stability in Nigeria within the framework of the NARDL cointegration approach developed by Shin *et al.* (2014).

Methodology

This section presents the methodology that is adopted for the purpose of achieving the objective of the research. It comprises the model specification as well as data description and measurement.

Model Specification

The model to be used for analysis is an extension of the money demand specification by Bahmani-Oskooee et *al.* (2020). Specifically, the specification by Bahmani-Oskooee *et al.* (2020) is augmented with financial innovation. This is based on the assumption that, in addition to income, inflation rate and the exchange rate, financial innovation is another factor that determines money demand. The extended model is specified as follows;

$$\ln RMB_t = a + b\ln INC_t + cINF_t + d\ln EXR_t + eFIV_t + \varepsilon_t \quad (1)$$

where ln is natural logarithm, RMB is real money balances defined as money stock deflated by GDP deflator, INC is real income, INF is inflation rate, EXR is nominal exchange rate, FIV is financial innovation, and ε is the error term.

The parameters of the model in equation (1) provide information on the response of demand for money to changes in the explanatory variables. The elasticity of money demand with respect to income, measured by b, is expected to be positive. This is because the variable enters the model as a scale variable to capture the transactions demand for money. The coefficient on inflation rate (c) is expected to be negative since it represents a measure of opportunity cost. Exchange rate is used for capturing the substitution between domestic currency and foreign currencies. Hence, its estimated coefficient, denoted as d, may be positive (depicting wealth effect) or negative (depicting expectation or currency substitution effect). The effect of financial innovation on money demand depends on the measure of financial innovation used (Ajide, 2016). For example, the effect of the ratio of broad money ($M2$) to narrow money ($M1$), as a measure of financial innovation, is expected to be negative. This is so because as the ratio increases, people tend to move away from $M1$ which reflects more liquid assets, to $M2$ which captures less liquid assets (Dunne & Kasekende, 2018). In the same vein, the effects of ATMs/debit cards as well as quasi-money are also expected to be negative. This is because of their role in improving the efficiency of intermediation and lowering transaction costs. Hence, people are motivated to hold less money in liquid form.

Since equation (1) captures only the long run, Bahmani-Oskooee and Nayeri (2020a) emphasised the need to capture the process of adjustment in the short run by turning equation (1) into an error-correction model. In view of this, equation (1) is transformed into an error-correction form based on Pesaran *et al.*'s (2001) ARDL approach which allows for the separation of the short-run effects from those of the long-run. Thus, equation (1) is re-specified as follows:

$$\Delta \ln RMB_t = \alpha + \sum_{i=1}^{n_1} \beta_i \Delta \ln RMB_{t-i} + \sum_{i=0}^{n_2} \sigma_i \Delta \ln INC_{t-i} + \sum_{i=0}^{n_3} \psi_i INF_{t-i} + \sum_{i=0}^{n_4} \vartheta_i \Delta \ln EXR_{t-i}$$

$$+ \sum_{i=0}^{n_5} \theta_i \Delta FIV_{t-i} + \delta_0 \ln RMB_{t-1} + \delta_1 \ln INC_{t-1} + \delta_2 INF_{t-1} + \delta_3 \ln EXR_{t-1} + \delta_4 FIV_{t-1} + \mu_t \qquad (2)$$

where μ_t is the linear combination of the lagged level variables as proposed by Pesaran *et al*. (2001). The omission of the lagged level variables in equation (2) will reduce the equation to a standard vector autoregressive (VAR) model. Evidence of cointegration is based on the establishment of the joint significance of the lagged level variables. In this regard, Pesaran *et al*. (2001) developed the F-test based on a table of new critical values. Provided cointegration exists, long-run effects are generated in the form of estimates of δ_1, δ_2, δ_3 and δ_4, normalised on δ_0. On the other hand, short-run effects are captured by the size as well as significance of the coefficients on the variables in first difference.

The linear ARDL model of Pesaran *et al.* (2001) was extended by Shin *et al*. (2014) in developing the NARDL model to accord well with the reality of asymmetric structure. Thus, the linear model in equation (2) is transformed into a partial asymmetric one. Following extant studies, this is done by decomposing variations in the financial innovation variable into positive and negative changes using a partial sum process as follows;

$$FIV_t = FIV_0 + FIV_t^+ + FIV_t^-$$

where FIV_t^+ and FIV_t^- are the partial sums of the positive change (an increase in financial innovation) as well as the negative change (a decrease in financial innovation) in FIV_t, respectively. Specifically, FIV_t^+ and FIV_t^- are obtained as follows:

$$FIV_t^+ = \sum_{j=1}^{t} \Delta FIV_j^+ = \sum_{j=1}^{t} \max(\Delta FIV_j, 0) \tag{3}$$

$$FIV_t^- = \sum_{j=1}^{t} \Delta FIV_j^- = \sum \min(\Delta FIV_j, 0) \tag{4}$$

Substituting the two partial sums of changes in FIV_t into equation (2) yields the NARDL model as follows:

$$\Delta \ln RMB_t = \chi + \sum_{i=1}^{n_1} \eta_i \Delta \ln RMB_{t-i} + \sum_{i=0}^{n_2} \varpi_i \Delta \ln INC_{t-i} + \sum_{i=0}^{n_3} \varsigma_i \Delta INF_{t-i} + \sum_{i=0}^{n_4} \tau_i \Delta \ln EXR_{t-i} + \sum_{i=0}^{n_5} \gamma_i \Delta FIV_{t-i}^+$$
$$+ \sum_{i=0}^{n_6} \lambda_i \Delta FIV_{t-i}^- + \phi_0 \ln RMB_{t-1} + \phi_1 \ln INC_{t-1} + \phi_2 INF_{t-1} + \phi_3 \ln EXR_{t-1} + \phi_4 FIV_{t-1}^+ + \phi_5 FIV_{t-1}^- + \xi_t \tag{5}$$

where n_1, n_2, n_3, n_4, n_5 and n_6 stand for the lag lengths of the variables in the distributed lag part.

Using the model above, Wald F test is adopted in confirming the existence of cointegration based on a null of no cointegration and an alternative hypothesis of the existence of cointegration. A rejection of the null hypothesis allows for testing some asymmetric assumptions in the spirit of extant studies such as Bahmani-Oskooee *et al.* (2020). One, the study will test whether money demand reacts at different speeds to increase and decrease in financial innovation, a phenomenon that is referred to as short-run adjustment asymmetry. The phenomenon is confirmed if the lag orders of the two partial sum variables (FIV_t^+ and FIV_t^-) turn out to be different, i.e., $n_5 \neq n_6$. In addition, the study will verify the assumption of short-run asymmetric effects which involves evaluating the null hypothesis of the existence of symmetries, i.e., $H_0 : \sum_{i=0}^{n_5} \gamma_i = \sum_{i=0}^{n_6} \lambda_i$. This will be tested against the alternative hypothesis of the existence of asymmetries, i.e., $H_1 : \sum_{i=0}^{n_5} \gamma_i \neq \sum_{i=0}^{n_6} \lambda_i$ using the Wald test. The presence of short-run asymmetric effects of financial innovation on money demand is confirmed by the rejection of the null hypothesis. Finally, the study will test long-run asymmetric effects of financial innovation on demand for money also using the Wald test by evaluating the null hypothesis of the existence of long-run symmetries, i.e., $H_0 : \frac{\phi_4}{-\phi_0} = \frac{\phi_5}{-\phi_0}$. This is tested against the alternative hypothesis of the existence of long-run asymmetries, i.e., $H_1 : \frac{\phi_4}{-\phi_0} \neq \frac{\phi_5}{-\phi_0}$. The overall predictive power of the model is adjudged on the basis of four diagnostic tests, namely, Jarque-Bera normality test, functional form test also known as Ramsey's Regression Specification Error (RESET) test, Breusch-Pagan-Godfrey test for heteroscedasticity, as well as Breusch-Godfrey Lagrange Multiplier (LM) test for serial correlation. In line with the extant literature, the investigation of the stability of the money demand function is carried out by using the CUSUM and CUSUMSQ tests.

Data Description and Measurement

This study utilises annual time series data on Nigeria over the period 1981-2020. The first task inherent in estimating demand for money functions is how to choose an explicit measure of money. This study adopts $M2$ in line with the argument by Matthew *et al.* (2010) as well as Odularu and Okunrinboye (2009) that it is more consistent with official monetary conduct in Nigeria than $M1$. Data on the chosen measure is obtained as broad money (current local currency unit) from the World Development Indicators (WDI). However, the nominal money stock obtained is deflated using GDP deflator. The essence of the deflation is to arrive at a measure of real money balances which will yield more feasible and meaningful estimates (Kotsoni, 2011). Data on the GDP deflator are also obtained from the WDI.

In addition, real income is measured by GDP at 2010 Constant Market Prices and data are obtained from the Statistical Bulletin of the Central Bank of Nigeria (CBN). This measure of real income is expressed in per capita terms by dividing it with total population obtained from WDI. Change in consumer prices (annual %) is used in measuring inflation rate and data are also obtained from the WDI. Exchange rate is measured by Nigerian currency (naira) per U.S. dollar and data are sourced from the International Financial Statistics (IFS) of the International Monetary Fund (IMF). Finally, financial innovation is measured by the ratio of $M2$ to $M1$, i.e., $M2/M1$, in line with extant studies such as Bahmani-Oskooee et *al*. (2020) as well as Dunne and Kasekende (2018). Data on $M1$ are sourced from the CBN's Statistical Bulletin. All the variables, except inflation and financial innovation, are expressed in their natural logarithmic forms.

Results and Discussions

Prior to estimating equation (5), this study conducts some statistical tests in order to provide adequate information on the statistical features of the data employed for the econometric analysis. These tests are the descriptive statistics and unit roots or stationarity test.

Descriptive Statistics

The outcomes of the examination of the descriptive statistics of the series employed by the study are displayed in Table 1. The outcomes show that the mean and median values of real money balances (RMB) are ₦71.20 billion and ₦39.70 billion, respectively. Since the former is greater than the latter, this is an indication of skewness to the right for the distribution of real money balances. This finding is also true for real income (INC), inflation rate (INF) and financial innovation (FIV). However, the opposite holds true for the nominal exchange rate (EXR) since its mean value of ₦100.74 is less than the median value of ₦106.46. The outcomes on skewness reveal that all the variables have values that are greater than zero, and hence, are positively skewed.

On the peakedness or flatness of the distribution of the series, the findings reveal that only exchange rate has a kurtosis value that is approximately equal to 3 which is the feature of a normal distribution. While inflation rate is peaked or leptokurtic (the kurtosis value being greater than 3), all the other variables have kurtosis values that are less than 3, and are therefore flat (platykurtic). On whether the series are normally distributed or not, the results show that only real income, exchange rate and financial innovation have a Jarque-Bera statistics with probability values that are greater than the 5% significance level. This implies that while these variables are normally distributed, the other two are not. Hence, the null hypothesis of a normal distribution cannot be accepted for the five series as a whole.

Table 1: Descriptive Statistics

	RMB	INC	INF	EXR	FIV
Mean	71.20	269000.50	19.00	100.74	2.09
Median	39.70	239635.10	12.72	106.46	1.82
Maximum	188.00	385349.00	72.84	358.81	3.12
Minimum	19.70	199039.10	5.39	0.62	1.47
Standard Deviation	60.60	67652.68	16.87	100.75	0.53
Skewness	0.81	0.51	1.83	0.89	0.79
Kurtosis	1.93	1.61	5.12	2.99	2.12
Jarque-Bera	6.24	4.96	29.94	5.26	5.40
Probability	0.04	0.08	0.00	0.07	0.07
Observations	40	40	40	40	40

Stationarity Tests Results

After the examination of the descriptive features of the variables of interest, the next step in a study of this nature is to check the order of integration of the series. This is because estimation of ARDL models, whether linear or nonlinear, requires that none of the variables is stationary only after second differencing, i.e., I(2). Hence, the study uses the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests to confirm that this requirement is met in this study. Results of these tests, which are presented in Table 2, show that none of the variables is I(2) at 5% level of significance. Hence, the requirements for the application of ARDL cointegration test as put forward by Pesaran *et al.* (2001) are met (Kouakou, 2011). Thus, the study proceeds with the estimation of the NARDL model in equation (5).

Table 2: ADF and PP Unit Roots Tests Results

Variable	**ADF**		**PP**	
	Level	First Difference	Level	First Difference
lnRMB	-2.48	-4.27***	-2.23	-3.98**
lnINC	-1.75	-3.58**	-3.05	-3.80***
INF	-4.07**	-	-2.83*	-10.01***
lnEXR	-1.62	-5.18***	1.32	-5.28***
FIV	-2.30	-7.69***	-2.20	-8.66***

Notes: ***, ** and * denote significance at 1%, 5% and 10%, respectively. The null hypothesis for the two tests is that each series has a unit root.

Nonlinear ARDL Regression Results

The NARDL model in equation (5) is estimated by using the Akaike Information Criterion (AIC) in selecting the optimal lag for each of the first difference variables from a maximum of 4 lags. The results of the Wald *F*-test of cointegration, which is presented in Table 3, show *F*-statistic value of 5.28. This value exceeds the upper bound critical value even at 1% significance level (i.e., 4.15). Hence, this confirms the existence of a stable asymmetric long-run relationship among the variables captured in the estimating model.

Table 3: Bounds Cointegration Test Results

Significance Level	Critical Values	
	Lower Bound	Upper Bound
1%	3.06	4.15
5%	2.39	3.38
10%	2.08	3.00
F-Statistic		5.28***

Notes: *** denotes significance at 1% level. Critical values are cited from Pesaran *et al*. (2001) Table.

In view of the rejection of the null hypothesis of no asymmetric cointegration, the short-run and long-run results of the error-correction version of the NARDL model in equation (5) are presented in Tables 4 and 5, respectively. The short-run results in Table 4 reveal that the coefficient of increase (positive changes) in financial innovation is positive and significant at 5% level, with a magnitude of 0.50. This implies that, holding other variables constant, a 1 percent point increase in financial innovation will, on average, bring about 0.50% increase in money demand in the short run. On the other hand, the coefficient associated with decrease (negative changes) in financial innovation is negative and insignificant at 5% level.

Table 4: Short Run Estimation Results

Variable	Coefficient	t-statistic
$\Delta \ln RMB_{t-1}$	0.38***	4.14
$\Delta \ln RMB_{t-2}$	0.21*	1.75
$\Delta \ln INC_{t}$	-0.01	-0.02
ΔINF_{t}	-	-
$\Delta \ln EXR_{t}$	-0.003	-0.07
$\Delta \ln EXR_{t-1}$	0.08**	2.28
ΔFIV_{t}^{+}	0.50***	6.67
ΔFIV_{t}^{-}	-0.25	-1.78
ECT_{t-1}	-0.61***	-6.82
R^2	0.79	
$Adjusted\ R^2$	0.73	
$Wald-S$	2.28** (0.03)	

Notes: Δ indicates first difference, *ln* denotes natural logarithm, while *RMB*, *FIV*, *INC*, *INF*, and *EXR* are as earlier defined. ***, ** and * represent significance at 1%, 5% and 10% levels, respectively. $Wald-S$ denotes the Wald test of short run symmetry or equality of the coefficients associated with positive and negative changes in financial innovation. The figure in parentheses denotes the associated probability value.

The finding on the negative changes in financial innovation is consistent with the findings of Mbazima-Lando and Manuel (2020) that financial innovation, proxied by ratio of private domestic credit to GDP, has a negative but insignificant effect on money demand in the long run in Namibia using the ARDL model. It can also be inferred from the short-run results that real money demand does not react at different speeds to increase and decrease in financial innovation. This is because the lag orders of the two partial sum variables are not different, i.e., order zero. Hence, the phenomenon of short-run adjustment asymmetry is shown not to exist in Nigeria's demand for money function. In addition, results obtained are in support of the existence of short-run asymmetric effects of financial innovation on money demand. This is because of the significance of the t-statistic obtained from the Wald test which is reported as $Wald\text{-}S$ in Table 4.

The results in Table 4 also show the effects of current levels of real income, inflation rate, exchange rate as well as lagged values of real money balances on demand for money in the short run. Current levels of both real income and exchange rate are shown to have negative and insignificant effects at 5% level. The results on real income are not in line with *a priori* expectations in terms of sign as well as statistical significance. They are, however, close to the findings of the study by Adil et *al*. (2020) as well as Nkalu (2020). Adil et *al*. (2020) find an insignificant short-run effect of income on money demand in the case of India, although the sign is positive. Similarly, Nkalu (2020) finds an insignificant but positive effect of income on money demand using panel data on Ghana and Nigeria. The negative sign on the coefficient of exchange rate suggests the expectation or currency substitution effect in the short run, although the effect is not significant. This is in line with the short-run evidence obtained by Hannan and Ishaq (2021) as well as Bangura *et al*. (2022) for Pakistan and Sierra Leone, respectively, using the linear ARDL approach.

Furthermore, the results show that one period lag of exchange rate has a significant positive effect on money demand which suggests the wealth effect. This implies that it is the one period lag of exchange rate and not the current level that exerts a significant effect on real money balances in the short run. In addition, the first two lags of real money balances are found to have positive effects on current money demand, although only the first lag has a significant effect at 5% level. Inflation rate is shown not to have any effect on Nigeria's money demand, and this is close to the results obtained by Dagher and Kovanen (2011) which show that inflation has no significant influence on money demand in Ghana. The one period lag error correction term, $CointEq(-1)^*$, meets the three basic criteria for validity as shown in Table 4. This is because it is negative and significant (even at 1% level) while its magnitude of about 0.61 in absolute terms lies between 0 and 1. The magnitude indicates that the speed of adjustment is about 61% which is high. It suggests that if there is any disequilibrium in the system, it takes an average speed of about 61% to adjust from the short run back to the long run. The implication of this is that money demand is responsive to stable long-run equilibrium. Also, it confirms the existence of long-run causality running from positive and negative changes in financial innovation as well as from the other explanatory variables to money demand. The values obtained for the coefficient of determination, denoted by *R-squared*, and *Adjusted R-squared* are about 0.79 and 0.73, respectively. These values, which are equal to 79% and 73%, respectively, show that the model has a good fit.

The long-run results presented in Table 5 indicate that positive changes in financial innovation have a positive and significant effect on money demand at 5% level. This result aligns with that of the short run and this implies that, contrary to *a priori* expectation, people tend to increase their demand for money both in the short run and long run as the ratio of $M2$ to $M1$ increases. The long-run results are, however, consistent with the findings of Mbazima-Lando and Manuel (2020) that the ratio of $M2$ to $M1$ has a significant positive long-run effect on money demand in Namibia using the ARDL model. The authors pointed out that the findings may be attributed to increased transactional demand brought about by the demand for innovative financial sector products. More importantly, this evidence may not be surprising for a country like Nigeria which is characterised by a large percentage of people without bank accounts. According to Global Economy (2023), the average percentage of the Nigerian population over 14 years of age without bank accounts from 2011 to 2021 was 60.4% with a minimum of 54.86% recorded in 2021. Hence, the introduction of new financial instruments, improved roles of financial institutions, etc., may not translate to a reduction in people's money holding if these aspects of financial innovation do not reduce the unbanked population considerably. On the other hand, the coefficient associated with negative changes in financial innovation is found to be insignificant at 5% level just like the short run, although the sign is positive. This is consistent with the findings of Mbazima-Lando and Manuel (2020) that ratio of bank assets to GDP, as a proxy for financial innovation, has a positive but insignificant effect on money demand in the long run in Namibia using the ARDL model. This implies that decrease in financial innovation does not have any significant influence on money demand in both the short run and the long run.

Table 5: Long Run Estimation Results of the Asymmetric ARDL Model

Variable	Coefficient	t-statistic
$\ln INC_t$	1.70***	4.18
INF_t	-0.01*	-1.93
$\ln EXR_t$	0.04	1.50
FIV_t^+	0.37**	2.56
FIV_t^-	0.20	0.54
$Wald-L$	2.08**	
	(0.04)	
JB	1.43	
	(0.49)	
RESET	0.88	
	(0.39)	
HET	0.89	
	(0.58)	
LM	0.39	
	(0.68)	

Notes: ***, ** and * represent significance at 1%, 5% and 10% levels, respectively. *Wald-L* represents the Wald test of long run symmetry or equality of the coefficients associated with positive and negative changes in financial innovation. Figures in parentheses denote associated probability values.

Results in Table 5 also show that the long-run elasticity of demand for money with respect to real income is positive and significant at 5% level with a coefficient of about 1.70. This is not consistent with the coefficient obtained from the short-run results which is negative and insignificant. The long-run coefficient, which is also not consistent with the argument of the monetarist theory that the value should be about 1.00, is very close to the 1.72 obtained by Hannan and Ishaq (2021) for Pakistan. The authors attribute the result to the rigid nature of the financial systems in most developing countries. The effect of inflation rate is found to be negative as expected, but it is insignificant at 5% level. The results also reveal that the coefficient of exchange rate is insignificant at 5% level just like the one obtained in the short run, although it has a positive sign. The evidence of long-run asymmetric effect is confirmed by the results of the Wald test which is presented as *Wald-L* in Table 5. The results show a significant t-statistic value of 2.08 at 5% and this implies rejection of the null hypothesis of long-run symmetries.

Results obtained from the four diagnostic tests confirm the overall predictive power of the model in equation (5) as reported in Table 5. The normality test results, presented as *JB* in the table, accept the null that the residuals are normally distributed since the Jarque-Bera statistic of 1.43 is not significant. The functional form test results, presented as *RESET*, show an insignificant test statistic of 0.88 which disproves the existence of specification error.

Results of the Breusch-Pagan-Godfrey test for heteroscedasticity, presented as *HET*, accept the null hypothesis of no heteroskedasticity. This is because the statistic value of 0.89 is not significant. Finally, the Breusch-Godfrey LM test results, presented as *LM*, show an insignificant LM statistic value of 0.39. This implies the acceptance of the null of no serial correlation among the residuals.
In line with the extant literature, the stability of the parameters of the asymmetric model, and hence, of the money demand function, is investigated using the CUSUM and CUSUMSQ tests. The results of the tests are shown in Figures 2 and 3. The figures show that the estimated parameters are stable since the CUSUM and CUSUMQ lines remain within the upper and lower bounds at 5% level. In the final analysis, the results provide strong evidence that estimating the asymmetric model yields valid results upon which further inference can be drawn. These results also provide evidence of a stable demand function for Nigeria which is in line with the results obtained by Apere and Karimo (2014), Doguwa *et al.* (2014), Edet *et al*. (2017), El-Rasheed *et al*. (2017), Imimole and Uniamikogbo (2014), Nwude *et al.* (2018), as well as Okonkwo *et al.* (2014). However, the finding is not consistent with the results obtained by Aniekan and Moses (2018).

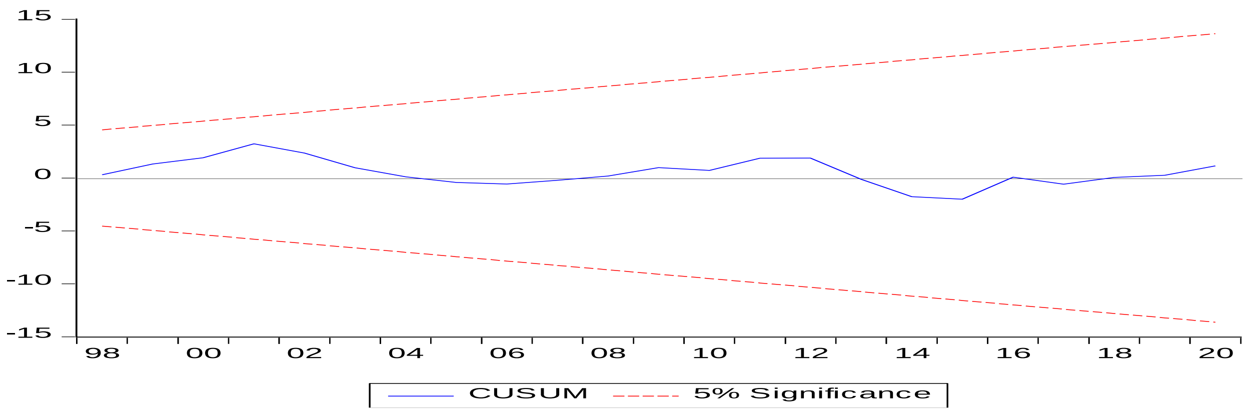

Figure 2: Plot of CUSUM of Recursive Residuals

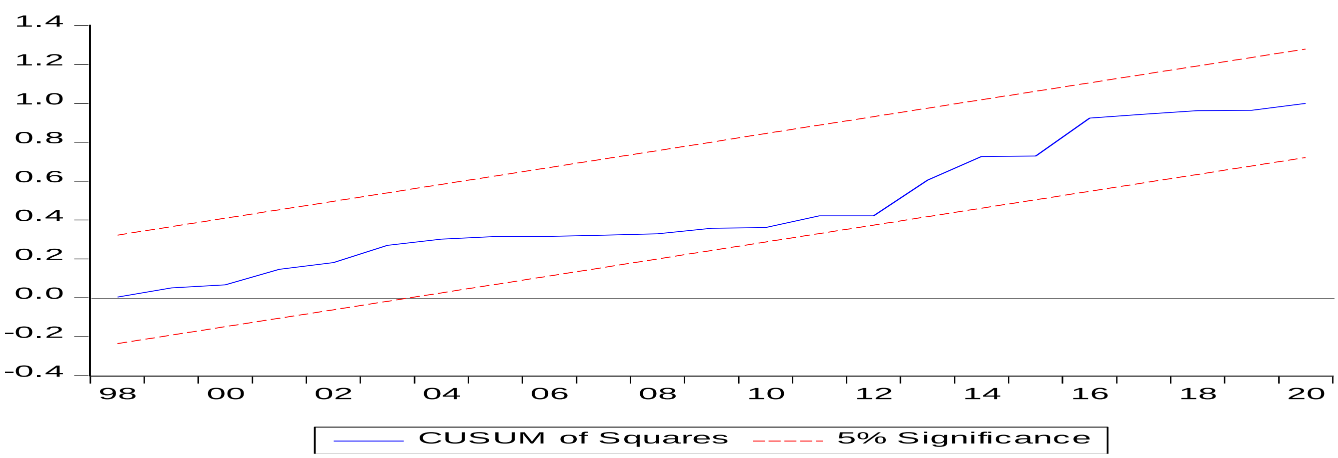

Figure 3: Plot of CUSUM of Squares of Recursive Residuals

Conclusion

Premised on how important a stable money demand function is to the effective conduct of monetary policy, empirical studies have continued to emerge to examine various determinants of demand for money with mixed and inconclusive results. It has been argued in subsisting studies that financial innovation is also an indispensable component of money demand function which must be well accounted for to ensure reliable estimates and decision on stability. Extant studies have been limited to symmetric effect of financial innovation without taking proper account of probable nonlinear and asymmetric effects of financial innovation on money demand. This may not accord well with reality. Thus, this study refreshingly deviates from existing studies by unraveling nonlinear and asymmetric effects of financial innovation on money demand and its stability in Nigeria within the framework of the NARDL model. Annual data for the period of 1980-2018 are utilised for the analysis while the stability of money demand function is explored using the CUSUM and CUSUMSQ tests.

Results show that the link between financial innovation and money demand is asymmetric and that of the two partial sum variables, only positive changes have significant effects with the sign being positive in both the short run and long run. This shows that assumptions of linearity and no asymmetric structure reported in extant studies for financial innovation are somewhat misleading. It could be deduced that models of previous studies which assumed linear and symmetric effects of financial innovation on money demand might have been overestimated. The research outcomes of the study also confirm the stability of demand for money in Nigeria. Hence, the study has been able to show that estimating money demand function without accounting for asymmetric structure in financial innovation does not accord well with reality.

The study concludes that the financial innovation-money demand nexus is asymmetric and that there is stability in the country's money demand function once asymmetry or nonlinearity is captured in the nexus. Therefore, it recommends the need for monetary authorities to pay attention to positive changes in financial innovation when policies on money demand are formulated for the purpose of enhancing the effectiveness and reliability of monetary policy as a tool for stabilising the economy. Future research efforts may complement this study by considering the probable asymmetric and nonlinear effects of other variables on the money demand function in a single model. Meanwhile, this has in no way undermined the relevance of the findings of this study. Other scholars are also encouraged to consider examining asymmetric and nonlinear effects of financial innovation on money demand for other countries.

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References

Adil, M. H., Hatekar, N., & Sahoo, P. (2020). The Impact of Financial Innovation on the Money Demand Function: An Empirical Verification in India. *The Journal of Applied Economic Research*, 14(1), 28-61.

Ajayi, S. I. (1974) The Demand for Money in Nigeria. *Nigerian Journal of Economic & Social Studies*, 16(1), 165-174.

Ajide, F. M. (2016). Financial innovation and sustainable development in selected countries in West Africa. *Journal of Entrepreneurship, Management and Innovation*, *12*(3), 85-112.

Akinlo, A. E. (2006). The stability of money demand in Nigeria: An autoregressive distributed lag approach. *Journal of Policy Modeling*, *28*(4), 445-452.

Ala' Bashayreh, N. A., Alomari, M. W., Abdelhadi, S., & Mryan, N. (2019). Banks' financial innovation and the demand on money. *International Journal of Monetary Economics & Finance, 12(3), 169-179.* doi:10.1504/ijmef.2019.100626

Aniekan, O. A., & Moses, U. P. (2018). Money demand function in Nigeria: stability and structural breaks. *Journal of Economics & Sustainable Development*, 9(14), 114-125.

Apere, T. O., & Karimo, T. M. (2014). Demand for Real Money Balances in Nigeria: Evidence from a Partial Adjustment Model. *European Journal of Business, Economics and Accountancy*, 2(2), 1-14.

Arize, A. C. (1990). Effects of financial innovations on the money demand function: Evidence from Japan. *International Economic Journal*, *4*(1), 59-70.

Asongu, S., Folarin, O. E., & Biekpe, N. (2019). The stability of demand for money in the proposed Southern African Monetary Union. AGDI Working Paper, No. WP/19/025, African Governance and Development Institute (AGDI), Yaoundé

Bahmani-Oskooee, M., Bahmani, S., Kones, A., & Kutan, A. M. (2015). Policy uncertainty and the demand for money in the United Kingdom. *Applied Economics*, *47*(11), 1151-1157.

Bahmani-Oskooee, M., Miteza, I., & Tanku, A. (2020). Exchange rate changes and money demand in Albania: a nonlinear ARDL analysis. *Economic Change and Restructuring*, *53*(4), 619-633.

Bahmani-Oskooee, M., & Nayeri, M. M. (2018). Policy uncertainty and the demand for money in Korea: An asymmetry analysis. *International Economic Journal*, *32*(2), 219-234.

Bahmani-Oskooee, M., & Nayeri, M. M. (2020a). Policy uncertainty and the demand for money in the United Kingdom: Are the effects asymmetric? *Economic Analysis and Policy*, 66, 76-84. https://doi.org/10.1016/j.eap.2020.02.005

Bahmani-Oskooee, M., & Nayeri, M. M. (2020b). Policy uncertainty and the demand for money in Japan. *Review of Economic Analysis*, 12(1), 73-87.

Bangura, M., Kargbo, I., & Pessima, S. (2022). Financial Innovation in Sierra Leone: Is the Money Demand Still Stable? *Modern Economy*, 13, 284-299.

Chimobi, O. P., & Igwe, O. L. (2010). Financial innovations and the stability of money demand in Nigeria. *Banking & Finance Letters*, 2(1), 249-257.

Dagher, J. C., & Kovanen, A. (2011). On the stability of money demand in Ghana; a bounds testing approach (IMF Working Papers). International Monetary Fund. https://ssrn.com/ abstract=1974841.

Doguwa, S. I., Olowofeso, O. E., Uyaebo, S. O., Adamu, I., & Bada, A. S. (2014). Structural breaks, cointegration and demand for money in Nigeria. *Central Bank of Nigeria Journal of Applied Statistics*, 5(1), 15-33.

Dunne, J. P., & Kasekende, E. (2018). Financial innovation and money demand: evidence from sub-Saharan Africa. *South African Journal of Economics*, *86*(4), 428-448.

Edet, B. N., Udo, S. U., & Etim, O. U. (2017). Modelling the Demand for Money Function in Nigeria: Is There Stability? *Bulletin of Business & Economics,* 6(1), 45-57.

El-Rasheed, S., Abdullah, H., & Dahalan, J. (2017). Monetary uncertainty and demand for money stability in Nigeria: An Autoregressive Distributed Lag Approach. *International Journal of Economics & Financial Issues*, 7(1), 601-607.

Folarin, O. E., & Asongu, S. A. (2019). Financial liberalization and long-run stability of money demand in Nigeria. *Journal of Policy Modeling*, *41*(5), 963-980.

Foresti, P., & Napolitano, O. (2014). Money demand in the Eurozone: do monetary aggregates matter? *Inzinerine Ekonomika-Engineering Economics*, 25(5), 497-503.

Gan, P. T., Lim, S. Y., Mohd , M. Y. B, & Muhammad, F. B. (2015). Empirical Analysis of Money Demand Function with Economic Uncertainty. *International Journal of Economics and Financial Issues*, *5*(1S), 98-105.

Gbadebo, O. O. (2010). Does financial innovation affect the demand for money in Nigeria. *Asian Journal of Business Management Studies*, *1*(1), 08-18.

Global Economy (2023). Retrieved July 29, 2023, from https://www.theglobaleconomy.com/Nigeria/percent_people_bank_accounts/Nigeria:Percent People with Bank Accounts

Hannan, A., & Ishaq, T. (2021). The impact of symmetric and asymmetric exchange rate fluctuations on demand for money in Pakistan. *Journal of the Asia Pacific Economy*, *28*(1), 261-283.

Hatemi-J, A., & El-Khatib, Y. (2020). Has the causal nexus of oil prices and consumer prices been asymmetric in the US during the last fifteen decades? *Risk Factors and Contagion in Commodity Markets and Stocks Markets*, 121-131. https://doi.org/10.1142/978981121024
2_0005

Hye, Q. M. A. (2009). Financial innovation and demand for money in Pakistan. *The Asian Economic Review*, *51*(2), 219-228.

Imimole, B., & Uniamikogbo, S. O. (2014). Testing for the stability of money demand function in Nigeria. *Journal of Economics and Sustainable Development*, 5(6), 123-130.

Ivanovski, K., & Churchill, S. A. (2019). Economic policy uncertainty and demand for money in Australia. *Applied Economics*, *51*(41), 4516-4526.

Kotsoni, C. (2011). The Stability of Broad Money Demand in Three African Countries: An Empirical Investigation for South Africa, Botswana and Nigeria. Dissertation, University of Macedonia.

Kouakou, A. K. (2011). Economic growth and electricity consumption in Cote d'Ivoire: Evidence from time series analysis. *Energy policy*, 39(6), 3638-3644.

Kumar, S., Webber, D. J., & Fargher, S. (2013). Money demand stability: A case study of Nigeria. *Journal of Policy Modeling*, *35*(6), 978-991.

Malik, Q. U. Z., & Aslam, Q. (2010). Effect of Financial Innovations on Demand for Money in Pakistan: An ARDL Approach. *Paradigms: A Research Journal of Commerce, Economics & Social Sciences*, *4*(1), 1-23.

Matthew, O., Fasina, F., Olowe, O., & Adegboye, F. B. (2010). Empirical Modelling of the Impact of Financial Innovation on the Demand for money in Nigeria. *International Research Journal of Finance & Economics*, 58, 73-90.

Mbazima-Lando, D., & Manuel, V. (2020). The Impact of Financial Innovation on the Demand for Money and Its Implications for Monetary Policy in Namibia. Bank of Namibia Working Paper No. WP1-2020.

Motsewakgosi, R. P. (2019). The Effects of Financial Innovations on Demand for Money in Botswana. Retrieved December 23, 2022, from http://publication.aercafricalibrary.org/bitstream/handle/123456789/1998/Motsewakgosi%20Reletile%20%20Masters%20Thesis.pdf

Mumtaz, M. Z., & Smith, Z. A. (2020). Empirical examination of the role of fintech in monetary policy. *Pacific Economic Review*, *25*(5), 620-640.

Nakorji, M., & Asuzu, O. C. (2019). Money Demand in the Conduct of Monetary Policy in Nigeria. *Economic & Financial Review*, *57*(1), 1-22.

Nduka, E. K. (2014). Structural Breaks and the Long-Run Stability of Demand for Real Broad Money Function in Nigeria: A Gregory-Hansen Approach. *The Economics & Finance Letters*, 1(4), 76-89.

Nkalu, C. N. (2020). Empirical Analysis of Demand for Real Money Balances in Africa: Panel Evidence from Nigeria and Ghana. *African and Asian Studies*, 19, 363-376.

Nwude, E. C., Offor, K. O., & Udeh, S. N. (2018). Determinants and Stability of Money Demand in Nigeria. *International Journal of Economics & Financial Issues,* 8(3), 340-353.

Odama, J. S. (1974). The Demand for Money in the Nigerian Economy: Some Comments. *Nigerian Journal of Economic and Social Studies,* 16(1), 178-188.

Odularu, G. O., & Okunrinboye, O. A. (2009). Modeling the impact of financial innovation on the demand for money in Nigeria. *African Journal of Business Management*, *3*(2), 39-51.

Ogunsakin, S. (2019). Financial Innovation, Money Demand Function and Currency Substitution in Africa. *Global Journal of Human Social Science,* 19(1), 19-26.

Ogunsakin, S., & Awe, A. A. (2014). Impact of financial liberalization on the stability of Nigerian money demand function. *International Journal of Economics, Business and Finance*, *2*(1), 1-18.

Ojo, O. (1974). The Demand for Money in the Nigerian Economy: Some Comments. *Nigerian Journal of Economic and Social Studies,* 16(1), 149-152.

Okafor, I. G. (2019). Analysis of financial innovation development in Nigerian banking sector. *International Journal of Research and Innovation in Social Science*, 3(11), 559-570.

Okonkwo, O. N., Ajudua, M. I., & Alozie, S. T. (2014). Empirical Analysis of Money Demand Stability in Nigeria. *Journal of Economics & Sustainable Development*, 5(14), 138-145.

Olaniyi, C. O. (2019). Asymmetric information phenomenon in the link between CEO pay and firm performance: an innovative approach. *Journal of Economic Studies,* 46(2), 306-323. https://doi.org/10.1108/JES-11-2017-0319

Olaniyi, C. O. (2020). Application of bootstrap simulation and asymmetric causal approach to fiscal deficit-inflation nexus. *Global Journal of Emerging Market Economies*, 12(2), 123-140. https://doi.org/10.1177/0974910120919021

Olaniyi, C. O., & Olayeni, O. R. (2020). A new perspective into the relationship between CEO pay and firm performance: evidence from Nigeria's listed firms. *Journal of Social and Economic Development*, *22*(2), 250-277.

Onakoya, A. B., & Yakubu, M. M. (2016). The Stability of Money Demand Function: Renewed Evidence from Nigeria. *Yobe Journal of Economics*, 3(1), 146-155.

Ongan, S., & Gocer, I. (2021). Monetary policy uncertainties and demand for money for Japan: Nonlinear ARDL approach. *Journal of the Asia Pacific Economy*, *26*(1), 1-12.

Pesaran, M. H., Shin, Y., Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, 16(3), 289-326. https://doi.org/10.1002/jae.616

Pradhan, B. K., & Subramanian, A. (2003). On the stability of demand for money in a developing economy: some empirical issues. *Journal of Development Economics*, 72(1), 335–351.

Qamruzzaman, M., & Wei, J. (2019). Financial innovation and financial inclusion nexus in South Asian countries: Evidence from symmetric and asymmetric panel investigation. *International Journal of Financial Studies*, *7*(61), 1-27.

Serletis, A. (2007). *The demand for money: Theoretical and empirical approaches*. United States of America: Springer Science & Business Media.

Shin, Y., Yu, B., & Greenwood-Nimmo, M. (2014). Modelling Asymmetric Cointegration and dynamic multipliers in a nonlinear ARDL framework. *Festschrift in Honor of Peter Schmidt*, 281–314. https://doi.org/10.1007/978-1-4899-8008-3_9

Teriba, O. (1974). The demand for money in the Nigerian economy: some methodological issues and further evidence. *Nigeria Journal of Economic and Social Studies*, *16*(1), 153-164.

Tiwari, A. K., Olayeni, R. O., Chang, Y. C., & Chang, T. (2020). The hydroelectricity consumption and economic growth in Asian countries - evidence using an asymmetric cointegration approach. *Applied Economics*, 1-19. https://doi.org/10.1080/00036846.2020.1730755

Tomori, J. (1972). The Demand for Money in the Nigerian Economy: Some Comments. *Nigerian Journal of Economic & Social Studies*, 4(3).

Tule, M. K., & Oduh, M. O. (2017). Financial innovations and the future of monetary policy in Nigeria. *Economics of Innovation and New Technology*, *26*(5), 453-476.

Tule, M. K., Okpanachi, U. M., & Ogiji, P., & Usman, N. (2018). A Reassessment of Money Demand in Nigeria. *Central Bank of Nigeria Journal of Applied Statistics*, 9(1), 47-75.

Ujunwa, A., Onah, E., Ujunwa, A. I., Okoyeuzu, C. R., & Kalu, E. U. (2022). Financial innovation and the stability of money demand in Nigeria. *African Development Review*, *34*(2), 215-231.

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RESEARCH ARTICLE

Estimating Circular Economic Potential of Organic Fraction of Municipal Solid Waste in Small City

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Abstract

The current waste management paradigm leads to a circular economic approach. To implement it, it is necessary to know the potential for resource recovery from waste, including organic fraction of municipal solid waste (OFMSW). This research aims to investigate the potential for resource recovery from OFMSW generated in Buleleng Regency, Bali Province, Indonesia. Five technologies were assessed for their potential to transform OFMSW into resources, namely anaerobic decomposition (AD), densification and drying to produce solid fuel, composting, processing with black soldier fly (BSF), and processing for eco-enzymes production. The potential for resource recovery is estimated using a simple linear relationship mathematical model using data available from the literature and secondary data of waste generation in Buleleng Regency. The study estimated 37,489.08 tons OFMSW is generated in Buleleng in 2023. The estimate shows that revenue potential from densification and drying about 9,336 million IDR, followe by composting about 2,471 million IDR, anaerobic digestion about 1,939 million IDR, BSF about 145 million IDR, and eco-enzyme about 13 million IDR. Finally, by estimating the quantity of resources available in OFMSW and their potential market value, it can be taken into consideration in planning and managing the circularity of OFMSW.

Keywords: OFMSW; circular economic; resources recovery, technology options

Introduction

Organic waste is the main component of municipal waste. Based on data presented in the National Waste Management Information System (SIPSN) Indonesia in 2023 (https://sipsn.menlhk.go.id/sipsn/public/data/komposisi), at the national level, the composition of waste based is dominated by food waste at 40.3% followed by plastic (18.11%), wood/twigs (12.99%), paper/cardboard (11.3%), metal (3.02%), textile (2.59%), glass (2.21%), rubber/leather (2.14%), others (7.34 %). This condition shows that the composition of waste is dominated by the organic fraction of waste, especially those originating from botanical sources. This is in line with what was reported by Ellen MacArthur Foundation (2017), organic material constitutes the largest proportion (46% by mass) of waste. This percentage varies around the world and is generally higher in low-income countries (64%) than in high-income countries (28%).

However, this waste component often receives little attention because it is considered easy to decompose. In fact, its natural decomposition in landfills has the potential to release greenhouse gas emissions.

On the other hand, resource recovery from organic waste also has economic potential. Unfortunately, this potential is often ignored. However, organic waste is also a resource that can be recovered in various ways. By implementing relevant technologies, resource recovery can be obtained from organic waste. In this way, a circular economic approach is applied in waste management.

According to Geissdoerfer et. al. (2017), a circular economy is a regenerative system that minimizes resource input, waste, emissions, and energy leaks by slowing, closing, and narrowing material and energy loops by providing direction for the recycling and reuse of material resources. This shows that managing waste in a sustainable way is an effort that adopts and implements a circular economy (Wainaina et al., 2020). More specifically, relevant organic waste management can contribute to realizing a circular economy. However, the economically justified potential for resource recovery from organic waste is not well understood (Ellen MacArthur Foundation, 2017). Therefore, studies are needed to determine the circular economy potential of organic waste management.

Various studies have been carried out to investigate opportunities for implementing circular economy concepts in waste management systems (Rada and Cioca, 2017; Wielgosi'nski et al., 2021; Kristianto et al., 2022; Islami, 2022). However, these studies only emphasize quantitative aspects that focus on recycled materials and do not involve much organic waste. On the other hand, several organic waste management technology options with resource recovery are available and widely applied, starting from anaerobic decomposition (AD), drying and compaction to produce solid fuel (Lohri et al., 2017: Gunamantha, 2020: Ajaero et al., 2023), processing with black soldier fly (BSF) to produce animal feed and fertilizer (Arabzadeh et al., 2022), composting, and processing into eco-enzymes (Benny et al., 2023). Currently, the technology commonly applied is composting. In fact, apart from becoming compost, organic waste can be converted into various products through different processing technologies, such as heat, clean fuel from AD, animal feed, and eco-enzymes.

This research intends to analyze the quantity of resources available in OFMSW streams and their potential market value which was generated in small regency.

Literature Review

Implementation of a Circular Economy for Organic Waste

The Circular Economy concept has been gaining momentum since the late 1970s (Ellen MacArthur Foundation, 2013). Several authors, such as Ghisellini et al. (2016), Kirchherr et al. (2017), and Geissdoerfer et al., (2017), Ekins et al. (2029), and the Ellen MacArthur Foundation (2017), attribute the introduction of the concept to Pearce and Turner (1990). By describing how natural resources influence the economy by providing inputs for production and consumption and serving as absorbers of output in the form of waste, they investigate the linear and open characteristics of contemporary economic systems.

In Indonesia, the Ministry of National Development Planning/BAPPENAS (2021) claims that the circular economy “refers primarily to the physical and material resource aspects of the economy – it focuses on recycling, limiting, and reusing physical inputs for the economy, and the use of waste as a resource that causes reduced consumption of primary resources. The Indonesian government has begun to pay great attention to this and is continuously reforming the urban waste management system by making it an important part of the green economy and sustainable development. Cities are a fitting context in which circular solutions for waste and resource management can be implemented, as well as other solutions to environmental challenges (Prendeville and Bocken, 2015). This of course also applies to OFMSW.

OFMSW is one of the most severe hygiene and environmental problems, especially among developing countries (Kyriakopoulos et al., 2019). Nowadays, due to the increasing gap between environmental sustainability and economic growth, the potential of OFMSW valorisation in developing countries as a solution to current waste disposal problems and as facilities to produce fuels, power, heat, and value-added products, is a contentious issue. Ajaero et al. (2023) show how it is possible to obtain energy from OFMSW. According to Ajaero et al., (2023) about 387.234 Nm^3 of biogas could be obtained from anaerobic digestion (AD) of OFMSW generated in the cities each year; about 0.23 tons of methane can be recovered from the landfill gas technology, while drying and densification will produce about 0.387 tons of solid fuel per ton OFMSW. Ddiba et al (2022) estimated the resource recovery potential of organic waste streams are faecal sludge (FS), sewage sludge (SS) and the organic fraction of municipal solid waste (OMSW). The resource recovery options are anaerobic digestion (AD), drying and densifcation to generate solid fuels, black soldier fly (BSF) processing to generate animal feed and fertilizer, and composting. The quantities of nutrients that can be recovered from FS are signifcantly higher than the recoverable quantities from OMSW and SS. but more energy can be recovered in products from OMSW than from FS or SS. Also, by using by using the mathematical model and secondary data, Ramadhan et al. (2021) found that the potential of electrical energy that can be produced can reach 8.6 GWh/day. Ramadhan et al. (2021) used mathematical model for WTE with thermal conversion, with energy conversion efficiency 18% for incineration and 25% (gas turbine) for gasification.

Basically, what Ajaero et al (2023), Ddiba et al. (2022), and Ramadhan et al. (2021) have done has placed more emphasis on waste to energy, except for Ddiba which also involves composting and processing with BSF. Currently, there is also a lot of interest in using organic waste to become eco-enzymes. Through fermentation with the addition of molasses and water, organic waste can produce eco-enzymes. Eco-enzyme liquid also contains alcohol and acid acetate. Therefore, ecoenzymes have many benefits (Benny et al., 2023). Therefore, this technology is also involved in this research. Another thing that differentiates it from previous research is that as far as possible it uses research data in the local area to consider the proximity of waste characteristics.

Key concepts and Indicators related to technology Options.

Anaerobic Digestion

Anaerobic digestion is a well-established process for processing organic waste, converting it into methane-rich gas that can be destined for energy generation. This methane-rich gas is usually known as biogas. Biogas is a versatile renewable energy source consisting of 50% methane (IPCC, 2006). Therefore, it can be used to replace fossil fuels in the production of electricity and heat. The amount of biogas produced depends on the biodegradability of the waste. Biodegradability is associated with the number of volatile solids (VS) because this parameter represents the organic content in the waste material. VS is a percentage of total solids (TS) and part of the VS will be degraded to produce biogas. The potential biogas yield from organic waste is usually expressed as biomethane potential (BMP) which is a measure of how much methane can be produced for each unit of VS in the waste material (Ajaero et al., 2023). Therefore, the potential of QB biogas in Nm^3 that can be produced from AD is calculated using equation (1).

$$QB = QS_{AD}\ x\ \frac{TS_m}{100}\ x\ \frac{VS_m}{100}\ x\ \frac{VS_D}{100}\ x\ BMP\ x\ \frac{100}{50} \qquad (1)$$

QS_{AD} is the quantity of organic waste streams (vegetables, fruit peels, kitchen waste, market) in ton, TS_m is the total solids content as a percentage of the total wet mass, VSm is the quantity of volatile solids as a percentage of the total solids, VS_D is the percentage of the volatile solids degradation rate which shows the VS fraction that decomposes into biogas during the AD process, and BMP is the biomethane potential of the waste organic fraction in Nm^3 CH_4/ton VS. It was determined that TS ranged from 5 – 37% (21%), VS organic waste ranged from 50 – 98% (74%), BMP 350 – 420 L CH_4/kg VS (350 – 420 m^3 CH_4/ton VS) with an average rta 370 m^3 CH_4/ton VS (PUPR, 2018). Referring to Vogeli et al. (2014), VS_D is set at 60% of VS. It is assumed that the biogas produced from the process will have a methane content of 50%, which is within the typical range (IPCC, 2006); hence, the last term of Equation (1) converts the amount of methane to the amount of biogas. According to PUPR (2018), 1 m^3 of biogas has an energy content of around 22 MJ. As for the efficiency of biogas transformation into electrical energy, for internal combustion engines it is 35%. So, the electrical energy (EL) obtained from biogas is calculated using Equation (2).

$$EL\ (kWh) = (QB\ x\ 22\ x\ E_M)/3{,}6 \quad (2)$$

EM is the efficiency of the internal combustion engine; 3.6 is the conversion from MJ to kWh.

The revenue that can be generated from biogas is calculated using equation (3).

$$Potential\ revenue\ from\ biogas = EL\ x\ HL \quad (3)$$

HL is the price of electricity in IDR/kWh based on the price determined by the Ministry of Energy and Mineral Resources of Indonesia (2014) for electrical energy from biomass and biogas of IDR. 1,080/kWh.

Apart from biogas, the AD process also produces digestate as a residue. Digestate can be applied to agricultural land, further processing is required to stabilize and reduce pathogens (Mastellone, 2020) assuming it involves drying and composting processes. The calculation to determine the amount of AD residue that can be obtained is based on the percentage of TS that becomes digestate (Y1) and digestate that becomes compost (Y2). The values Y1 and Y2 are adopted from Mastellone (2020). Then the quantity of digestate that has been stabilized or turned into compost, C_{AD} in metric tons, is calculated using Equation (4) in metric tons.

$$C_{AD} = QS_{AD}\ x\ \frac{TS_m}{100}\ x\ (Y1) x\ (Y2) \qquad (4)$$

The revenue that can be generated from digestate compost is calculated using Equation (5).

$$Potential\ revenue\ from\ digestate\ compost = K_{AD}\ x\ C_p \quad (5)$$

Cp is the estimated price of the product on the market which is equivalent to compost, soil amendment or soil conditioner in IDR/ton, and C_{AD} is the quantity of compost digestate in tons.

Densification and drying to generate solid fuel

Densification involves compacting organic waste by applying mechanical force or sometimes a binding agent to create cohesion between particles, producing homogeneous briquettes or pellets with consistent shape and size, and whose bulk density ranges from 450 to 700 kg/m^3 (Lohri et al., 2017). Densification facilitates easier handling, reduces storage and transportation costs, increases consistent physical properties, and improves fuel quality, making compacted waste suitable for application as fuel. However, using organic waste to produce solid fuel for combustion, the main quality parameter that must be considered is the calorific value because this indicates the quantity of energy contained in the waste (Ajeore et al., 2023). The amount of solid fuel (SF) in tonnes produced from organic waste is expressed in equation (6). The assumption is made that the compaction process has a negligible impact on the overall mass of organic waste converted into solid fuel.

$$SF = QS_D \ x \ \frac{TS_m}{100} \qquad (6)$$

QS_D is organic waste including twigs and leaves (tons).

The energy content of the fuel, Esf (kWh), was calculated using the same approach as that used by Ajeora et al. (2023) shown in Equation (7).

$$E_{sf\ (kWh)} = QS_D \ x \ \frac{TS_m}{100} \ x \ 1000 \ x \ GCV \ x \ \eta \ x \ 0{,}277778 \qquad (7)$$

GCV is the gross calorific value of organic waste, which is the same as LHV in MJ/kg TS; η is the efficiency of conversion into electrical energy, and 0.277778 is the constant for the standard conversion of MJ to kWh. The calculated TSm is 21% (PUPR, 2018) and GCV (or LHV-MSW) is 17 MJ/kg (Gunamantha, 2020). The efficiency of collecting conversion into electrical energy of 25% is adopted from Cardenas-Rodriguez et al. (2021). The revenue that can be obtained from solid fuel is calculated using Equation (8).

$$Potential\ revenue\ from\ solid\ fuels = E_{sf} \ x \ HL \qquad (8)$$

HL is the price of electricity in IDR/kWh based on the price set by the Ministry of Energy and Mineral Resources of Indonesia for electricity from biomass of IDR. 1,080/kWh.

Black soldier fy processing

The use of BSF is a new technology in processing organic waste. This processing process involves the transformation of bio-organic waste into insect protein and insect oil (Lohri et al., 2017). The BSF can degrade organic waste by using its larvae to extract energy and nutrients from vegetable waste, food waste, animal carcasses and feces as food (Lohri et al., 2017). Bioconversion of food waste by black soldier fly (*Hermetia illucens* (L.) (*Diptera: Stratiomyidae*)) larvae (BSFL) is a promising solution for the management and valorization of organic waste streams (Dortmans et al., 2017; Arabzadeh et al., 2022). BSFL can feed on a variety of organic substrates, including food waste, processing residues, and human and animal waste to efficiently convert organic matter (OM) into a high-value biomass protein and fat source that provides a sustainable solution for both organic waste management and food security (Lohri et al., 2017; Arabzadeh et al., 2022). Frass is an important byproduct of the BSFL bioconversion process. Frass consists of larval feces, exuviates, and unconsumed raw materials; a few recent studies have reported its use as an organic fertilizer (Lopes et al., 2022; Arabzadeh et al., 2022). Like other organic amendments such as compost or vermicompost, frass is considered a very valuable source of nutrients for horticultural crops to improve soil structure, provide slow-release micro and macro nutrients, minimizing excess nutrients and runoff into the environment (Arabzadeh et al., 2022). Frass originating from BSFL raised from food waste had an average NPK value of 4.54; 1.23; 2.44 (Arabzadeh et al., 2022). Beesigamukama et al. (2021) evaluated the frass produced by BSF larvae fed a diet of spent brewer's grain containing 21 g kg^{-1} N, 11.6 g kg^{-1} P, and 1.7 g kg^{-1} K.

In BSF processing, the bioconversion rate (BCR) is an important factor that shows the efficiency of BSF larvae production (Hosseindoust et al., 2023). BCR is the percentage ratio of the dry mass of larvae produced to the dry mass of the substrate (Hosseindoust et al., 2023). This indicates the efficiency of waste conversion by BSF larvae into useful energy (Beesigamukama et al., 2021). According to Dortmans et al. (2017), the conversion rate of waste-to-biomass (larvae) is up to 25% of their total weight. Equation (9) is used to calculate the number of BSF larvae (tons) that can be obtained from organic waste (food waste).

$$BSF = QS_{BSF}\ x\ \frac{TS_m}{100}\ x\ \frac{BCR}{100} \qquad (9)$$

BCR is in percentage, QS_{BSF} is the quantity of organic waste streams (vegetables, fruit peels, kitchen waste, market waste) in tons, and other parameters as explained in the previous section.

BSF larvae contain around 35% protein and 30% fat (Dortmans et al., 2017), so that the protein and fat content in the number of BSF larvae are calculated using Equations (10) and (11), respectively:

$$Protein\ content\ in\ BSF\ larvae\ (ton) = BSF\ x\ 0.35 \qquad (10)$$

$$Fat\ content\ in\ BSF\ larvae\ (ton) = BSF\ x\ 0.30 \quad (11)$$

The revenue that can be generated from BSF larvae is calculated using Eq. (12).

$$Potential\ income\ from\ BSF\ larvae = \ BSF\ x\ BSF_p \quad (12)$$

BSF_p is the estimated price of BSF larvae in IDR/ton on the market. The basic production price for BSF maggots is Rp. 2,700/kg (Widodo et al., 2021) with a selling price of around IDR. 5000/kg.

Residues from BSF processing are used as compost through a drying and composting process for stabilization (Dortmans et al., 2017). Calculations to determine the amount of stabilized residue from the BSF treatment process consider the reduction in dry weight because of bioconversion by BSF larvae and during composting. Referring to Dortmans et al. (2017), 70% total reduction was used. Therefore, calculations are carried out using Equation (13).

$$R_{BSF} = QS_{BSF}\ x\ \frac{TS_m}{100}\ x\ \left(1 - \frac{DMR_{BSF}}{100}\right) \qquad (13)$$

R_{BSF} is the amount of stabilized BSF residue in DM metric tons, DMR_{BSF} is the percentage reduction in the dry weight of the residue due to drying and composting.

The revenue that can be generated from residual compost after BSF processing and stabilization is calculated using Equation (14).

$$Potential\ revenue\ from\ BSF\ residue = \ R_{BSF}\ x\ C_p \qquad (14)$$

Cp is the estimated price of a product equivalent to soil amendment or compost on the market in IDR/ton (IDR 500/kg).

Composting

Composting involves the controlled aerobic decomposition of organic materials by microorganisms resulting in a relatively stable organic product called humus. According to Elfeki et al. (2017) 40-50% of the initial substrate becomes compost through an aerobic composting process. Setyawati (2013) reported that 46.4% of compost was produced from organic waste through aerobic composting. In this paper it is set at 45%. Therefore, the amount of compost that can be obtained, C_m (tons) is also calculated based on the TS of waste using Equation (17).

$$C_m = QS_C \, x \, \frac{TS_m}{100} \, x \, Y \qquad (17)$$

Y is the percentage reduction in dry weight of waste due to the composting process. The revenue that can be generated from compost is calculated using Equation (18).

$$Potential\ revenue\ from\ compost = C_m \, x \, C_p \qquad (18)$$

Cp is the price of compost in IDR. 750/kg (Situmeang, 2020).

Eco-Enzym

Eco-enzyme is a type of natural compound that can be extracted normally from citrus fruit peel or waste and various other organic waste. Changes in kitchen waste such as vegetable and fruit peels. These Eco-enzymes are produced by complex fermentation. Eco-enzyme is a type of vinegar made by fermenting food waste with sugar to form alcohol. Eco enzyme is a fermentation solution made from a mixture of sugar, fruit peel and water mostly in a ratio of 1:3:10 (Benny et al., 2023). Making this eco-enzyme only uses kitchen waste at home such as vegetables, fruit peels and food waste. Eco-enzyme solution contains many types of natural enzymes derived from fruit and vegetables, as well as those produced by microbes. Therefore, eco-enzymes have many benefits in the fields of health, agriculture and improving environmental quality, including being used as organic plant fertilizer, compost mixture, healing various types of wounds, aromatherapy liquid, air purifier, hand sanitizer, dish soap, and others. clothes detergent, toilet drain cleaner, and various other benefits (Yuliani et al., 2022; Benny et al., 2023). Yuliani et al. (2022) reported that 0.8 L of Eco-enzyme was produced from every liter of the total mixture of raw materials. Therefore, the amount of Ecoenzyme that can be obtained, L, is calculated by equation (20).

$$Ee = Y_{EE}\left(M + QS_E \, x \left(1 - \frac{TSm}{100}\right) + Air\right) \quad (20)$$

Ee is the Eco-Enzyme produced (L); M is added molasses (L); QS_E is the quantity of organic waste flow (vegetables, fruit peels) in tons, Y_{EE} is the conversion yield (0.8); Water is the amount of water added. (the ratio of sugar: waste: water is 1: 3 : 10).

The revenue that can be generated from Eco-enzym is calculated using Equation (21). The price per 10 L of Eco-enzym is IDR. 20,000 (Ramli and Peniyanti, 2021).

$$Potential\ revenue\ from\ Ee - enzym = C_{Ece} \, x \, C_p \qquad (21)$$

Cp is the price of eco-enzyme in IDR/L.

Residues from processing to eco-enzym production also require further treatment for stabilization and the assumption is made that this treatment may consist of a simplified drying and composting process. Therefore, calculations to determine the amount of stabilized residue, the reduction in dry maater due to bioconversion by microorganisms as well as further reduction in dray matter during fermentation. Equation (22) is used for the quantity of waste input in metric tons.

$$R_{EE} = QSE\ x\ \frac{TS_m}{100}\ x\ Y_c \qquad (22)$$

R_{FE} is the amount of stabilized fermentation residue (tons), Y_C is the percentage of compost produced due to fermentation of residue from the eco-enzyme process (13%) referring to the compost obtained from digestate during anaerobic decomposition.

The revenue that can be generated from the residue after BFE processing and stabilization is calculated using Equation (23).

$$Potential\ revenue\ from\ residuals\ REE = R_{EE}\ x\ C_p \qquad (23.$$

Methodology

In this research, a quantitative approach was used to measure the potential for circular economic recovery of urban organic waste flows. This is done by quantitatively estimating the products that can be produced from each resource recovery option based on material flow analysis. In this case, a linear relationship between the physical and chemical quality parameters of the waste stream and the potential quantity of resource recovery products from each technology optios were involved. For each technology, quality parameters that determine the quantity of recoverable resources were identified from the literature. Mathematical relationships between the related parameters and the quantities of recoverable resources and usable products were also adopted and developed based on the data available in the literature. The resource recovery technology options involved were anaerobic decomposition (AD), drying and compaction to produce solid fuel, black soldier fy (BSF) processing to produce animal feed and fertilizer, ecoenzymes, and composting. This technology was selected based on which is currently the most mature and commonly used for resource recovery from organic waste in Indonesia.

Organic waste data managed by the Singaraja city government, Buleleng Regency, Bali, Indonesia is used as a case study. Two scenarios were assessed for both case study sites; the first is based on the amount of organic waste collected by the current city government (Scenario 1) and the other is based on the projection amount of organic waste that can be collected by increasing the coverage and efficiency of waste management infrastructure and logistics up to 2030 (Scenario 2).

This research uses secondary data. There are four main groups of data required. First, data on the quantity of organic waste obtained from management agencies in the local city area. Second, data on physical and chemical quality parameters and energy content of waste. Third, data relating to the processing process and potential quantity of recovery products from each technology involved. Fourth, price data is used to estimate the revenue potential of resource recovery products. The last three data were obtained from the literature, especially from articles published in scientific journals. In more detail, the required data is presented in table 1.

Table 1. Physico-chemical quality parameters and processing process parameters are used to determine the amount of resource recovery product.

Resource Recovery Products	The processing parameters and data are used to determine the amount of resource recovery product.
Biogas	Total Solids (TS), Volatile Solids (VS), Biomethane Potential (BMP), Degradation rate of volatile solids
Solid Fuel	Total Solids (TS), Calorific Value (CV)
Larva	Total Solids (TS), Biomass Conversion Rate (BCR)
Compost	Total solids (TS), Percentage reduction in dry mass during composting (DMR), Nitrogen, phosphorus, and potassium content in compost (NPK)
Eco-enzyim	Total Solids (TS),

Detailed steps for applying the method to estimate circular economic potential**.**

Estimating the sircular economic potential from organic waste requires valuing product from each technology options, which can be achieved using quantity and characteristic of organic waste. The following steps can be taken to apply these methods to estimate the economic circular of organic MSW:

Step 1: Identify the procees, parametres and product in each technology.

The first step in estimating the circular economic is to identify the product that can be valued. This may include compost, energy, or other products that have economic value.

Step 2: Collect relevant data.

Once step one has been identified, the next step is to collect relevant data. This may include data on the characteristics of the organic waste and parameters process, such as the size of the total solid (TS), volatile solid (VS), Biomethanation potential (BMP), efficiency/yield process, etc. It may also include data on the economic value of products, such as the price of compost, electric energy, eco-enzym, and larva.

Step 3: Model to estimate product from each technology.

The linear correlation of the related paramters were used to model for product estimation. This involves transforming input into product. The model can be used to calculate the main product and residu, considering the convertion effeciency. The conversion efficiency (e.g. kg output product/kg OFMSW input) of each each technology was estimated based on data available in the studies and applying conversion factors from literature. The unit of conversion efficiency depends on the type of products produced.

Step 4: Use main parameters to simplify mathematically complex relations that may arise in the estimation product. This involves linear relation.

Step 5: Estimate the circular economic potential.

Once the products have been estimated, the circular economic potential can be calculated by multiplying this value to the price. In this, the potential revenues of the identified products (IDR) were estimated from the output and data on market prices.

Results and Analysis

Referring to Ministry of Environment and Forestry of Indonesia Regulation No. 6 of 2022 concerning the National Waste Management Information System, the calculation of waste generation is based on Tier 1. Tier 1 is a calculation of the estimated waste generation based on the population multiplied by the estimated waste generation factor determined by the ministry that carries out government affairs in the field of environmental protection and management.

potential waste generation = number of populations × waste generation estimation factors

The estimated factors depend on the city classification. Based on the population in urban areas, Singaraja is included in the medium city category because the population has exceeded 100,000 but is less than 500,000. So, the estimation factor used is 0.5 kg/person/day (PUPR. 2021).

Waste growth is calculated based on the contribution of household consumption expenditure to GRDP (gross regional domestic product). This refers to Daskalopoulos et al. (1998) which proposed that the generation of waste is a consequence of human activities. It was further emphasized that human activity is indicated by the contribution of total consumer expenditure (TCE) to GDP. This means that an increase in a country's GDP or rgions GRDP also indicates an increase in TCE. In the local context, the contribution of household consumption expenditure (including non-profit private institutions) in the formation of GRDP indicates people's purchasing power so that consumption increases. This means that an increase in household consumption will lead to an increase in the amount of waste produced.

Based on Buleleng GRDP target on 2023 in the Buleleng Regency Regional Development Plan for 2023-2026 (Buleleng District Regional Government, 2022), in this study, GRDP growth of 3.3% was used. Processed from Buleleng in figures, an average household consumption expenditure contribution of 48.80% are considered. So, waste growth is assumed to be 3.3 x 0.488 or 1.61% annually.

Another thing that is also involved in determining waste generation projections is service coverage. Based on the results of data processing, the current coverage of waste handling services in Buleleng Regency has only reached 28%. Furthermore, service coverage is assumed to increase from year to year as presented in table 2. the percentage of 67.27% organic waste shown in table 2 is the average value of the percentage of organic waste from 2019 to 2022. This average value is then used and assumed to remain constant in subsequent years. The organic waste involved for this purpose is only food waste and wood-twigs, excluding paper/cardboard.

Table 2. Projection of organic waste generation

Year	**Popula-tion**	**Service covering (%)**	**kg/cap/ day**	**Organic (%)**	**Organic waste (Ton/y)**
2021	807,000	28	0.50	67.27	27740.60
2022	825803	30	0.51	67.27	30904.27
2023	845044	35	0.52	67.27	37489.08
2024	864734	40	0.52	67.27	44548.81
2025	884882	45	0.53	67.27	52110.84
2026	905500	50	0.54	67.27	60203.95
2027	926598	55	0.55	67.27	68858.42
2028	948188	60	0.56	67.27	78106.12
2029	970281	65	0.57	67.27	87980.53
2030	992888	70	0.58	67.27	98516.89

Based on feedstock requirements, the distribution of OFMSW processed in each technology is shown in the table 3. These organic waste fractions are involved differently for each processing technology. In processing with AD and composting it involves food waste and garden waste as input, in densification all fractions are involved, whereas for BSF and Eco-enzym it only uses food waste as input.

Table3. OFMSW processed in each technology in 2023

Technology Options	Food Waste (%)	Garden waste (%)	Total (%)
Anaerobic Digestion	3.24	64.03	67.27
Densification and drying	-	64.03	-
Composting	-	64.03	-
BSF Processing	3.24	-	-
Eco-enzym Production	3.24	-	-

The results of this study indicate that more energy recovery is obtained from the compaction and drying process compared to the anaerobic decomposition process. For OFMSW was generated in 2023, the potential electrical energy that can be generated from the densification and drying process is 8644.80 MWh. This potential is obtained from 34,869 tons (64.03%) OFMSW which be processed through densification and drying. This means that every ton of organic waste will produce 0.274 MWh or 274 KWh from the densification and drying. This result is lower than Ajaero et al. (2023) who reported that the energy potential of densification and drying processes per ton of treated OFMSW was 0.55 MWh/ton waste (densified solid fuel) but more higher than incineration 0.211 MWh/ton. In anaerobic decomposition process involving food waste and garden waste (leaves and twigs). Through this process the potential electrical energy obtained is 1475.35 MWh or 0.039 MWh/ton waste. In this process, the amount of organic waste considered to be processed was 37,489.08 tons (67.27%). This value is much lower than that obtained from densification. The results is also lower those reported by Ajaero et al. (2023). Ajaero et al. (2023) has reported 0.43 MWh/tonne of waste recovered from the AD process. This is possible due to the low biodegradability of waste. However, the densification and drying process requires a large initial energy for the compaction and drying process.

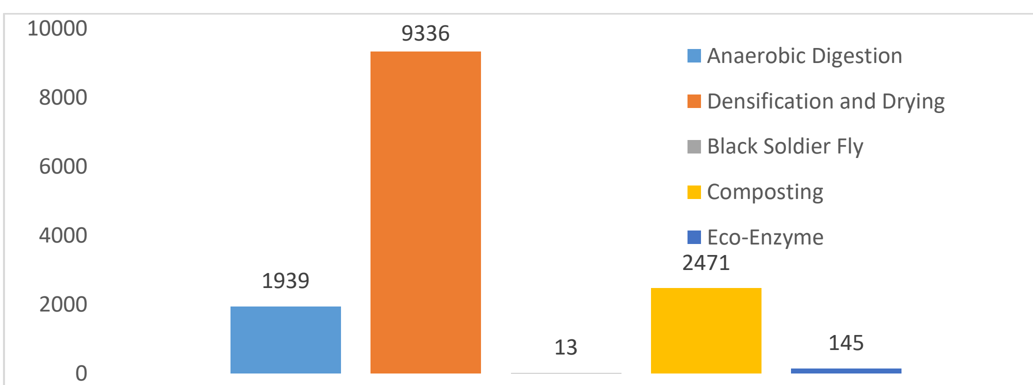

Figure 1. Cellular Economic Potential for organic waste generation in Buleleng Regency for 2023

The potential for collecting energy from this waste is inline to the potential revenue obtained. Figure 1. shows that the potential revenue from densification and drying is much greater than from the anaerobic digestion process. However, consideration of investment, operational and maintenance costs has not been involved. If we look at the installed power, electricity production, and electricity sold in Bali, respectively amounting to 301 MW, 349,328 MWh, and 334,423 MWh (Central Bureau of Statistics, 2022), the percentage of electricity demand in Buleleng Regency that can be supplied by generators waste to energy can be estimated. According to the value reported by Central Bureau of Statistics, the electricity consumed is assumed to be the same as the electricity sold by generators in the Buleleng Region in 2022, which is 334.423 MWh. This means that there is potential to cover 2.58% of this demand through densification and drying technology. Organic waste for energy as a renewable energy source. In this case, it can contribute to obtaining 23% renewable energy in the energy mix in Indonesia in 2025 and 31% in 2050 as stated by the government in the Energy Policy Guidelines (National Energy Council, 2019).

In processing with BSF, 451 tons of larvae potential can be produced from food organic waste generated in Buleleng Regency for 2023. In contrast to anaerobic decomposition, only food waste is processed through a process with BSF. In composting, While with composting, 3,295 tonnes of potential compost is produced with potential revenue of IDR. 1,645,000,000. in 2023. The potential is quite large when it comes to the distribution of subsidized granular organic fertilizer (tons), 2021 in Bali which reaches 2,145.20 (Ministry of Agriculture, 2021). By changing the form of bulk organic fertilizer to granular organic fertilizer, this of course has the potential to save state finances. Table 4 summarizes the potential energy and resources that can be recovered from projected organic waste managed in Buleleng Regency until 2030.

Table4. Projections of resource and energy potency from managed organic waste in Buleleng Regency until 2030

Technology Options	**Resources/Energy**	**Quantity**							
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Anaerobic Digestion	Biogas (1000M^3)	690	820	959	1108	1267	1437	1619	1813
	Electricity (MWh)	1475	1753	2051	2369	2710	3074	3462	3877
	Digestate (ton)	461	547	640	740	846	960	1081	1210
	Revenue (IDR. million)	1939	2304	2695	3114	3561	4039	4550	5095
Densification and Drying	Electricity (MWh)	8645	10273	12017	13883	15878	18011	20288	22718
	Revenue (IDR. million)	9336	11095	12978	14993	17149	19452	21911	24535
BSF Process	BSF Larva (ton)	451	536	627	725	829	940	1059	1186
	Residue BSF (ton)	542	644	753	870	995	1129	1271	1423
	Revenue (IDR. million)	13	15	18	20	23	26	30	33
Composting	Compost (ton)	3295	3916	4580	5292	6052	6865	7733	8659
	Revenue (IDR. million)	2471	2937	3435	3969	4539	5149	5800	6495
Eco-enzym Production	Eco-enzym (Liter)	5363	5635	5927	6239	6572	6929	7309	7715
	Compost (ton)	76	91	106	122	140	159	179	200
	Revenue (IDR. million)	145	158	171	186	201	218	236	254

Conclusion

This research shows that there are a number of resources hidden in the organic fraction of municipal waste and these can be recovered using a circular economy approach. At current levels of waste collection, there is

significant potential for resource recovery from the organic waste stream through products such as biogas, densified solid fuels, compost, insect larvae and eco-enzymes. Densified solid fuel has proven to be the best option to introduce the organic fraction into the circular economic model, because the energy content of the biomass. It found out that the potential energy and revenue from the densification and drying reaches 8645 MWh and 9336 million IDR. The second highest potential revenue is through the composting process followed by anaerobic digestion. As for the BSF and eco-enzyme processes, the revenue generated is relatively small, this is because only food waste is considered and can be processed in this way. As a note that, this analysis does not yet consider investment, operational and facility maintenance costs. H
owever, the research can support efforts to implement a circular economy in organic waste management. Given that the results are influenced by the quantity and quality of the organic waste stream, it is important to check the data used. For example, the physical and chemical characteristics of waste can of course vary with time and source. TS and calorific value are determined by the type of organic waste that dominates it. This highlights the need for detailed waste characterization as part of the feasibility process for any technology option.

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Authors contribution: I Made Gunamantha: devised the project, the main conceptual ideas and proof outline, conceived of the presented idea, derived the models and analysed the data, supervised the project, and contributed to the final manuscript. I Gede Astra Wesnawa: verified the analytical methods, encourage and supervised the findings of this work. Ni Made Vivi Oviantari: collected the data, performed the analysis, and worked on the manuscript. Ni Wayan Yuningrat: analysis of the results and worked on the manuscript.
Ni Putu Lilik Pratami Kritiyanti: collected the data performed the analysis. Komang Widiadnyana: collected the data and performed the analysis.

Data availability: This research relies on literature and secondary data. The mathematical models were adopted from literature. Data sets of organic waste generation and composition were estimated from population and the average waste composition on the last three year in area study.

References

Ajaero, C.C., Okafor, C.C., Otunomo, F.A., Nduji, N.N., & Adedapo, J.A. (2023). Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria. *Clean Technologies and Recycling*, 3(1): 44–65.

Arabzadeh, G., Delisle-Houde, M., Tweddell, R.J., Deschamps, M-H., Dorais, M., Lebeuf, Y., Derome, N., & Vandenberg, G. (2022). Diet composition influences growth performance, bioconversion of black soldier fly larvae: agronomic value and in vitro biofungicidal activity of derived frass. *Agronomy*, 12, 1765. 1-19

Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Subramanian, S., Wangu, M.M., Dubois, T., Ekesi, S., & Tanga, C.M. (2021). Lo-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly. *Waste Manage*, 119, 183–194. https://doi. org/10.1016/j.wasman.2020.09.043.

Benny, N., Shams, R., Dash, K.K., Pandey, V.K., & Bashir O. (2023). Recent trends in utilization of citrus fruits in production of eco-enzyme. *Journal of Agriculture and Food Research*, 13, 100657

Buleleng District Regional Government (2022). Buleleng District Regional Development Plan for Year 2023-2026. Buleleng, Bali, Indonesia.

Cardenas-Rodriguez, H de N., Martins, R., Oliveira, L., Bonaldi, E., Assunção, F., Lambert-Torres, G., Villa-Nova, H., Sant'ana, W.C., Borges-da-Silva, L.E., Bomfin, C.B., & Haddad, J. (2021). Analysis on the use of briquettes as an alternative to improve the generation of thermal energy in the locality of Aripuana-Brazil. *Energies*, 14, 6355. https://doi.org/10.3390/en14196355

Central Bureau of Statistics (BPS). 2022. Buleleng Regency in Numbers. BPS Buleleng RegencyBiro Pusat Statistik (BPS). 2022. Kabupaten Buleleng dalam Angka. BPS Kabupupaten Buleleng.

Daskalopoulos & Probert, (1997). Economic and environmental evaluations of waste treatment ans disposal technologies fo municipal solid waste. *Applied Energy*, Vol. 58(4), pp. 209-255.

Ddiba, D., Andersson, K., Rosemarin, A., Schulte-Herbrüggen, H., & Dickin, S. (2022). The circular economy potential of urban organic waste streams in low- and middle-income countries. *Environment, Development and Sustainability*, 24, 1116–1144. https://doi.org/10.1007/s10668-021-01487-w

Dortmans, B.M.A., Diener, S., Verstappen, B.M., & Zurbrügg, C. (2017). Black soldier fly biowaste processing - a step-by-step guide. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., & Lotti, L. (2019). The circular economy: what, why, how and where, background paper for an OECD/EC workshop on 5 July 2019 within the workshop series: managing environmental and energy transitions for regions and cities, Paris.

Elfeki, M., Elbestawy, E., & Tkadlec E. (2017). Bioconversion of Egypt's Agricultural wastes into biogas and compost. *Pol. J. Environ. Stud*, Vol. 26(6), 1-10

Ellen MacArthur Foundation. (2013). Towards the circular economy vol.1: economic and business rationale for an accelerated transition. https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Ellen MacArthur Foundation. (2017). Urban biocycles. https://emf.thirdlight.com/file/24/MC1eXz-MW2hiiSMCEvuMcsrYg/Urban%20Biocycles.pdf

Geissdoerfer, M., Savaget P., Bocken N.M.P., & Hultink, E.J. (2017). *Journal of Cleaner Production*, 143, 757-768

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, Vol. 114, 11–32.

Gunamantha, M. (2020). Assessment of the potential of energy recovery from organic fraction of municipal solid waste. *The Journal of Solid Waste Technology and Management*, 46(2), 160-167.

Hosseindoust A., Ha S.H., Mun, J.Y., & Kim, J.S. (2023). Quality characteristics of black soldier flies produced by different substrates. *Insects*, 14(500), 1-10.

IPCC. (2006). 2006 IPCC Guidlines for National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Programme. Japan. http://www.ipcc-nggip.iges.or.jp

Islami, P.Y.N. (2022). Penerapan Ekonomi Sirkular pada Pengelolaan Sampah Pesisir: Studi Kasus Pengelolaan Sampah Pulau Pasaran Bandar Lampung/Application of Circular Economy to Coastal Waste Management: Case Study of Waste Management on Pasaran Island, Bandar Lampung. The 4th International Conference on University-Community Engagement (ICON-UCE) IAIN Syekh Nurjati Cirebon, October 24-26, 2022.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation & Recycling*, 127, 221–232

Kristianto, A.H., br Siahaan, S.V., & Vuspitasari, B.K. (2022). Potensi pengembangan ekonomi sirkular kerakyatan dan solusi permasalahan sampah tidak terkelola (Studi kasus Desa Sungai Duri Kabupaten Bengkayang)/Potential for developing a people's circular economy and solutions to the problem of unmanaged waste (Case study of Sungai Duri Village, Bengkayang Regency). Jurnal Maneksi, 11(1), 231-236

Kyriakopoulos, G.L., Kapsalis. V.C., Aravossis, K.G., Zamparas, M., & Mitsikas, A. (2019). Evaluating Circular Economy under a Multi-Parametric Approach: A Technological Review. *Sustainability*, 11, 6139; doi:10.3390/su11216139

Lohri, C.R., Diener, S., Zabaleta, I., Mertenat, A., & Zurbru¨gg, C. (2017). Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income setting. *Rev Environ Sci Biotechnol*, 16, 81–130.

Lopes, I.G., Yong, J.W.H., & Lalander, C. (2022). Frass derived from black soldier fly larvae treatment of biodegradable wastes. A critical review and future perspectives. *Waste Management*, 142, 65–76

Mastellone, M.L., & Lotito, R. (2017). Hydrous pyrolysis of digestate as alternative to post composting in a biowaste anaerobic digestion facility, in biochar: production, characterization and applications, Franco Berruti, Western University, London, Ontario, Canada Raffaella Ocone, Heriot-Watt University, Edinburgh, UK Ondrej Masek, University of Edinburgh, Edinburgh, UK Eds, ECI Symposium Series, (2017). http://dc.engconfintl.org/biochar/56

Ministry of Agriculture. (2021). Statistik pertanian. pusat data dan sistem informasi pertanian/Center for agricultural data and information system. Ministry of Agriculture of the Republic of Indonesia. Jakarta

Ministry of Energy and Mineral Resources of Indonesia. (2014). Minister of Energy and Mineral Resources Regulation Number 27 of 2014 concerning Purchase of Electric Power from Biomass Power Plants and Biogas Power Plants by State Electricity Company Limited.

Ministry of Environment and Forestry of Indonesia. (2022). Regulation of the Minister of Environment And Forestry of The Republic of Indonesia Number 6 ff 2022: Concerning The National Waste Management Information System. Jakarta, Indonesia.

Ministry of National Development Planning/BAPPENAS. (2021). The economic, social, and environmental benefits of a circular economy in Indonesia. Jakarta, Indonesia.

National Energy Council. (2019). Indonesia Energy Outlook. 2019. Secretariat General of the National Energy Council. Jakarta

Pearce, D., & Turner, R. (1990). Economics of natural resources and the environment, Harvester Wheatsheaf, Hemel Hempstead, Herts., UK.

Prendeville, S., & Bocken, N. (2015). Design for remanufacturing and circular business models, product innovation management, industrial design engineering, TU Delft (https://tinyurl.com/jd6le77).

PUPR. (2018). Modul 4. Teknologi WtE berbasis proses biologis AD. Pusat Pendidikan dan Pelatihan Jalan, Perumahan, Permukiman, dan Pengembangan Infrastruktur Wilayah/Module 4. WtE technology based on

AD biological processes. Education and Training Center for Roads, Housing, Settlements and Regional Infrastructure Development. Jakarta

PUPR. (2021). Pelatihan kepemimpinan nasional tingkat II angkatan V Tahun 2021, pengembangan kompetensi manajemen badan pengembangan sumber daya manusia kementerian pekerjaan umum dan perumahan rakyat: Laporan proyek perubahan strategi implementasi kebijakan pembangunan pengolahan sampah berbasis teknologi refuse derived fuel (RDF). Balai Pengembangan Kompetensi PUPR Wilayah IV Bandung Pusat Pengembangan Kompetensi Manajemen Badan Pengembangan Sumber Daya Manusia Kementerian Pekerjaan Umum dan Perumahan Rakyat/National leadership training level II Batch V 2021, development of management competency for the human resource development agency of the Ministry of Public Works and Public Housing: Project report on changes to strategy for implementation of waste processing development policies based on refuse derived fuel (RDF) technology. PUPR Competency Development Center Region IV Bandung Management Competency Development Center Human Resources Development Agency Ministry of Public Works and Public Housing. Jakarta

Rada, E., & Cioca, L. (2017). Optimizing the methodology of characterization of municipal solid waste in EU under a circular economy perspective. International conference on technologies and materials for renewable energy, environment and sustainability, TMREES17, 21-24 April 2017, Beirut Lebanon. *Energy Procedia*, 119, 72-85.

Ramadhan, M.R.S., Ikhsan, M., Putra, R.M., Simatupang, J.W., Mau, S., & Kaburuan, E.R. 2021. Waste-to-Energy Potential Using Municipal Solid Waste as One Implementation of Jakarta Smart City. *Serambi Engineering*, VI(4), 2382 – 2394.

Ramli, I., & Peniyanti, Y.Jap. 2(021). Eco-enzyme pemberdayaan kelompok petani Desa Ciranjang Cianjur Tahun 2021. *Jurnal Bakti Masyarakat Indonesia*, 4(2), 389-397

Setyawati, L.M. (2013). Potensi sampah organik menjadi pupuk organik pada kawasan perkantoran/Potential for organic waste to become organic fertilizer in office areas. *Jurnal Permukiman*, 8(1), 45-52.

SISPN. (2022). Komposisi sSampah/Municipal solid waste composition. https://sipsn.menlhk.go.id/sipsn/public/data/komposisi

Situmeang, Y.P., Andriani, A.A.S.P.R., Suart, M., Yuliartini, M.S., & Resiani, N.M.D. 2017. Aplikasi biochar, kompos, dan phonska terhadap kelayakan hasil jagung di lahan kering/Application of biochar, compost, and phonska on the feasibility of corn yields in dry land. *Buletin Teknologi dan Informasi Pertanian*, 15(44), 1-7

Vögeli, Y., Lohri, C. R., Gallardo, A., Diener, S., Zurbrügg, C. (2014). Anaerobic digestion of biowaste in developing countries: practical information and case studies, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf, Switzerland

Wainaina, S., Awasthi, M.K., Sarsaiya, S., Chen H., Singh E., Kumar A., Ravindran B., Awasthi S.K., Liu T., Duan Y., Kumar S., Zhang Z., & Taherzadeh, M.J. (2020). Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. *Bioresource Technology*, 301, 122778. https://doi.org/10.1016/j.biortech.2020.122778

Widodo, E.M., Yuwono, M.A., Haryadi, R., Noverizka A.H., Sholahudin, G.S., and Ainayya, A. (2021). Budidaya maggot dari sampah organik untuk meningkatkan nilai ekonomi pada TPS 3R Enggal Nyaman, Gondosuli, Muntilan/Cultivating maggots from organic waste to increase economic value at TPS 3R Enggal Nyaman, Gondosuli, Muntilan. *Community empowerment*, 6(12), 2187-2192

Wielgosi´nski, G., Czerwi´nska, J., & Szufa, S. (2021). Municipal solid waste mass balance as a tool for calculation of the possibility of implementing the circular economy concept. *Energies*, 14, 1811. https://doi.org/10.3390/en14071811.

Yuliani, F., Kristiowati, D., & Hermyantono C. (2022). Pelatihan pembuatan cairan serbaguna eco-enzyme dari sampah organik dan cara pemanfaatannya di Desa Gondangmanis, Bae, Kudus/ Training on making multi-purpose eco-enzyme liquid from organic waste and how to use it in Gondangmanis Village, Bae, Kudus. *PRIMA: Journal of Community Empowering and Services*, 6(1), 37-45.