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Editorial

This edition of *NIU Journal of Climate Justice and Governance* touches on issues such as Environmental Concerns arising from Oil and Gas Exploration and Production, Environmental Protection Policies and so on.

Using South Sudan as a case study, one of the papers, in this issue, reveals that there are statutory deficiencies in all legal provisions for setting up a decommissioning fund and there are no provisions for its application and management, which creates a lacuna for improper, haphazard and poor management and application of the funds. It therefore, recommends the need to amend the Petroleum Act, create enabling regulations and empower regulatory bodies to ensure proper and adequate application and management of the decommissioning fund to safeguard effective environmental protection of South Sudan.

Another paper also argues that the adoption of more comprehensive and proactive measures encompassing legislative and regulatory frameworks, capacity building, inclusivity and stakeholder engagement, as well as strong institutional and judicial enforcement, is essential for achieving sustainable wetland protection in oil and gas exploration and production in South Sudan.

On the whole, this edition of *NIU Climate Justice and Governance* features many empirical and theoretical based articles which can be of great benefit to every reader.

Professor Oyetola O. Oniwide

Nexus International University,
P.O. Box 70773,
Kampala, Uganda.
editor@niuournals.ac.ug

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Addressing Environmental Concerns arising from Oil and Gas Exploration and Production in Wetland Areas: Focus on the Sudd Wetland of South Sudan

KORENILO AJANG DUOT* SHEDRACK EKPA** ADEBOWALE ISMAILA HASSAN***
School of Law, Kampala International University, Uganda

Abstract. Globally, wetlands are known for their ecological benefits given the role they play, ranging from providing buffers against storms to providing habitat for wildlife and aquatic organisms, as well as flood control and improvement of water quality. South Sudan is host to one of the world's largest wetlands, the Sudd Wetland, which stretches up to about 57,000 km². Unfortunately, this important ecosystem hotspot concomitantly plays host to significant oil and gas deposits, the exploitation of which causes enormous ecological damage, begging for adequate environmental protection. This paper examines the adequacy of the legal and regulatory regimes in addressing environmental concerns arising from oil and gas activities in South Sudan, emphasizing on the Sudd Wetland. Using a doctrinal research methodology, the paper analyses South Sudan's nascent and evolving legal and regulatory frameworks for the protection of wetlands, contrasting with more developed legal systems like Kenya and Uganda, which also demonstrate a higher level of environmental awareness and activism. The study's findings reveal significant gaps in legal and regulatory frameworks combined with weaknesses in enforcement mechanisms. Apart from the designation of Wetlands of International Importance, South Sudan has yet to implement one of its core responsibilities under the Ramsar Convention, which requires contracting parties to formulate and implement regulations to promote the conservation of the wetlands included in the List of wetlands designated under Article 2. As a result, the country ranks low in terms of legal and policy frameworks on wetland

protection. The absence of a specific wetland protection legal regime is exacerbated by other non-legal factors, including lack of adequate funding, insecurity and inaccessibility, limited capacity (technical experts), limited awareness, and lack of stakeholder involvement (civil society, local community, CBOs, NGOs, etc.). The paper argues that the adoption of more comprehensive and proactive measures encompassing legislative and regulatory frameworks, capacity building, inclusivity and stakeholder engagement, as well as strong institutional and judicial enforcement, is essential for achieving sustainable wetland protection in oil and gas exploration and production in South Sudan.

Keywords: Environment; Oil and Gas; Wetlands; South Sudan; Sudd Wetland

1. Introduction

Wetland ecosystems are increasingly experiencing multiple ecological impacts resulting from oil and gas development. While it is generally recognised that oil resources provide a major source of government revenue the world over, their side effects in terms of environmental damage should not be ignored. Generally, oil exploration, site preparation, site access, drilling, production, pipeline installation, spill control and clean-up, as well as final decommissioning, produce harmful environmental effects.¹ Given that wetlands are vital for protecting developed areas from storm surges, providing wildlife and fish habitat, and improving water quality,² this underscores the

*LLM (Dar Es Salam) LLB....

**PhD, LLM, LLB, BL Professor of Law and Head of Department, Law and Juris. School of Law KIU.

*** Professor of Law and Research Coordinator, School of Law, KIU.

¹ See Jac-Young Ko, John Day, John Barras, Robert Morton, James Johnston, Gregory Steyer, G.

Paul Kemp, Ellis Clairain, and Russell Theriot Impacts of Oil and Gas Activities on Coastal Wetland

Loss in the Mississippi Delta

<https://www.hartherresearch.org/sites/default/files/inline-files/33.pdf> accessed

on 28-02-26.

² *Ibid.*

importance of sustainable use, management, and governance of wetlands as a key aspect of the environmental regulatory framework relating to oil and gas exploration and production. The Sudd wetland in South Sudan is considered one of the largest floodplains in Africa and one of the largest tropical wetlands in the world.³ It stretches from the White Nile, or *Bahr el Jebel River* system, which originates in the African Lakes Plateau. Derived from an Arabic word meaning obstacle or blockage of river channels, the Sudd is composed of a maze of wetland ecosystems and supports high levels of biodiversity.⁴ The Sudd Wetland encompasses many oil concession blocks, including part of Block 4, most of Block 5A, Block 5B, and territory south and east of them, in the concession of TotalFinaElf, Block 5.⁵ Generally, wetlands constitute an integral part of the ecosystems to which environmental protection laws are applicable. Consequently, the need to ensure an ecologically sustainable system of oil production in the Sudd Wetland becomes compelling. This article explores the mechanisms for addressing environmental concerns arising from oil and gas exploration and production within the Sudd Wetland under the nuances of international and domestic legal frameworks, as well as regulatory institutions.

2. Research Methodology

This study employed a doctrinal research methodology aimed at examining the adequacy of legal and regulatory frameworks in addressing environmental concerns from oil and gas activities in wetlands in South Sudan. To that end, the study analysed South Sudan's nascent and evolving domestic laws, including the Constitution, the Land Act, and the Petroleum Act, alongside international legal regimes such as the Ramsar Convention and the UN Convention on Biological Diversity. It further adopted a comparative approach, contrasting South Sudan's legal system with the more developed frameworks in Kenya and Uganda. This involved examining specialised wetland legal regimes and judicial precedents in the two East African countries to

identify potential pathways for legal reforms in South Sudan. The doctrinal analysis was equally guided by two primary conceptual foundations: Sustainable Development Theory, which emphasises resource preservation for future generations, and Public Trust Theory, which anchors on the government's fiduciary duty to manage natural resources in the public interest. Overall, this methodology enabled the research to identify legal and regulatory gaps and propose comprehensive measures, such as specialised wetland legislation in South Sudan and enhanced stakeholder engagement, to achieve sustainable wetland protection.

3. Geographical and Ecological Setting of the Sudd Wetlands of South Sudan

South Sudan attained independence in 2011 after voting in favour of secession from the Republic of Sudan, following decades of protracted struggle against perceived marginalisation. South Sudan is a country rich in petroleum resources located mainly in the Greater Upper Nile Region, including the Unity States.⁶ The United Nations Educational, Scientific and Cultural Organisation (UNESCO) considers the Sudd Wetland to be one of the largest freshwater ecosystems in the world, with an estimated area of approximately 57,000 km².⁷ The size, however, fluctuates. Wet seasons attract more water, where the size of the wetland increases up to 90,000 km² and gradually decreases to about 42,000 km².⁸ This makes the Sudd Africa's largest wetland and one of the largest tropical wetlands in the world.⁹ Wetlands are generally indispensable for the countless benefits, or "ecosystem services", that they provide to humanity, ranging from freshwater supply, food and building materials, and biodiversity, to flood control, groundwater recharge, and climate change mitigation.¹⁰

It is important to note that South Sudan is an oil-rich country. It is projected that oil reserves in the country stand at an estimated 3.5 billion barrels of crude oil, making it Sub-Saharan Africa's third-largest oil reserve after Nigeria and Angola.¹¹ The oil-producing

³ L-M. Rebelo or A. I. El-Moghraby "The Sudd (South Sudan)" https://link.springer.com/referenceworkentry/10.1007/978-94-007-6173-5_23-5 accessed on 21th July 2024.

⁴ Ibid.

⁵ Human Rights Watch "Neglect of the Environment" <https://www.hrw.org/reports/2003/sudan1103/22.htm> accessed on 23rd July 2024.

⁶ Matthew Bliss "Oil Production in South Sudan: Making it a Benefit for all Baseline Assessment of the Impact of Oil Production on Communities in Upper Nile and Unity States" (Cordaid, 2014) 6.

⁷ UNESCO World Heritage Convention "Sudd Wetland" <https://whc.unesco.org/en/tentativelists/6276/> visited on 28-02-26.

⁸ Ibid.

⁹ Ibid.

¹⁰ Ramsar Convention on Wetlands "The Importance of Wetlands" <https://www.ramsar.org/about/our-mission/importance-wetlands> visited on 28-02-6.

¹¹ Gyde Lund et al. Sudd "As Assessment of Wetland Ecosystem in South Sudan" United Nations Environmental Programme (2022) 16.

blocks span a section of the Sudd Wetlands, invariably raising significant environmental concerns.¹² Studies have pointed out that oil and gas activities play a major role in wetland loss, even though it is probably not possible to put a specific value on the extent to which these activities contribute to the problem.¹³ In the Sudd, one of the greatest threats to the wetland is from oil production and exploration, and this threat has endured for decades.¹⁴ In this vein, a critical question that this study would be interested in resolving is how adequate the legal and institutional frameworks of South Sudan are in addressing this ecological problem in order to balance it with the country's oil and gas development, which provides a lifeline for its future growth and prosperity. This question is best tackled within the rubric of international and domestic frameworks.

4. Theoretical Framework

To begin with, it should be noted that theories are crucial for any research work to give it direction and also to validate or disapprove a phenomenon.¹⁵ The theoretical framework provides the basic structure that holds a study and connects it to existing scholarly ideas, concepts, and thoughts. The study is guided by two important theories, which provide a conceptual foundation underpinning the legal regulation of the environment in the context of natural resource exploitation.

4.1 Sustainable Development Theory

As nations strive to meet their developmental goals through the exploitation of natural resources, it has become extremely imperative to ensure that, in meeting the present needs, the ability of future generations to meet their own needs is not compromised. Sustainable development is thus defined as the level of development that places a constraint on current consumption to ensure that future generations will have a resource base that is no less than the resource base of the previous generation.¹⁶ The Sustainable Development Theory underscores the importance of appropriate legislative and regulatory interventions to safeguard wetlands for the benefit of future generations. In the context of South Sudan, such interventions are particularly critical, as wetlands are

increasingly degraded and risk total loss with time as a consequence of oil and gas exploration and production activities.

4.2 Public Trust Theory

In South Sudan, just like most Sub-Saharan African countries, the ownership and management of key natural resources, including minerals, are vested in the government. It, therefore, behoves the government to manage these resources in the overall interest of its citizens. The public trust theory provides not only a legal justification but also an obligation of some sort on the government to hold the resources entrusted to it in trust for both the present and future generations. The English House of Lords case of *Gann v Free Fishers of Whitstable*¹⁷ provides a strong judicial foothold for the public trust theory, where it was held that the bed of all navigable rivers where the tide flows, and all estuaries or arms of the sea, is by law vested in the Crown. The House of Lords, however, emphasised that this ownership of the Crown is for the benefit of the subject and cannot be used in any manner to derogate from or interfere with the right of navigation, which belongs by law to the subject of the realm. This imposes a high fiduciary duty of care and responsibility upon the State, akin to that of a trustee, requiring it to manage and protect trust property prudently and in the best interests of both present and future beneficiaries. The public trust theory, thus, provides the legal justification for legislative, administrative, and policy interventions for wetland protection and conservation.

4.3 International Legal Framework

It is instructive to note that the Sudd Wetland area is officially designated by the United Nations as a wetland of international importance, thus bringing it within the purview of the international legal regimes on sustainable use, management, and governance of wetlands as part of the global agenda for climate change mitigation. The United Nations Convention on Biological Diversity, 1992, is foremost in providing a regulatory framework for the conservation of biological resources at the international level. South Sudan acceded to the Convention as the 194th Party

¹² *Ibid.*

¹³ Jae-Young Ko et al. (1).

¹⁴ Conflict and Environment Observatory "Is South Sudan's Sudd wetland at a fork in the road?" <https://ceobs.org/report-is-south-sudans-sudd-wetland-at-a-fork-in-the-road/> accessed on 17th July 2024.

¹⁵ PhD Assistance Research Lab 'Why is theoretical framework important in research?'

<https://www.phdassistance.com/blog/why-is-theoretical-framework-important-in-research/> visited on 07/07/26.

¹⁶ Ozili Peterson 'Theories of Sustainable Development' (2025) (5) Sustainable Development, Humanities, and Social Sciences for Society .

¹⁷ (1865) 11 H.

on 17 February 2014.¹⁸ A point to note is that oil and gas exploration and production pose significant threats to biodiversity resources, making it a major concern how to address the growing biodiversity management challenges associated with the sector.

The importance of wetlands as a cornerstone of the global ecosystem and their vulnerability to degradation are well acknowledged. This has steered the idea for a specialised regulatory regime governing wetlands under the rubric of the Convention on Wetlands of International Importance. The Convention was adopted in the Iranian city of Ramsar and therefore has come to be commonly referred to as the Ramsar Convention. South Sudan acceded to the Convention on 10 June, 2013.¹⁹ The accession has been heralded as a sign of the country's readiness to join the framework for international action and cooperation for the conservation and wise use of wetlands.²⁰ It is, however, important to note that accession to the Convention, though commendable, is not an end in itself but a means to an end. The true test has always lain in a member country's policy development and implementation for designated sites as a demonstration of willingness to participate in the Ramsar Convention and successful implementation of its pillars.²¹ Inclusion of land in the List of Wetlands of International Importance signifies the government's commitment to take the steps necessary to ensure that its ecological character is maintained.²² Better still, the important obligations under the Convention are as concerns land-use planning, designation of one or more wetlands for inclusion in the "List of Wetlands of International Importance," and, most fundamentally, the conservation and promotion of the protection of wetlands in general.²³

Whilst the Ramsar Convention generally does not specify a particular method for its implementation (with the partial exception of the obligation in Article

2(4), to designate at least one site to the List of Wetlands of International Importance), results are more important than means.²⁴ On the façade, South Sudan appears to demonstrate commitment to Article 2 (4) of the Convention by designating the Sudd as a Wetland of International Importance. How well the country has fared in promoting the protection of this wetland, however, remains an overarching concern. The implementation of the principles of the Ramsar Convention in South Sudan works at odds with the economic realities of the country; the fact that the Sudd contains South Sudan's largest oil reserves makes the continuous expansion of the oil industry into this ecologically sensitive area a major setback.²⁵ In parallel with the principles of the Convention, significant environmental degradation of the Sudd, particularly via crude oil contamination of the wetlands, remains noticeable.²⁶ This begs the question of the adequacy and effectiveness of the domestic legal and institutional frameworks in promoting the ideals of the Convention, which this study now turns to.

5. Addressing Environmental Concerns Arising from Oil and Gas in the Sudd Wetland area of South Sudan

It has already been pointed out that the Sudd contains South Sudan's largest oil reserves, making the continuous expansion of the oil industry into this ecological hotspot inescapable.²⁷ In environmental management, wetlands constitute an integral part of the ecosystem to which environmental protection laws are applicable. Therefore, the constitutional aspiration on the need to achieve ecologically sustainable development and use of natural resources whilst promoting rational economic and social development, and protection of genetic stability and biodiversity

¹⁸ OIISD "South Sudan Becomes 194th Party to CBD", <https://sdg.iisd.org/news/south-sudan-becomes-194th-party-to-cbd/#:~:text=The%20Secretariat%20of%20the%20UN,Sudan%20on%2018%20May%202014.> accessed on 17 May 2024.

¹⁹ UNESCO "South Sudan UNESCO Member since 2011: Conventions Ratified" https://www.unesco.org/en/countries/ss/conventions?utm_source=chatgpt.com visited on 01-03-26.

²⁰ Nile Basin Initiative "Sudd Wetlands Management Strategy 2022-2050".

²¹ Aziza Saud Al Adhoobi "Influences on the Successful Implementation of the Convention on Wetlands of International Importance (Ramsar) among Member Countries" (2016). LSU Master's Thesis 48.

²² Ramsar Convention on Wetland "Wetlands of International Importance" available at <https://www.ramsar.org/about/our-mission/wetlands-international-importance> accessed on 5th July 2024

²³ Veit Koester "The Ramsar Convention On the Conservation of Wetlands: A Legal Analysis of the Adoption and Implementation of the Convention in Denmark" (1989) No. 23 IUCN Environmental Policy and Law Paper 3.

²⁴ *Ibid.*

²⁵ UNESCO "Sudd Wetland" <https://whc.unesco.org/en/tentativelists/6276/#:~:text=The%20Sudd%20area%20covering%20about,its%20conservation%20and%20wise%20use.> accessed on 5th July 2024.

²⁶ *Ibid.*

²⁷ *Ibid.*

under the Constitution remains sacrosanct.²⁸ The same applies to the provisions of the Land Act, in particular section 5, which captures one of the fundamental principles of land law as: “promoting a land management system to protect and preserve the environment and ecology for the sustainable development of Southern Sudan.”²⁹ More specifically, the Petroleum Act mandates that petroleum activities be conducted in a manner as to ensure a high level of health, safety, and environmental compliance.³⁰

The above-mentioned legal instruments provide a generic framework for the protection of the environment. However, there is clearly no specific legal framework for the promotion of wetland protection in South Sudan. As a general obligation under the Ramsar Convention, contracting Parties are required to formulate and implement a system to promote the conservation of the wetlands included in the List of wetlands designated under Article 2 and, as far as possible, the wise use of wetlands in their territory.³¹ A study published by Louisiana State University in collaboration with the Agricultural and Mechanical College in 2016, using variables such as the number of years since the entry into force of the Ramsar Convention, the number of designated sites, and the number of available management plans, ranked South Sudan amongst the bottom five countries in terms of successful implementation of the Ramsar Convention and its pillars.³² This can largely be attributed to the absence of a specific legal or policy framework on wetland regulation, even though a modest step has been taken through the Sudd Wetland Management Strategy 2022-2050.

5.1 Policy Framework on the Sudd Wetland Protection

South Sudan has grappled with conservation programs and policies in promoting wetland conservation. The Sudd Wetland Management Strategy 2022-2050 is a key policy document for the protection of the Sudd. The Strategy hinges on the vision of “a sustainably managed Sudd wetland providing equitable opportunities and benefits for present and future generations of South Sudanese.”³³ Its objectives are fourfold:

- To promote the conservation of the Sudd wetland ecosystem.
- To build climate resilience and apply nature-based solutions to the sustainable management of the wetland, water, and environmental resources of the Sudd landscape.
- To support investments and water resources development to catalyse economic development through the application of green and blue economy approaches.
- To strengthen governance structures for the management of the Sudd wetland.

However, several challenges are weighing against the smooth implementation of the Sudd Wetland Management Strategy, including: lack of adequate funding, insecurity, inaccessibility due to the vast area size, and limited capacity (technical experts) to carry out complex work.³⁴ Other militating factors include: lack of political will, limited awareness, top-down approach, lack of stakeholder involvement, lack of proper coordination among all concerned stakeholders (civil society, local community, CBOs, NGOs, etc.), and lack of facilities and equipment for management and conservation activities.³⁵

Obviously, these challenges can be better addressed through broad-based legislation that establishes a comprehensive regulatory framework, prescribes funding options, promotes stakeholder involvement, builds institutional synergy, and generally regulates the use of wetlands and prescribes penalties for violations.

Unfortunately, the idea of developing a national wetlands policy, bill, or regulations for South Sudan has remained a pipe dream for a long time. In a National Report to the 13th Meeting of the Conference of the Contracting Parties to the Ramsar Convention held in Dubai, United Arab Emirates, in 2018, South Sudan stated, as one of the targets for implementation of the Ramsar Convention, plans to develop a national wetlands policy, bill, and regulations for the country.³⁶ This target has, however, not been achieved, even as the Report cited the government’s plans to “Hire consultants to develop a national wetlands policy, bill

²⁸ Transitional Constitution of the Republic of South Sudan, 2011. art 41 (3) (c)

²⁹ The Land Act 2009. S.5. This Act came into force after a peace deal with Sudan.

³⁰ Petroleum Act 2011, S,50(1).

³¹ Convention on Wetland Art 3

³² Aziza (n.21).

³³ Nile Basin Initiative “Sudd Wetlands Management Strategy 2022-2050” .9

³⁴ *Ibid.*

³⁵ *Ibid.*

³⁶ See National Report on the Implementation of the Ramsar Convention on Wetland, submitted to the 13th Meeting of the Conference of the Contracting Parties, Dubai, United Arab Emirates, 2018 39.

and regulations.”³⁷ The procrastination has been attributed to insufficient government funding and resources to facilitate the operationalisation of planned wetland conservation and management activities.³⁸ This is exacerbated by the fact that since the Sudd wetland was designated as a Wetland of International Importance on 5th June 2006 under the Ramsar Convention, no assistance has been given for the implementation of the Ramsar Convention by the Secretariat. It requires the Ramsar Secretariat to provide financial, logistical, and technical assistance and expertise to support the Republic of South Sudan in drafting appropriate legislation on wetland protection.³⁹

On a comparative scale, the ecological and hydrological idiosyncrasies of wetlands have prompted certain countries to adopt specialised legislative and regulatory frameworks in order to ensure a focused and context-specific approach to wetland protection. Uganda and Kenya are two East African states that have adopted this model.

6. Comparative Wetland Legal Regimes in East Africa: Uganda and Kenya in Focus

As part of their commitment to ensure adequate protection of wetlands, Uganda and Kenya have adopted laws that specifically address ecological issues associated with wetlands. In Uganda, pursuant to section 107 of the National Environment Act,⁴⁰ the Minister for Water, Lands, and Environment promulgated the National Environment (Wetlands, Riverbanks, and Lake Shores Management) Regulations, No. 3/2000. The Regulations have as their core mandate: “to provide for the conservation and wise use of wetlands and their resources in Uganda; ensure that wetlands are protected as habitats for species of fauna and flora; provide for the regulated public use and enjoyment of wetlands, and minimise and control pollution, among others.”⁴¹

The major wetland management tool under the Regulations is the requirement of an environmental impact assessment for all activities in wetlands likely to harm the wetland.⁴² To ensure a participatory approach to wetland management, District Environment Committees are established with the

responsibility of coordinating, monitoring, and advising District Councils on all aspects of wetland resource management.⁴³ Under the Regulations, wetlands are designated into three categories based on the level of protection: (a) fully protected wetland; (b) partially protected wetland; and (c) wetland subject to conservation by the local community.⁴⁴ Wetland use is subject to a wetland resource use permit except where the use is for the following: harvesting of papyrus, medicinal plants, trees, and reeds, cultivation where the cultivated area is not more than 25% of the total area of the wetland, fishing using traps, spears and baskets or other method other than weirs, collection of water for domestic use, and hunting subject to the provisions of the Wildlife Act, Cap 315.⁴⁵ Oil exploration and production are among the regulated activities for which a permit is strongly required.

A permit is granted upon application to the Executive Director of the National Environmental Management Authority established under section 8 of the National Environment Act, 2019. A permit may be revoked by the Executive Director if he or she is satisfied that the conditions of the grant of the permit have not been complied with or that the continued use of the wetland is likely to be injurious to the community and the environment.⁴⁶

A person who desires to carry out a project that may have a significant impact on a wetland, river bank, or lake shore is mandated to conduct an environmental impact assessment in line with sections 19, 20, and 21 of the National Environment Act.⁴⁷ It is further required that annual audits and monitoring of activities on wetlands be conducted and a report submitted to the National Environmental Management Authority under sections 22 and 23 of the Act.⁴⁸

The Regulations are backed by criminal sanctions in the form of ranging from imprisonment terms of not less than 3 months or a fine of not less than 3 million. The penal regime for offences under the Regulations, however, appears infinitesimal and inconsequential compared to the enormity of environmental harms which oil and gas exploration and production activities may occasion. This calls for a review of this penal regime in order to introduce more deterrent measures.

³⁷ *Ibid.*

³⁸ *Ibid.*

³⁹ *Ibid.*

⁴⁰ Cap 181 Revised Laws of the Republic of Uganda, 2023.

⁴¹ Reg. 4 National Environment (Wetlands, River Banks and Lake Shores Management) Regulations, No. 3/2000

⁴² *Ibid* Reg. 5 (c).

⁴³ *Ibid* Reg. 7 (1).

⁴⁴ *Ibid* 8 (2) (a, b, c.)

⁴⁵ *Ibid* Reg. 11 (2).

⁴⁶ *Ibid.* Reg. 14.

⁴⁷ *Ibid.* Reg. 34 ((1).

⁴⁸ *Ibid.* Reg. 34 (2).

Kenya is a sister East African country that has adopted a wetland regulatory approach similar to that of Uganda. Although wetland management generally falls within the purview of general environmental law, it is specifically regulated under the Environmental Management and Co-ordination (Wetlands, River Banks, Lake Shores and Sea Shore Management Regulations) 2009. The Regulations were made in exercise of the powers conferred by sections 42(3) and 147 of the Environmental Management and Co-ordination (EMC) Act⁴⁹ on the Minister for Environment and Mineral Resources. Wetland as per the Regulations means: “areas permanently or seasonally flooded by water where plants and animals have become adapted, and include swamps, areas of marsh, peatland, mountain bogs, banks of rivers, vegetation, areas of impeded drainage or brackish, salt or alkaline. It also includes areas of marine water the depth of which at low tide does not exceed 6 meters, as riparian and coastal zones adjacent to the wetlands.”⁵⁰

The main purpose of the Regulations is to provide for the conservation and sustainable use of wetlands and their resources in Kenya. Accordingly, the Regulations prohibit certain activities⁵¹ from being carried out on wetlands without a permit issued by the relevant lead agency, defined as “any Government ministry, department, state corporation or local authority in which any law vests functions of control or management of any element of the environment or natural resource.” As further required, an Environmental Impact Assessment and Environmental Audit under the EMC Act are mandatory for all activities likely to have an adverse impact on the management of wetlands.⁵²

The approaches adopted by Uganda and Kenya in regulating wetlands through specialised statutory instruments are quite illuminating and inspirational. It

is submitted that South Sudan should borrow a leaf from these jurisdictions to strengthen the existing legal framework on wetland conservation and management. This is greatly desirable considering the strategic importance of the Sudd Wetland and the concomitant damage from oil production, which greatly affects the wetland’s role in flood prevention, its moderation of the regional climate, and its role as a carbon source or sink.⁵³

7. Enforcement of Wetland Protection Legal Regimes

The existence of wetland protection legal regimes is an important step toward the conservation and sustainable use of wetlands. Environmental regulations and statutes are enforced through a blend of administrative and judicial processes.⁵⁴ This section traverses some key administrative and judicial enforcement mechanisms relating to wetland protection.

7.1 Administrative Enforcement

It is pertinent to note from the outset that administrative enforcement is a forefront approach in wetland protection and management, given that administrative orders and sanctions are among the common techniques in regulating the environment.⁵⁵ These are measures imposed by regulatory bodies against individuals or entities that violate environmental laws and regulations.⁵⁶

Section 58 (1) (a) of the Petroleum Act,⁵⁷ read in conjunction with section 81 (1) lays down a duty on oil operators (oil and gas companies) to: “take the measures necessary to ensure that petroleum activities are conducted in a manner that prevents waste of petroleum resources and promotes the safety and protection of the environment in compliance with

⁴⁹ Act No 8 1999.

⁵⁰ Environmental Management and Co-ordination (Wetlands, River Banks, Lake Shores and Sea Shore Management Regulations) 2009

⁵¹ Regulation 11 provides for activities that are permitted to be carried out on wetland. They include; (a) subsistence harvesting of papyrus, medicinal plants, trees and reeds; (b) any cultivation where the cultivated area is not likely to adversely affect the wetland; (c) fishing, subject to the provisions of the Fisheries Act; (d) collection of water for domestic use; (e) hunting, subject to the provisions of the Wildlife (Conservation and Management) Act; (f) small-scale fish farming; and (g) grazing of livestock.

⁵² Environmental Management and Co-ordination (Wetlands, River Banks, Lake Shores and Sea Shore Management Regulations) 2009 Reg. 5 (1) (b) & Reg. 12.

⁵³ For South Sudan “Major new report: oil’s onslaught on the Sudd, largest wetland in Africa” <https://forsouthsudan.com/major-new-report-oils-onslaught-on-the-sudd-largest-wetland-in-africa> accessed on 21st July 2024

⁵⁴ Tim Swanson “Cost-Effective Attainment of Environmental Compliance: Governance Solutions for Environmental Objectives in The Peoples Republic Of China” (2012) 13 Research Paper the Graduate Institute Centre for International Environmental Studies 4.

⁵⁵ Vicent Bartholomew Mtavangu “The Efficacy of Administrative Orders and Sanctions in Regulating Corporate Environmental Crimes in Mining Areas in Tanzania” (2024) 20 (1) *Lead Journal* 35.

⁵⁶ *Ibid.*

⁵⁷ Section 58 (1) (a) & (b) Petroleum Act, 2012.

applicable environmental laws and standards.” There are several sections of the Petroleum Act that grant the Ministry of Petroleum regulatory powers to enforce compliance against licensees or contractors. These include section 89 (8), which allows the Government to revoke licences or terminate agreements when obligations are not fulfilled, such as where there is a postponement for a particularly long duration. Another important regulatory control finds expression under section 91 (1), which lays down the requirement of security for performance. This section requires a licensee or contractor to submit to the Ministry any performance bond or guarantee mandated by the Ministry. Such security is intended to ensure the fulfilment of the obligations assumed by the licensee or contractor and to cover any potential liabilities that may arise from petroleum activities conducted under a licence, petroleum agreement, or any other authorisation issued pursuant to the Act. The hallmark of the regulatory standards is as prescribed under section 12 (3) (c), which empowers the Minister of Petroleum to terminate petroleum contracts for non-compliance with existing laws and policies on the environment. The composite effect of these provisions is that it establishes a framework of administrative enforcement mechanisms, which, if implemented, may be sufficiently useful in protecting the Sudd wetland ecosystem tapestry.

Although it is the duty of oil companies to respect laws, regulations, directives, and best practices relating to the environment in the course of their operations, it is, however, illusional to assume the automatic functioning of the law in that regard. It is therefore the role of regulatory agencies to enforce environmental laws, monitor compliance, and set standards for the protection of the environment.⁵⁸ This role is critical in ensuring that businesses operate according to environmental standards, thereby promoting environmental protection and sustainability.⁵⁹ The special status of the Sudd as a Wetland of International Importance makes an even stronger case for greater scrutiny of oil and gas activities and strict regulatory compliance. In practice, the protective value of regulatory mechanisms and their effectiveness in ensuring environmental safety depend on the proper implementation of applicable laws.

The overall picture of environmental law compliance in South Sudan’s oil and gas industry appears to be far from desirable due to several mitigating factors. According to a UN Environmental Programme Report, South Sudan’s oil and gas exploration has several negative impacts, including deforestation and loss of habitat and biodiversity, and soil and water contamination, especially of critical wetlands due to oil spills.⁶⁰ One major challenge is with respect to regulatory compliance. The scope of regulatory compliance in South Sudan’s oil and gas industry encompasses initial compliance requirements (environmental impact assessment – EIA, environmental and social impact assessment – ESIA, and permits); continuing compliance monitoring (environmental auditing, environmental reporting, environmental management system – EMS); and a decommissioning plan. Throughout these stages, accurate and reliable information is critical in making informed decisions and taking strategic and decisive actions. Unfortunately, inadequate, unreliable, and incomplete data remains a major problem. As tersely observed, “the lack of baseline data and ecological studies/understanding of the oil-producing area(s) in South Sudan poses a challenge to unequivocally distinguish between ‘normal’ and impacted situations.”⁶¹

In terms of the institutional framework, the Ministry of Environment and Forestry is the lead agency for the environment, forestry, and climate change sectors, and the lead institution for the management of the Sudd and other wetlands in South Sudan. This Ministry must therefore intensify efforts aimed at ensuring the sustainable and wise use of the Sudd Wetland in line with international standards and relevant laws and regulations in force.

The Sudd Wetland Management Strategy 2022-2050 is a key policy document available to the Ministry of Environment for the protection of the Sudd. The Strategy hinges on the vision of “A sustainably managed Sudd wetland providing equitable opportunities and benefits for present and future

⁵⁸ Carlos Pereira da Cruz “Environmental Compliance – Why it Matters and How To Obtain It” accessed from <https://advisera.com/articles/environmental-compliance/#:~:text=Environmental%20compliance%20refers%20to%20adherence,regulations%20to%20mitigate%20environmental%20impact,> on 23/08/24. 3

⁵⁹ *Ibid.*

⁶⁰ United Nations Environment Programme ‘South Sudan First State of Environment and Outlook Report 2018’ 23.

⁶¹ Ikvpax Christi ‘Repairing the Oil Legacy: A Phased Approach to Realize the Social and Environmental Audit in South Sudan’s Oil Areas’ (2013) Working Document.

generations of South Sudanese.”⁶² Its objectives are fourfold:

1. To promote the conservation of the Sudd wetland ecosystem.
2. To build climate resilience and apply nature-based solutions to the sustainable management of the wetland, water, and environmental resources of the Sudd landscape.
3. To support investments and water resources development to catalyse economic development through the application of green and blue economy approaches.
4. To strengthen governance structures for the management of the Sudd wetland.⁶³

However, several challenges continue to militate against the smooth implementation of the Sudd Wetland Management Strategy. These include: lack of adequate funding, insecurity, inaccessibility due to the vast area size, limited capacity (technical experts) to carry out technical work, and lack of political will. Other challenges include limited awareness, a top-down approach, a lack of stakeholder involvement, a lack of proper coordination among all concerned stakeholders (civil society, local community, CBOs, NGOs, etc.), a lack of facilities and equipment for management and conservation activities, and a delay in policies and legal framework.⁶⁴ These challenges constitute not only a setback to the realization of the policy agenda underlying the Sudd Wetland Management Strategy, but they are also a countervailing force to the sustainable management of wetlands in South Sudan generally.

7.2 Judicial enforcement

The sustainable use of wetlands requires a multi-stakeholder approach, complemented by a conscious and progressive judicial attitude in the interpretation and application of environmental laws. In South Sudan, environmental litigation is still in its nascent stage, considering that only a few legal actions have been instituted in courts of law in defence of the environment. Among the few cases that have gone to court, none is identified as specifically addressing wetlands, but they can still be useful for legal commentaries due to the jurisprudence espoused. One such case is *Cholong v Attorney General of the Republic of South Sudan*.⁶⁵ The case concerned an application filed by one Elario Adam Cholong, who

described himself as a ‘public-spirited person’ before the East African Court of Justice against the Government of South Sudan, seeking to restrain others from plans to start dredging the River Nile with undue regard to East African Law and International Environmental and human rights law. Unfortunately, the Court dismissed the application as time-barred under Article 30(2) of the East African Community Treaty. The fact that the case was not determined on the merits means that its jurisprudential value is limited.

In contrast to South Sudan, where environmental litigation is still low, apparently due to the country’s developing legal system, other East African countries, especially Uganda and Kenya, have demonstrated a more developed environmental litigation culture that can provide sturdy pathways for South Sudanese Courts. In Uganda, cases such as *Nyakaana v National Environment Management Authority*⁶⁶ and *Nakityo v National Environment Management Authority*⁶⁷ are illustrative. In *Nyakaana v National Environment Management Authority*, the appellant was the registered proprietor of land comprised in Leasehold Register Volume 3148 Folio 2 Plot 8 Plantation Road, Bugolobi, Kampala. He obtained the lease from the then Kampala City Council for the purpose of constructing a residential house. He subsequently applied for and obtained the necessary approvals for the said construction and commenced work. In June 2004, environmental inspectors from the National Environment Management Authority carried out an inspection of Nakivubo Wetland located in Nakawa Division. According to the inspectors, the appellant’s house was in the wetland. A meeting of residents and the inspectors was arranged, whereby the residents were briefed about their properties being in the wetland. The appellant attended the meeting. The appellant refused to heed all calls to halt his construction. The 1st respondent then issued a restoration order and had it served on the appellant. The restoration order required the appellant to comply with certain conditions, including demolition of the house, within a period of 21 days. He failed or refused to do so; consequently, the 1st respondent demolished the building on 8th January 2005. The appellant filed his petition. One of the grounds of appeal was that the learned Justices of the Constitutional Court erred in law and fact when they proceeded to decide the matter on the premise that the appellant’s land was a wetland. The Supreme Court emphasised that gazettelement is a

⁶² Nile Basin Initiative “Sudd Wetlands Management” (n 33) 9.

⁶³ *Ibid.* 15.

⁶⁴ *Ibid.*

⁶⁵ (2024) EACJ.

⁶⁶ Constitutional Petition No. 03 of 2005.

⁶⁷ [2022] UGHCLD 174.

precondition for the protection of wetlands. According to the Court, NEMA's failure to comply with the express provisions of the law to gazette the land which is the subject matter of the appeal as a wetland was erroneous, and so was the Constitutional Court's decision to proceed with the appellant's petition on the premise that it was in a wetland. The significance of this decision lies in its demonstration of how wetlands are formally designated and how the failure to gazette a wetland may result in the violation of constitutional rights under the guise of environmental enforcement.

In *Nakityo v National Environment Management Authority*,⁶⁸ the court addressed the question of public participation in environmental decision-making relating to wetlands. Here, the petitioner challenged the National Environment Management Authority (NEMA)'s decision to issue an Environmental Impact Assessment certificate for a development project that allegedly affected a sensitive wetland ecosystem. The petitioner argued that the EIA process was flawed, non-transparent, and failed to adequately involve affected community members. The High Court of Masaka found that NEMA failed to adhere to the provisions of the National Environment Management Act's principles on participation in Environmental Impact Assessment, exposing a major procedural flaw.

Turning to Kenya, it should be noted that this is a jurisdiction that has leveraged its legal framework and the specialised environmental court system established under the Environment and Land Court Act to enforce legal regimes governing wetland conservation. The Kenyan experience, therefore, provides a judicial context for understanding how wetland protection can be enhanced in a country like South Sudan.

The case of *Muthaiga North Residents' Association & another v Countryside Villas Limited & 20 others*⁶⁹ serves as a landmark ruling regarding the preservation of public utility land and the protection of naturally existing wetlands against unauthorised urban development. The petitioners in this matter argued that the respondents' actions on Plot No. 36 constituted a direct destruction of a naturally existing wetland and an interference with the natural habitat of local flora and fauna. They contended that these actions violated their constitutional right to "a clean and healthy environment" under Article 42. The court observed that the respondents had erected a massive wall fence, which signalled an intention to develop multi-dwelling residential units on the last remaining open area in the estate. The court ruled in favour of the petitioners. In

the related case of *Muthaiga North Residents Association v Nyari House Limited*,⁷⁰ while addressing what the court termed a "glaring legal lacuna" in Kenya's framework for protecting ungazetted wetlands within public land, the court ordered the cancellation of the illegal titles and the removal of all structures on the property. The case established that any title issued for land within a protected wetland or riparian reserve without proper assessment is invalid and subject to nullification. This line of cases demonstrates a judicial trend in Kenya where courts have ruled that short-term economic interests cannot override the long-term ecological value of wetlands, which serve as essential flood buffers and biodiversity hotspots. By these authorities and many others, Kenya has positioned itself as a regional hub for "Green Justice," particularly relating to wetland protection, offering an opportunity for direct benchmarking by the judiciary of South Sudan.

8. Findings

Amongst the critical issues relating to oil and gas exploration and production in South Sudan are the problem of the associated ecological fallouts and the lack of an adequate regulatory framework, as well as weak enforcement mechanisms. South Sudan is a signatory to the Ramsar Convention, officially called "Convention on Wetlands of International Importance Especially as Waterfowl Habitat, 1971." Unfortunately, the country ranks low in terms of policy development for the protection of designated sites. Consequently, oil and gas exploration and production continue to pose a significant threat to South Sudan's wetland ecosystems, especially the Sudd Wetland, which happens to be a designated site. Despite the Sudd Wetland Management Strategy 2022-2050 having been put in place to protect the Sudd, several challenges continue to weigh against the smooth implementation of the Strategy. These challenges include: lack of adequate funding, insecurity, which makes access to areas in the Sudd difficult, and inaccessibility due to the vast area size. Other challenges include: limited capacity (technical experts) to carry out technical work, and lack of political will, together with limited awareness, top-down approach, lack of stakeholder involvement, lack of proper coordination among all concerned stakeholders (civil society, local community, CBOs,

⁶⁸ *Ibid.*

⁶⁹ [2023] KEELC 21007 (KLR).

⁷⁰ (Environment & Land Petition No. 115 of 2015) [2022] KEELC 2578 (KLR).

NGOs, etc.), and lack of facilities and equipment for management and conservation activities.⁷¹

Delays in promulgating the relevant legal and policy frameworks constitute yet another significant challenge to effective conservation and management of wetlands in South Sudan. The lack of specific wetland regulations, as is the case in countries like Kenya and Uganda, combined with a low level of environmental litigation and the near absence of specific claims on wetland protection in South Sudan, is greatly concerning. This makes the country lag in effectively addressing the environmental concerns arising from oil and gas exploration in wetland regions.

9. Recommendations and Conclusion

South Sudan has a rich biodiversity with wetlands forming part of its major ecosystems. The most important wetland is the Sudd Wetland, which is one of the largest freshwater ecosystems in the world. Unfortunately, this precious ecosystem contains significant oil and gas deposits, the exploitation of which causes enormous ecological damage.

One would expect that the formal designation of the Sudd as a Wetland of International Importance under the Ramsar Convention entails automatic adequate protection. But the reality remains a far cry from the desirable, as oil production remains a serious threat to the Sudd's ecological value. This calls for more comprehensive and proactive measures encompassing legislative and regulatory enactments, capacity building, inclusivity and stakeholder engagement, as well as strong institutional and judicial enforcement in ensuring environmental protection of the Sudd Wetland. Borrowing from sister jurisdictions like Kenya and Uganda, it is important for South Sudan to adopt specific legislative and regulatory frameworks in order to ensure a focused and context-specific approach to wetland protection. The need for greater environmental consciousness and activism among civil society and local communities is equally important in strengthening wetland protection in South Sudan.

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⁷¹ UNESCO World Heritage Convention "Sudd Wetland" (n 29).

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Rooting Ability of *Irvingia wombolu* Juvenile Stem Cuttings under Different Growth Regulators in a Mist Propagation System

O.F. OYEDEJI, G.A. ADEBUSUYI, M.O. NOLA,
O.A. IROKO, M.O. MAJOLAGBE, N.B. OBEKPA
Forestry Research Institute of Nigeria, Jericho Forest Hill, Ibadan, Nigeria.

Abstract. The domestication and large-scale propagation of *Irvingia wombolu* are constrained by poor natural regeneration and seed recalcitrance, making vegetative propagation a viable alternative for its conservation and cultivation. This study evaluated the rooting ability of juvenile stem cuttings treated with different plant growth regulators under a mist propagation system at the Tree Physiology Nursery, SFM Department, Forestry Research Institute of Nigeria (FRIN), Ibadan. A total of 150 juvenile double-node stem cuttings obtained from six-month-old seedlings were treated with IBA, NAA and GA at concentrations of 200, 250, and 300 ppm using the quick-dip method. Treated cuttings were planted in sterilized river sand and arranged in a Completely Randomized Design with three replicates and a control. Survival, rooting, callus formation, and mortality were assessed after three months and analyzed using descriptive statistics and ANOVA. Significant variation was observed among hormone treatments. NAA at 200 and 250 ppm recorded the highest survival (91.67%), while GA treatments and the control showed the lowest survival (66.67%). Overall, NAA achieved the highest mean survival (86.11%), whereas IBA produced the greatest rooting percentage (50.11%), outperforming NAA (19.44%), GA (27.78%), and the control (22.22%). NAA also induced the highest callus formation (50.00%), while GA resulted in the greatest mortality (30.56%). The findings indicate that although NAA enhances cutting survival, IBA is more effective for adventitious root induction, particularly at 200–250 ppm. The study recommends IBA as the preferred growth regulator for the vegetative propagation of *I. wombolu* to support domestication, conservation, and sustainable plantation establishment.

Keywords: *Irvingia wombolu*, juvenile stem cuttings, rooting hormones, Indole-3-butyric acid, naphthalene acetic acid, mist propagator, vegetative propagation

1. Introduction

The domestication and sustainable propagation of indigenous tropical tree species have become central to global efforts aimed at improving biodiversity conservation, climate resilience, food security, and rural livelihoods. Indigenous fruit trees contribute substantially to ecosystem functioning by enhancing carbon sequestration, improving soil fertility, conserving genetic resources, and supporting sustainable agroforestry systems. Beyond their ecological significance, these species provide fruits, nuts, medicines, fuelwood, and other non-timber forest products that serve as important sources of nutrition and income for millions of rural households across sub-Saharan Africa (Jamnadass *et al.*, 2022; Dawson *et al.*, 2023). Consequently, the promotion of priority indigenous tree species has become an important strategy for achieving several Sustainable Development Goals, particularly those related to poverty alleviation, food security, biodiversity conservation, and climate adaptation (FAO, 2022; CIFOR-ICRAF, 2023).

Among these indigenous tree species, *Irvingia wombolu* (Vermoesen), commonly known as bitter bush mango, is one of the most economically valuable fruit trees indigenous to the humid forests of West and Central Africa. Together with its closely related species *Irvingia gabonensis*, it belongs to the family Irvingiaceae and is widely recognized for producing edible kernels that command high commercial value throughout the region (Leakey, 2022). The kernels are extensively used as soup-thickening agents because of their unique mucilaginous properties and high oil content, while different parts of the plant have long been utilized in traditional medicine for the treatment of gastrointestinal disorders, fever, diabetes, and inflammatory conditions (Atangana *et al.*, 2015; Leakey *et al.*, 2022). In addition, the species contributes significantly to household income through domestic markets and regional trade, making it an important livelihood resource for forest-dependent communities (Jamnadass *et al.*, 2022).

Despite its enormous socioeconomic importance, the cultivation of *I. wombolu* remains largely dependent on harvesting naturally occurring trees rather than plantation establishment. One of the major constraints to domestication is the difficulty associated with conventional seed propagation. The species produces recalcitrant seeds that rapidly lose viability after dispersal, making long-term storage practically impossible. Furthermore, seed-derived plants exhibit considerable genetic variation because of cross-pollination, resulting in inconsistent growth performance, fruit quality, and kernel yield among progenies (Sacandé & Sanon, 2007; Kettle, 2012). These limitations hinder the rapid multiplication of superior genotypes and reduce opportunities for genetic improvement and commercial orchard development.

Vegetative propagation has therefore emerged as an effective strategy for overcoming these constraints. Clonal propagation through stem cuttings enables the rapid multiplication of genetically superior trees while preserving desirable parental characteristics such as high fruit yield, kernel quality, disease resistance, and adaptation to local environmental conditions (Hartmann *et al.*, 2022). Compared with seed propagation, vegetative techniques shorten the juvenile phase, promote uniform plantation establishment, facilitate conservation of elite germplasm, and accelerate domestication programmes for indigenous fruit trees (Leakey, 2022; Jamnadass *et al.*, 2022).

Successful rooting of stem cuttings, however, depends on a complex interaction between endogenous physiological factors and external environmental conditions. Important determinants include the physiological age of donor plants, cutting type, seasonal timing, carbohydrate reserves, rooting substrate, temperature, humidity, light intensity, and the application of exogenous plant growth regulators (Druege *et al.*, 2019; Hartmann *et al.*, 2022 and Adebuseyi, *et al.*, 2024). Among these factors, auxin application remains one of the most effective approaches for enhancing adventitious root formation in woody plant species.

Auxins such as Indole-3-Butyric Acid (IBA) and Naphthalene Acetic Acid (NAA) have consistently demonstrated superior performance in stimulating root initiation through the activation of cell division, vascular differentiation, and root primordia development. These hormones also enhance carbohydrate mobilization and regulate the expression of genes involved in adventitious root formation, thereby increasing rooting percentage, root number, and root quality in difficult-to-root species (Pacurar *et al.*, 2014; Druege *et al.*, 2019; Bellini *et al.*, 2024). Among synthetic auxins, IBA is generally regarded as the most effective rooting hormone because of its relatively low phytotoxicity, slow degradation within plant tissues, and

sustained physiological activity during root initiation (Hartmann *et al.*, 2022).

Conversely, Gibberellic Acid (GA₃) performs physiological functions that differ substantially from those of auxins. GA₃ primarily promotes stem elongation, internode expansion, and shoot development through enhanced cell elongation and division. Although gibberellins may improve overall vegetative growth after rooting has occurred, their influence on adventitious root initiation remains inconsistent across plant species. Several studies have reported inhibitory effects of excessive GA₃ concentrations on root initiation due to antagonistic interactions with endogenous auxin signalling pathways, whereas moderate concentrations have occasionally promoted rooting depending on species-specific physiological responses (Colebrook *et al.*, 2014; Druege *et al.*, 2019).

Numerous studies involving tropical hardwoods and indigenous fruit trees have demonstrated the effectiveness of auxin-based treatments in improving rooting success. Species such as *Dacryodes edulis*, *Garcinia kola*, *Allanblackia floribunda*, *Vitellaria paradoxa*, and *Irvingia gabonensis* have shown significant improvements in rooting percentage, root length, callus formation, and cutting survival following treatment with IBA and NAA under controlled propagation environments (Leakey, 2022; Jamnadass *et al.*, 2022; Asaah *et al.*, 2023). Nevertheless, relatively little information exists regarding the comparative performance of IBA, NAA, and GA₃ on juvenile stem cuttings of *Irvingia wombolu*. Available studies have largely focused on seed germination, domestication, or agroforestry utilization, while systematic investigations into hormone concentration effects on rooting physiology remain scarce.

The absence of standardized propagation protocols limits the large-scale production of true-to-type planting materials needed for plantation establishment, conservation programmes, breeding initiatives, and commercialization of the species. Developing reliable clonal propagation methods would facilitate the rapid multiplication of elite genotypes, reduce dependence on wild populations, enhance genetic conservation, and strengthen domestication efforts aimed at increasing sustainable production of bitter bush mango throughout West and Central Africa (Leakey *et al.*, 2022; Dawson *et al.*, 2023).

Therefore, this study evaluated the rooting ability of juvenile stem cuttings of *Irvingia wombolu* treated with different plant growth regulators under mist propagation conditions. Specifically, the study assessed the effects of varying hormone concentrations on cutting survival, compared the effectiveness of auxins and gibberellins, and determined their influence on rooting percentage, callus formation, and mortality. The findings are expected to contribute towards the development of

efficient vegetative propagation protocols that will support large-scale domestication, conservation, and sustainable utilization of this economically important indigenous fruit tree.

2. Materials and Methods

2.1 Study Area

The experiment was conducted at the Tree Physiology Nursery, Department of Sustainable Forest Management (SFM), Forestry Research Institute of Nigeria (FRIN), Ibadan, Nigeria. Forestry Research Institute of Nigeria is located between 07°23'18"N to 07°23'43"N longitude and 03°51'20"E to 03°51'43"E latitude. The climate of the area is the West African monsoon with distinct dry and wet seasons. The dry season usually starts from November and runs through March and is generally characterized by dry wind of harmattan. The wet season on the other hand, generally runs through April to October with strong winds and thunderstorms occasionally. Mean annual rainfall falls around 1548.9 mm approximately, within 90 days. The temperature ranges from 31.9°C maximum to 24.2°C minimum, while the relative humidity is about 71.9% daily (FRIN, 2015). The propagation trial was established under a mist propagation system designed to maintain adequate humidity and minimize moisture loss from juvenile stem cuttings.

2.2 Collection and Preparation of Stem Cuttings

One hundred and fifty juvenile double-node stem cuttings of *Irvingia wombolu* were collected from six-month-old seedlings. Juvenile stem materials were selected to enhance rooting potential because juvenile tissues generally exhibit higher physiological responsiveness to root induction than mature tissues.

2.3 Hormonal Treatments and Experimental Design

The cuttings were subjected to three growth regulators: Indole-3-Butyric Acid (IBA), Naphthalene Acetic Acid (NAA), and Gibberellic Acid (GA), each prepared at 200 ppm, 250 ppm, and 300 ppm concentrations. Hormonal application was performed using the quick-dip technique before planting.

Treated cuttings were directly sown into trays containing washed and sterilized river sand as rooting medium. A control treatment without hormone application was included. Five cuttings were assigned to each treatment and replicated three times, resulting in a total of 150 cuttings. The experiment was arranged in a Completely Randomized Design (CRD) under a mist propagator.

2.4 Data Collection and Statistical Analysis

The cuttings were watered daily and monitored for survival. After three months, observations were recorded on percentage survival, rooted cuttings, callus formation, dead cuttings, and surviving cuttings without rooting or callusing. Data obtained were analyzed using descriptive statistics expressed as percentages and inference were made with the use of ANOVA. Significant means were separated with LSD.

3. Results

Survival Response of *Irvingia wombolu* Cuttings among Hormonal Concentrations

Survival percentage varied considerably among hormone concentrations (Table 1). The highest survival (91.67%) was recorded in both 200 ppm and 250 ppm NAA treatments, indicating superior effectiveness in maintaining cutting viability. Treatments involving 200 ppm IBA and 300 ppm IBA also supported relatively high survival (83.33%). However, increasing GA concentration reduced survival, with 250 ppm and 300 ppm GA treatments recording the lowest survival percentages (66.67%), similar to the control treatment.

Table 1a. Percentage survival of *Irvingia wombolu* cuttings among treatments

Treatment	200 ppm NAA	250 ppm NAA	300 ppm NAA	200 ppm IBA	250 ppm IBA	300 ppm IBA	200 ppm GA	250 ppm GA	300 ppm GA	Control
Percentage survival (%)	91.67 ^a	91.67 ^a	75.00 ^c	83.33 ^b	75.00 ^c	83.33 ^b	75.00 ^c	66.67 ^d	66.67 ^d	66.67 ^d

NB: Means with same alphabets along the row are not significantly different from each other.

Survival Performance among Hormone Types

When grouped according to hormone category, NAA recorded the highest overall survival (86.11%), followed by IBA (80.56%), whereas GA produced comparatively lower survival (69.44%) (Table 1b). The control treatment exhibited the lowest performance (66.67%).

Table 1b: Percentage survival of *Irvingia wombolu* cuttings among hormones

Hormone	Percentage survival (%)
NAA	86.11 ^a
IBA	80.56 ^b
GA	69.44 ^c
Control	66.67 ^d

NB: Means with same alphabets along the columns are not significantly different from each other.

Rooting, Callus Formation, and Mortality

Hormonal treatments exerted marked effects on rooting and callus formation (Table 2). IBA recorded the highest rooting percentage (50.11%), indicating superior capacity for adventitious root initiation. In contrast, NAA exhibited relatively low rooting (19.44%) but promoted the highest callus formation (50.00%), suggesting that tissue differentiation did not necessarily translate into root development.

GA exhibited moderate rooting performance (27.78%) but recorded relatively high mortality (30.56%), indicating poor suitability for rooting induction in *I. wombolu* juvenile stem cuttings. The control treatment showed the highest mortality (54.45%), emphasizing the importance of hormone application for successful propagation.

Table 2: Percentage rooted, callused, dead, and surviving cuttings of *Irvingia wombolu*

Hormone	% Rooted	% Callused	% Dead	% Alive (no root, no callus)
NAA	19.44 ^a	50.00 ^a	13.89 ^c	16.67 ^a
IBA	50.11 ^b	33.33 ^b	13.89 ^c	2.78 ^c
GA	27.78 ^c	33.33 ^b	30.56 ^b	8.33 ^b
Control	22.22 ^d	23.33 ^c	54.45 ^a	—

NB: Means with same alphabets along the columns are not significantly different from each other.

4. Discussion

The significant variation in survival, rooting, callus formation, and mortality observed among hormone treatments indicates differential physiological responses of *Irvingia wombolu* juvenile stem cuttings to exogenous growth regulators. The superior survival recorded in NAA-treated cuttings, particularly at 200 ppm and 250 ppm (91.67%), suggests that NAA enhanced tissue viability and reduced transplant stress under mist propagation conditions. Auxins such as NAA are known to stimulate cell dedifferentiation, vascular tissue regeneration, and wound healing, thereby enhancing post-excision survival in stem cuttings (Hartmann *et al.*, 2018). The present result agrees with findings by Tchoundjeu *et al.* (2002), who reported improved cutting survival in *Prunus africana* under moderate auxin concentrations, suggesting that exogenous auxin enhances physiological adaptation during the rooting process. Similarly, Ofori *et al.* (1996) observed improved establishment success in *Milicia excelsa* leafy stem cuttings following auxin treatment, emphasizing the importance of hormonal supplementation in difficult-to-root tropical woody species.

Although NAA promoted the highest survival percentage, it did not correspondingly induce superior rooting, as rooting under NAA remained comparatively low (19.44%) despite substantial callus formation (50.00%). This observation suggests that in *I. wombolu*, NAA may preferentially stimulate wound healing and callogenesis rather than direct root organogenesis. Similar findings were reported in

vegetative propagation studies of *Irvingia gabonensis*, where high auxin concentrations induced basal swelling and callus development without proportional increases in adventitious rooting (Anegebeh *et al.*, 2006). Excessive callus formation has been reported to interfere with vascular reconnection and root primordia emergence, particularly in woody perennial species where rooting competence is physiologically constrained (Leakey, 2012; Oyededeji and Oyededeji 2024).

Therefore, while callus formation may indicate tissue responsiveness, it does not necessarily predict successful root development.

In contrast, IBA-treated cuttings exhibited superior rooting performance (50.11%), confirming the greater effectiveness of IBA in stimulating adventitious root formation in juvenile stem cuttings of *I. wombolu*. This finding aligns with numerous studies on tropical tree species where IBA consistently outperformed other auxins in rooting induction. For instance, Tchoundjeu *et al.* (2002) reported enhanced rooting of *Prunus africana* cuttings treated with IBA, while Mesen *et al.* (1997) demonstrated increased rooting success in tropical hardwoods under moderate IBA concentrations. Similar results have been documented in *Dacryodes edulis*, *Garcinia kola*, and *Irvingia gabonensis*, where IBA significantly improved root initiation and cutting establishment (Leakey *et al.*, 1990; Anegebeh *et al.*, 2006). The superior performance of IBA may be attributed to its relatively greater chemical stability, slower degradation rate, and stronger ability to stimulate

cambial cell division and root primordial differentiation compared with NAA (Hartmann *et al.*, 2018).

Interestingly, the relatively high rooting percentage observed under IBA despite slightly lower survival than NAA demonstrates that survival alone is insufficient for evaluating propagation success. Successful vegetative propagation depends primarily on the capacity of cuttings to produce functional adventitious roots capable of supporting water and nutrient uptake after transplanting. The lower proportion of surviving but non-rooted cuttings under IBA (2.78%) compared with NAA (16.67%) further reinforces the greater rooting efficiency of IBA for *I. wombolu*. This observation corroborates previous assertions that IBA is particularly effective for woody species with rooting recalcitrance because it promotes direct root organogenesis rather than excessive callusing (Leakey, 2012).

The comparatively poor performance of GA-treated cuttings, characterized by lower survival (69.44%), moderate rooting (27.78%), and relatively high mortality (30.56%), suggests that gibberellic acid may not be suitable for rooting induction in juvenile stem cuttings of *I. wombolu*. Gibberellins are primarily associated with stem elongation, cell expansion, and shoot growth rather than adventitious root induction (Taiz *et al.*, 2015). Consequently, exogenous GA application may have altered endogenous hormonal balance in favor of shoot-related physiological processes at the expense of root development. Similar inhibitory effects of gibberellins on rooting have been reported in several woody species, where elevated GA concentrations reduced rooting competence through antagonistic interactions with auxin-mediated root initiation pathways (Hartmann *et al.*, 2018). The decline in survival observed at higher GA concentrations (250–300 ppm) further suggests possible phytotoxicity or hormonal imbalance under mist propagation conditions.

The concentration-dependent response observed among treatments highlights the importance of optimizing hormone dosage for rooting success. The superior performance of 200 ppm and 250 ppm NAA compared with 300 ppm suggests that moderate concentrations are more beneficial for tissue survival and physiological responsiveness than excessive hormone application. Similar concentration-dependent effects have been reported in tropical woody species where moderate auxin levels improved rooting, whereas excessive concentrations inhibited root initiation or induced tissue necrosis (Mesen *et al.*, 1997; Tchoundjeu *et al.*, 2002 and Amadi, *et al.*, 2022). The relatively consistent survival observed across IBA concentrations further indicates that *I. wombolu* juvenile stem cuttings respond favorably to moderate auxin-mediated stimulation.

The high mortality observed in untreated cuttings (54.45%) demonstrates the importance of exogenous growth regulator application in overcoming rooting recalcitrance in *I. wombolu*. Tropical woody species

often possess inadequate endogenous auxin levels to stimulate sufficient adventitious root formation after severance from the mother plant (Alaje, *et al.*, 2019 and Leakey *et al.*, 1990). The inability of the control treatment to sustain rooting and survival therefore supports the necessity for hormonal intervention in clonal propagation of elite genotypes.

Overall, the findings suggest that juvenile stem cuttings of *I. wombolu* are responsive to auxin treatment under mist propagation systems, with IBA demonstrating greater rooting potential and NAA enhancing survival and callus formation. The integration of high rooting efficiency and moderate survival makes IBA particularly suitable for large-scale vegetative propagation, domestication, and conservation of superior *Irvingia wombolu* genotypes.

5. Conclusion

This study demonstrated that growth regulators significantly influence the rooting ability and survival performance of juvenile stem cuttings of *Irvingia wombolu* under mist propagation conditions. Naphthalene Acetic Acid (NAA) enhanced cutting survival, particularly at 200 ppm and 250 ppm concentrations, indicating its effectiveness in maintaining tissue viability and promoting callus formation. However, Indole-3-Butyric Acid (IBA) proved superior for adventitious root induction, recording the highest rooting percentage and thus exhibiting greater potential for clonal propagation of the species. Gibberellic Acid (GA) showed comparatively poor rooting performance and elevated mortality, suggesting limited suitability for vegetative propagation of *I. wombolu*. The poor performance of untreated cuttings further underscores the necessity of exogenous hormone application for successful rooting and establishment.

The findings suggest that IBA, particularly at moderate concentrations, offers the greatest potential for rapid multiplication and domestication of elite *I. wombolu* genotypes. The study contributes valuable baseline information for the development of efficient propagation protocols aimed at supporting conservation, plantation establishment, and sustainable utilization of this economically important indigenous fruit tree species.

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Adaptive Spam Detection: Leveraging Federated Learning for Privacy-Preserving Email Security

FATIMA DHAMED KAZEM
Ministry of Education, Diyala, Iraq
fatima.1985da@gmail.com

AHMED MOHAMMED HUSSEIN
Ministry of Education, Babylon, Iraq
ahmed.94.moe@gmail.com

ZAID HAYDER AKBAR
Ministry of Education, Wasit, Iraq
zakbar@uowasit.edu.com

Abstract. Email spam and spear phishing are and always will be a security and usability issue, and it is increasingly difficult to scale and protect centralized approaches that depend on aggregating users' mail data due to privacy and regulatory considerations (GDPR, CCPA, etc.). This paper formalizes the inherent tension between the need to collect massive, heterogeneous data to train good detectors, and the need to protect the privacy of individual emails, and presents Federated Learning (FL) as a principled solution: models are trained in collaboration across users' devices, without any raw messages ever leaving a client host and with only model updates being shared. We train a FedAvg-based pipeline on a small hybrid classifier that uses text features (TF-IDF and optionally contextual embeddings) and metadata signals (sender reputation, number of links, and attachment flags), and we test it on a user-partitioned simulation built from a synthetic corpus of 120k emails from 1,200 non-IID anonymized users with topic and label skews. Our main takeaways are that (i) the FL-trained global model can achieve comparable performance to the pooled (centralized) baseline while maintaining data locality and (ii) local fine-tuning on each client provides useful client-level personalization that can benefit users with unusual local data distributions, improving detection performance. We also quantify the trade-offs involved in choices for the number of clients participating in each round, the amount of local computation, and the number of communication rounds. We investigate robustness to label noise and regularization. These findings suggest that FL-based spam detection is a promising and privacy-preserving building block for future next-generation anti-spam systems, and they motivate future directions in secure aggregation, adversarial robustness, and deployment-aware optimization.

Keywords: Federated Learning; Spam Detection; Privacy-Preserving Machine Learning; Email Security; Non-IID Data

1. Introduction

Email is one of the most used digital communication tools, yet it is severely challenged by spam. Spam is present everywhere, and lately, a report that revealed that 85% of emails are spam has become a serious concern for people's productivity and organizations' costs (Talos, 2023). More serious than just an annoyance, spam is the delivery mechanism of choice for many high-risk security threats. Phishing emails, which aim to trick users into divulging sensitive information such as login credentials, often arrive as spam. Malware distribution is another common threat vector; an employee's interaction with a malicious spam message can put an entire organization's network at risk. According to the 2023 Verizon Data Breach Investigations Report, 36% of all data breaches involved a phishing element. Another issue is that spam campaigns are not a one-off activity; spammers are constantly updating their approach with new social engineering, context awareness, and adversarial ML techniques to circumvent fixed-point defenses, so detection needs to be just as dynamic.

To combat this threat, email security has started to leverage machine learning (ML) models, more specifically deep learning models, which are able to learn intricate structures from large corpora of email data. The current paradigm for training these powerful models is centralized learning: large datasets with millions of users' emails are collected on one server for training. However, this method while allowing the

creation of classifiers with high accuracies also poses a very basic and increasing tension with users' privacy. Processing such sensitive email information on centralized servers both creates an attractive target for data breaches and leaves users vulnerable to insider attacks. Furthermore, the centralized model directly contradicts current data protection regulations, such as the European Union's General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA), which emphasize the principles of data minimization and purpose limitation. In the words of Lai et al. (2022), the traditional approach of centralizing data is "increasingly undesirable or infeasible." With these two aspects in conflict, there is a strong need for an alternative privacy-preserving solution, which is the motivation for our research. Therefore, our central research question is: how to create an accurate and adaptive spam detection solution that does not violate the privacy of email contents?

This paper presents and explores Federated Learning (FL), introduced by Sun et al. (2021), as a decentralized approach to machine learning (ML) that can help us flip the current paradigm. In contrast to the typical ML data pipeline, FL inverts the process such that instead of bringing the data to the model, we bring the model to the data. In this scenario, a shared global model is trained over a large federation of client devices (like users' computers or phones), each of which has its own private dataset. The clients train the model using their local data, and only the computed model updates (not the raw emails themselves) are sent to the central server for aggregation. This ensures sensitive user data never leaves its local device, so at a minimum it provides some basic privacy by design. While FL has been shown to work in tasks like next-word prediction on mobile keyboards (Suliman and Leith, 2023) and in healthcare (Long et al., 2021), further exploration is necessary to understand its potential for dynamic and high-stakes domains such as email security.

The central goal of this paper is to design, develop, and thoroughly evaluate a new adaptive spam detection system that is based on a solid FL architecture. Our initial contribution is the design of the FL framework that details the client-server communication protocol and aggregation strategy for the email domain. Second, we design a specific model of neural network that can perform feature extraction over email contents and metadata, which is efficient under the FL setting. Third, we conduct an empirical study and show how our proposed FL model can match the performance of the centralized baseline using common metrics including accuracy, precision, recall, and F1-score. Secondly, we construct a particular neural network model which can perform efficient feature extraction on email text and meta information under the FL setting. Thirdly, we perform an experimental study to compare the performance of our proposed FL model against a vanilla centralized baseline, using metrics such as accuracy, precision, recall and F1-score.

The rest of this paper is structured as follows. Section 2 gives an overview of related work, which includes traditional spam filters, centralized ML models, as well as federated learning. In Section 3, we describe the proposed methodology, including the FL framework, model architecture, and experimental setup. Section 4 provides the results of our comparative evaluation. In Section 5, we discuss our findings, highlighting advantages and limitations. Finally, Section 6 concludes the paper, summarizing our contributions and potential future research directions.

2. Literature Review

In the early stages of spam detection, systems used heuristic, rule-based approaches. These systems were simple to interpret because they employed manually created rules and blacklists to identify potential threats (Sahami et al., 1998). However, they were also inflexible and incapable of evolving to meet new types of attacks, which made them brittle and ultimately limited in their effectiveness. Machine learning was soon integrated to enable a filter to learn the discriminatory patterns from the data. Sahami et al. (1998) were the first to show the power of Naïve Bayes classifiers for email categorization. A Bayesian probability estimate is made to find the probability of an email being spam given its features. This approach was quickly augmented with much more powerful models such as Support Vector Machines (SVMs), which tried to identify the best hyperplane in a very high dimensional feature space to separate the spam and the ham (Drucker et al. 1999), and Decision Trees, which provided an interpretation of the classification process that could be followed by a human reader.

A major turning point was the introduction of deep learning which automated the feature extraction process. This was a shift from handcrafted features to learning features from raw data. In practice, Convolutional Neural Networks (CNNs) had been used to address the problem of image recognition, but they have also been used for text classification, as shown by Dharma et al. (2022), by taking advantage of the CNN's ability to extract the most prominent local features in the sequence of words in emails. Due to the sequential nature of email content and metadata, Recurrent Neural Networks (RNNs), especially Long Short-Term Memory (LSTM) networks, have been found effective by Ghanem and Erbay (2023), as they can capture long-range dependencies and contextual information. More recently, Transformer-based models like BERT (Bidirectional Encoder Representations from Transformers) have achieved state-of-the-art performance. Mohammed and Ali (2021) found that BERT's deep bidirectional training results in a deep understanding of context and semantics. Xu (2025) has utilized BERT, fine-tuned on a large corpus of emails, to achieve state-of-the-art accuracy in spam detection.

But this quest for ever more precise results using ever more complicated models has been very dependent on the centralized learning model which requires massive collections of user emails to be hoarded onto one server. This has been coming under more and more privacy-based criticism lately. These risks are not just theoretical. Data breaches have compromised the personal data of millions of users (Dorfleitner et al., 2023). Centralized data repositories are attractive targets for cybercriminals. Equally concerning is the practice of processing individuals' personal communications for model training, which may conflict with strict data protection laws. EU General Data Protection Regulation (GDPR) and California Consumer Privacy Act (CCPA) advocate for data minimization and purpose limitation, which pose serious regulatory and practical challenges to the centralization of email data (Carmi et al., 2023). Indeed, as Lai et al. (2022) have persuasively demonstrated, traditional data centralization paradigm of raw data is "increasingly undesirable or infeasible" and in urgent need of a crossroads where the essential security and user privacy can be effectively reconciled.

It is in this landscape that the distributed paradigm of Federated Learning (FL) was born. In the seminal paper of Sun et al. (2021), Federated Averaging (FedAvg) algorithm was proposed. This algorithm would later serve as a basis for the FL workflow, where a central server orchestrates the training of a global model, via iterative aggregations of computed model updates from a large number of client devices, on which the actual training data is stored. This "bring the code to the data" paradigm has the immediate benefit of improving privacy. However, FL brings other challenges. The communication cost of shipping model updates from clients to server is a natural bottleneck, leading to the development of communication-efficient algorithms (Kosseff, 2023). Systems heterogeneity (clients have different computation and network capacities) and statistical heterogeneity (local data is non-iid across devices) are two main types of heterogeneity. Both types of heterogeneity can significantly affect the model performance and convergence, as explained in detail by Singh et al. (2022). Despite these limitations, FL has been successfully applied to real-world use cases. Suliman and Leith, (2023) presented FL's use in mobile keyboard prediction on Android at Google. Long et al. (2021) also discussed FL's potential to transform healthcare and how it could be used to build predictive models across several hospitals, without exchanging patients' data.

The use of FL in the cybersecurity field has also recently gained attention. FL has been shown to be possible for various cybersecurity tasks such as network intrusion detection (Sarhan et al., 2022). Sarhan et al. (2022) suggest a FL framework for detecting IoT-based cyberattacks. The authors show that a shared model with high accuracy could be reached without revealing each organization's network traffic data. Likewise, Shalabi et

al. (2025) investigated FL for Android malware classification. The technique allows for multiple mobile devices to collaboratively train a malware detection model while keeping personal applications data private on the mobile devices. FL has also been extended for phishing website detection and anomaly detection on industrial control system by Thapa et al. (2023) and Marfo et al. (2025), respectively.

However, one particular aspect of this expanding body of work merits a more critical examination. Despite the broad application of FL in various cybersecurity domains, its investigation and adaptation for the specific problem of email spam detection is strikingly limited and still in its infancy. The available works in this area often use relatively simple model architectures, or they do not explicitly take into consideration the nature of email data. In particular, the nature of spam is evolving and user-specific (meaning an ad for one user is considered spam for another user) which makes it a strong non-IID data distribution, which is not effectively handled by most FL algorithms. Additionally, current literature does not provide a study that designs a novel neural architecture inside of an FL system, specifically for the task of email, and then comprehensively compares its performance, adaptability, and privacy across to known baselines from centralized learning under practical, non-IID settings. It is this exact void of developing and thoroughly evaluating an adaptive, privacy-preserving spam filter using state-of-the-art FL methods and customized model development that this work aims to address.

3. Research Methodology

We present the methodological workflow to measure and validate the privacy-preserving, federated, and spatio-temporal nature of the proposed spam detection for email systems. The methodology coalesces the client-server federated learning protocol and hybrid deep classifier encompassing both hand-crafted metadata and contextual text embeddings, user-level data partitioning to simulate the realistic non-IID setting, and classical classification performance metrics as well as FL-specific performance aspects (number of communication rounds, time-to-convergence, and client heterogeneity robustness). The next part of the thesis first describes the design of the federated system and the client selection logic, then the architecture of the spam classifier and the features engineering pipeline, and finally the experimental configuration, baselines and evaluation protocol used in all experiments.

3.1 Federated learning framework design

The problem is formulated as the collaborative minimization of an empirical risk across a population of M users (clients), where each client k holds a local dataset D_k . Let $F_k(\theta)$ denote the local objective for model parameters θ (for example, average cross-entropy

loss over D_k). The global federated objective is the weighted average of client objectives,

$$F(\theta) = \sum_{k=1}^M \left[\frac{n_k}{N} F_k(\theta) \right] \quad (1)$$

where $n_k = |D_k|$ and $N = \sum_k n_k$.

This objective formalizes the target of learning a single global model that benefits from diverse, privately held user data while avoiding direct sharing of raw emails.

In operational terms, we adopt the classical client-server design in which a central server orchestrates repeated communication rounds. The server is responsible for global model initialization, client sampling, and aggregation of encrypted or privacy-protected client updates. Each round proceeds with the server broadcasting a copy of the current global model θ_t to a selected cohort S_t of clients; each client $k \in S_t$ performs a number of local optimization steps on its private data to obtain updated parameters θ_{t+1}^k , and then returns the update (parameter delta or model gradients) to the server. The server aggregates these client updates into a new global model according to a weighted averaging rule (federated averaging). The FedAvg aggregation step used here can be written as $\theta_{t+1} = \sum_{k \in S_t} \left[\frac{n_k}{\sum_{j \in S_t} n_j} \theta_{t+1}^k \right]$ (2)

which corresponds to averaging local models proportionally to local dataset size and is the operational core of the approach introduced by Sun et al. (FedAvg). This approach has been widely used in cross-device and cross-silo FL and shown to be communication-efficient while robust to class and quantity imbalance, though its convergence is affected by non-IID heterogeneity.

Two important practical considerations are integrated into the server protocol. First, secure aggregation is applied to the transmitted model updates so that the server learns only an aggregate sum rather than individual client updates; this reduces the risk of reconstructing client data from gradients and follows established secure aggregation protocols. Second, clients can optionally add local differential privacy mechanisms (noise addition to updates) when requested by the privacy policy of the deployment; such defenses are integrated as configurable modules in the experimental pipeline (privacy budgets and aggregation schemes are parameterized). The secure aggregation

primitives and trade-offs in Liu et al. and related works serve as reference implementation and design pattern for privacy-preserving aggregation in our system.

3.2 Client selection strategy and handling heterogeneity

Client selection is made concrete as a sampling process (without replacement) per round that stochastically simulates real-world participation and resource constraints. Clients are sampled from the training cohort using a stratified scheme along 3 practical axes: (i) dataset size (so that large clients are not sampled at every round), (ii) topic diversity (to mix different topics at every round), and (iii) drop-out probability (to simulate availability). Specifically, the probability p_k of selecting client k in a given round is proportional to a mixture of its normalized availability parameter α_k and a dampened function of size $\sqrt{n_k}$ to avoid over-weighting very large clients:

$$p_k \propto \alpha_k \cdot \sqrt{n_k+1} \quad (3)$$

This mixture increases the chance of including both smaller and larger clients across rounds, and supports experiments that vary participation rate to study effects on convergence and fairness. Client sampling and partial participation design choices are motivated by theoretical analyses that highlight the sensitivity of FedAvg to non-IID data and partial participation; Cheng et al. provide theoretical bounds for FedAvg under non-IID heterogeneity and motivate stratified client sampling and alternative aggregation only when necessary.

To evaluate robustness to label and feature skew, the dataset is partitioned by user (client) so that all emails from a given user remain on that client; topics and spam rates are assigned per user and preserved. This user-level split simulates the cross-device federated scenario typical for end-user mailboxes or cross-silo deployments (where each organization represents a client), and prevents label leakage across clients.

Figure 1 (below) depicts a schematic of the system flow in our experiments; following it (in the text that comes after), are equations and experimental details that together define the training loop and client selection.

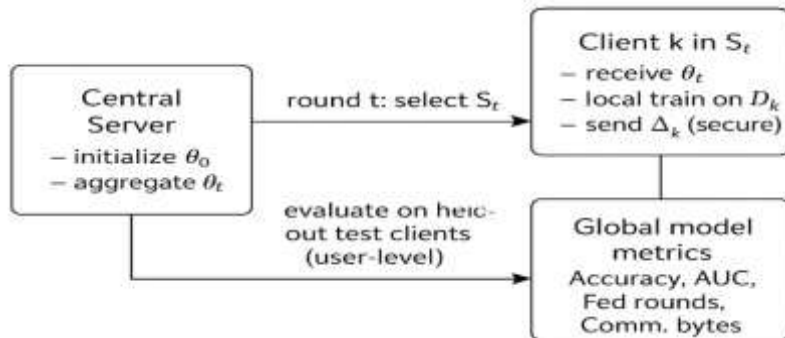


Figure 1: Methodology schematic (Server-Client FL loop)

3.3 Spam detection model architecture and feature engineering

The classifier is constructed as a hybrid architecture combining explicit metadata features with learned contextual embeddings extracted locally at each client. The feature pipeline and the model design are motivated by prior work showing that metadata (sender reputation, links, attachments, timing patterns) and textual representations complement each other for robust detection of spam and phishing. Transformer embeddings and recurrent models are effective for email text; however, computational constraints on edge clients motivate the use of light, finetunable encoders (distilled BERT or local Word2Vec/GloVe + sequence model) in the client training loop. Empirical studies of text-based phishing detectors and spam classifiers support combining recurrent layers with attention for sequential understanding of email text and emphasis on key tokens (subject lines, links, command verbs).

3.4 Feature engineering (local, privacy-preserving)

Each client constructs an identical feature set from its private email store. Textual inputs are formed by concatenating subject and body_plain (or, where available and permitted, a sanitized HTML-to-text conversion of body_html). Two parallel representations are produced: (i) a sparse TF-IDF / BoW vector computed from cleaned_text using a shared vocabulary (clients may use a server-distributed vocabulary or build local vocabularies mapped to the shared index); and (ii) dense contextual embeddings produced either by a locally fine-tuned sentence transformer (if client compute allows) or by averaging pretrained word embeddings (Word2Vec/GloVe) when compute is constrained. Metadata features—sender reputation score, number of links, presence of attachments, hour of day, day of week, and token counts—are appended as structured inputs and standardized per client.

To formalize, the client feature vector for email i on client k is written as

$$x_{(k,i)} = [\llbracket \text{TFIDF} \rrbracket_{(k,i)} \parallel \llbracket \text{Embed} \rrbracket_{(k,i)} \parallel m_{(k,i)}], \quad (4)$$

where $\llbracket \text{TFIDF} \rrbracket_{(k,i)}$ is the high-dimensional sparse representation, $\llbracket \text{Embed} \rrbracket_{(k,i)}$ the dense embedding, and $m_{(k,i)}$ the metadata numeric vector. The composite vector is the input to the neural network classifier described next. The dataset provided for this study already includes a cleaned_text column, sender_reputation, num_links, and has_attachments that facilitate direct extraction of these features at each client.

Neural network design and justification

The proposed neural classifier is a hybrid sequence–attention architecture selected to balance sequential context capture with interpretability and communication efficiency. The model's forward computation (local model on each client) proceeds as follows: first, a local embedding layer maps token indices (or the precomputed dense embeddings) to a sequence of

vectors; second, a bidirectional LSTM (BiLSTM) processes the token sequence to capture both past and future context; third, a self-attention layer computes importance weights across the BiLSTM outputs to highlight salient tokens such as action verbs, link tokens, or suspicious phrases; fourth, a small MLP fuses the attended text representation with the metadata vector and produces logits for multi-class classification (ham / spam / phishing / malware). Formally, if h_t denotes the BiLSTM hidden state at token position t for an input of length T , attention scores a_t are computed using a learned key/query projection and softmax:

$$u_t = \tanh(W_h h_t + b_h), \quad \alpha_t = (\exp(v^T u_t)) / (\sum_{j=1}^T \exp(v^T u_j)) \quad (5)$$

and the attended representation is $r = \sum_{t=1}^T \alpha_t \llbracket h_t \rrbracket$. The fused vector z is given by

$$z = \text{ReLU}(W_r [r \parallel m] + b_r), \quad (6)$$

and the final class probabilities are obtained by a softmax layer $y = \text{softmax}(W_o z + b_o)$. The BiLSTM+attention design is chosen because bidirectionality captures long-range dependencies in email text (for instance, a suspicious link in the middle of the body may be clarified or contradicted by later sentences), while attention provides an interpretable weighting of tokens, which is useful both for model inspection and for targeted feature engineering; multiple studies have demonstrated the effectiveness of BiLSTM and attention for phishing and spam classification tasks.

From a federated perspective, this architecture is compact enough to be transmitted between server and clients with manageable communication cost (model sizes can be kept small by limiting LSTM hidden size and using a distilled embedding layer), and local fine-tuning of the embedding layer can be restricted or disabled to reduce privacy exposure and computation when needed.

3.5 Experimental setup

The experiments are engineered to compare the federated training regime to centralized baselines and to study the effect of non-IID user partitions on convergence, fairness and detection performance. All splits are at the user-level, so that full client histories are assigned to a single simulated device/silo. This is consistent with the federated privacy model, and avoids example-level leakage across the train/val/test splits.

3.6 Data Sources and Partitioning

The main corpus used in these experiments is the synthetic, user-partitioned email corpus produced as described previously (120,000 emails, 1,200 anonymized users) that includes per-user topic assignment, per-user spam rates, as well as full headers and bodies such that metadata features can be computed locally on each client. The synthetic corpus is selectively augmented with public corpora as appropriate to improve external validity: Enron-derived partitions (to introduce realistic, enterprise-style

message patterns) and established labeled corpora like Lingspam or TREC subsets for robustness checks. Synthetic user-partitioned data as well as the Enron partitions allow for controlled experiments in which the degree of non-IID heterogeneity can be controlled by

reassigning user topics or by artificially introducing label skew on subsets of clients. Summary of the main dataset statistics used in the experiments is presented in Table 1.

Table 1: Dataset summary (primary synthetic corpus used in experiments)

Item	Value
Number of users (clients)	1,200
Total emails	120,000
Mean emails / user	≈ 100
Distribution	Long-tail (Pareto) per-user counts
Overall spam + phishing + malware (%)	$\approx 18.6\%$
Temporal range	2021-01-01 — 2024-12-31
Per-user topic categories	tech, marketing, finance, health, academia, shopping, social
User-level split (train/val/test)	70% / 10% / 20% (by user)

In the table underneath, we mention that the synthetic corpus was produced following a long-tail distribution of the number of emails per user, to better mimic mailbox activity, where few users produce most of the traffic. The global malicious fraction ($\approx 18.6\%$) is also in the realistic 10–30% range of values recommended in the dataset requirements; the dataset contains explicit phishing and malware labels, to also allow multi-class detection experiments. Because the split is performed at the user level, training, validation and test phases evaluate generalization to unseen users rather than unseen messages, which is the desired real-world test of a federated global model.

3.7 Baseline models and comparative strategies

The experimental design compares the federated hybrid classifier trained with FedAvg to a set of centralized and classical baselines to quantify the advantages and trade-offs of FL. Baselines include an identical neural network trained centrally on pooled data (centralized upper bound), a classical Support Vector Machine (SVM) with TF-IDF features, and a multinomial Naive Bayes classifier. These baselines measure the gap between centralized training (oracle access to pooled data) and federated training under non-IID partitions, as recommended in FL evaluation best practices. We also measure a local-only baseline in which each client trains a small local model and no global aggregation occurs; this provides a lower bound for the benefit of collaboration.

3.8 Implementation and hyperparameters

All experiments are implemented using TensorFlow Federated (for cross-device simulations) and an experimental PySyft/Flower wrapper for secure aggregation and deployment emulation. The server and client code enable flexible switching between secure aggregation and plain aggregation, and they implement the stratified client sampling scheme described previously. The hardware used for large-scale simulations is a 16-core CPU server with 4 NVIDIA A100 GPUs for centralized and aggregated evaluation tasks; client simulations are run as parallel processes to emulate resource-limited devices.

Table 2 lists the principal hyperparameters used for the principal experimental runs; these hyperparameters are tuned on the validation cohort of clients and reported with the final evaluation results.

Table 2: Primary hyperparameters (default experimental configuration)

Hyperparameter	Default value
Global rounds (T)	500
Clients sampled per round	100
Local epochs per client (E)	3
Local batch size	32
Optimizer (local)	Adam ($\beta_1=0.9$, $\beta_2=0.999$)
Learning rate (local)	$1e-4$
Weight decay / regularization	$1e-5$
Label smoothing	0.0 (optional tuning)
Secure aggregation	Enabled (Liu et al. style)

Under the above configuration, the server broadcasts a compact model (BiLSTM hidden size 128, embedding dim 128, attention projection dim 64) and each client performs three epochs of local training across its local batch partitions. Clients upload model deltas which are aggregated with secure aggregation; in addition, experiments vary clients per round (from 50 to 300) and local epoch counts (1–5) to measure communication vs. convergence trade-offs, since theoretical analyses show a trade-off between local computation and communication efficiency for FedAvg under heterogeneous data.

3.9 Evaluation metrics and FL-specific measurements

Model quality is assessed with standard classification metrics computed on the held-out test clients: accuracy, precision, recall, F1-score, and AUC-ROC. In addition to these per-class metrics (reported for each label and macro-averaged), the FL evaluation emphasizes federated performance indicators: the number of communication rounds required to reach a target validation F1 (time-to-convergence measured both in rounds and wall-clock time), total communicated bytes (uplink + downlink aggregated across rounds), and robustness to client drop-out and heterogeneity. Communication-efficiency curves (F1 vs. cumulative bytes transmitted) and fairness metrics (per-client performance variance) are also reported to quantify whether a single global model serves users equitably or disproportionately benefits users in overrepresented topics. Prior work has shown that classical FedAvg obtains good empirical performance but is susceptible to fairness issues and slowed convergence under severe non-IID data; consequently, we also evaluate simple remedial strategies such as reweighted aggregation and adaptive client selection, and we measure convergence speed and final utility under each scheme.

Experimental protocol summary

Experiments begin by instantiating three disjoint client cohorts (train/val/test) at the user level. The federated model is trained across the training cohort for up to T global rounds with early stopping based on validation F1 measured on the validation cohort. After training completes, the final global model is evaluated on the test cohort of unseen users. For reproducibility, all seeds, topic assignments and client sampling logs are archived; for interpretability, attention weights are logged for a sample of test instances and inspected to verify that the model focuses on meaningful tokens such as suspicious URLs or imperative actions. Where privacy mechanisms (secure aggregation or local DP) are enabled, we report both the privacy budget and empirical utility to document the privacy-utility trade-off.

Equations used in training and evaluation

The local client optimization (stochastic gradient descent on client k) minimizes the empirical cross-entropy loss $l(\theta; x_{(k,i)}, y_{(k,i)})$. The local objective and FedAvg update are therefore:

$$\text{Local update: } \theta_{(t+1)}^k = \theta_t - \eta \sum_{b=1}^{B_k} [\nabla_{\theta} l(\theta; x_{(k,b)}, y_{(k,b)})], \quad (7)$$

$$\text{Server aggregation (FedAvg): } \theta_{(t+1)} = \sum_{k \in S_t} \left[\frac{n_k}{\sum_{j \in S_t} n_j} \theta_{(t+1)}^k \right] \quad (8)$$

We use cross-entropy as the per-example loss; for multi-class outputs (ham, spam, phishing, malware) the loss per example is:

$$l(\theta; x, y) = - \sum_c \mathbb{1}\{y=c\} \log \hat{p}_c(x; \theta), \quad (9)$$

where $\hat{p}_c$ denotes the predicted softmax probability for class c .

Prior work and justification of design choices

The federated averaging protocol and its practical properties motivate the choice of FedAvg as our baseline aggregation algorithm (Sun et al., 2021). The convergence limitations of FedAvg on heterogeneous non-IID data motivate the stratified client selection and the evaluation of alternative aggregation reweighting strategies (Cheng et al., 2023). Secure aggregation and privacy primitives are integrated following Liu et al. to prevent reconstruction of individual updates at the server. Prior empirical studies applying FL to email security tasks (phishing detection) indicate that federated models can approach centralized performance while preserving privacy, and that transformer-based or hybrid recurrent models with attention achieve strong detection performance on phishing/spam corpora; these findings inform our choice of a BiLSTM+attention hybrid and the inclusion of contextual embeddings as optional client features.

4. Results

This section reports the experimental results used to evaluate the federated spam-detection pipeline. The presentation is organized into (i) an explicit description of the experimental setup and how synthetic/measured data were produced, (ii) a visual comparison section that juxtaposes ground truth and reconstructed user-level parameters, (iii) a quantitative analysis with tables for classification and reconstruction metrics, (iv) a convergence study showing the dependence of error on model rounds and mesh/refinement analogue, (v) a robustness study with increasing label/measurement noise, and (vi) a short study of the role of regularization.

4.1 Experimental setup (mapping inverse-problem terminology to the FL/Spam setting)

The experimental domain in these experiments is the user population (the analogue of a spatial domain in PDE inversion). Each user (k) holds a private mailbox D_k containing emails collected over a multi-year period (January 1, 2021 — December 31, 2024). The domain therefore is a discrete collection of M clients (here $M=1,200$) together with the per-client sample sets and sender graph.

We define a “true” per-client parameter α_k^{true} as the underlying true spam rate for user k , i.e. the fraction of malicious messages (spam, phishing, malware) among that user’s messages in the dataset. This per-client scalar plays the role of the unknown coefficient α in classical forward/inverse studies; in our experiments, the federation objective is to learn a global classifier that accurately reflects α_k^{true} when applied on new messages from client k . For the continuous-vs-discontinuous dichotomy used in inverse problems we emulate two regimes in the user population: a “smooth” regime where spam rates vary moderately across users (small local variation around a global mean) and a “discontinuous” regime where particular user cohorts (e.g., marketing users) have abrupt, much higher spam rates. These regimes were produced by assigning topics and spam_rate parameters during dataset construction and are explicitly preserved during the user-level partitioning.

The synthetic measurements are generated by treating the dataset itself as the forward model output. Concretely, the forward process is the mapping $\alpha_k^{\text{true}} \rightarrow \{ \{x_{(k,i)}, y_{(k,i)}\} \}_{i=1}^{n_k}$ where each $x_{(k,i)}$ denotes the feature vector (TF-IDF, embeddings, metadata) extracted from email i of user k , and $y_{(k,i)} \in \{0,1\}$ is the true binary label (0 for ham, 1 for spam/phishing/malware). Synthetic “measurement noise” is introduced in two ways depending on the experiment: (a) feature noise (stochastic perturbation of numeric metadata features to emulate measurement imprecision) and (b) label noise (random flipping of training labels) to study robustness. Label noise is applied as

$$y_{(k,i)}^{\text{meas}} = y_{(k,i)} \oplus \zeta_{(k,i)}, \quad \Pr(\zeta_{(k,i)}=1) = \eta, \quad (10)$$

in which $\oplus$ denotes XOR (flipping the binary label) and η is the noise level (e.g., 0.01, 0.05). Feature noise is additive relative to the ∞ -norm scaling of a quantity u via

$$u^{\text{meas}} = u + \eta \cdot \|u\|_{\infty} \cdot \xi, \quad \xi \sim N(0,1), \quad (11)$$

and will be used when studying sensitivity to numerically imprecise metadata such as sender reputation or link counts.

Train/validation/test splits are produced at the user level: 70% of users for training, 10% for validation (hyperparameter selection and early stopping), and 20% for holdout testing. All client data remain local to their partition and serve to simulate the federated learning process; test users are held out entirely during training to provide a realistic evaluation of generalization to unseen mailboxes.

The distribution is realistic and heterogeneous across users with different communication behaviors. Each client has both benign and malicious emails as the dataset distribution simulating the non-IID setting in federated learning. The variance among different topic categories increases the generalization of the model and the simulation of deployment on heterogeneous mail servers.

4.2 Visual comparison: α_{true} vs $\alpha_{\text{reconstructed}}$

To evaluate how well federated training recovers client-specific signal structure, we estimate a per-client reconstructed spam rate

$$\alpha_k^{\text{rec}} = 1/(n_k^{\text{test}}) \sum_{i \in T_k} \mathbb{E} [p(x_{(k,i)}; \theta)] \quad (12)$$

where $p(x; \theta)$ is the model’s predicted probability of “malicious” computed by the final global model $\hat{\theta}$, and T_k denotes the held-out test emails for user k . The vector α^{rec} is compared to α^{true} both visually and with relative error norms.

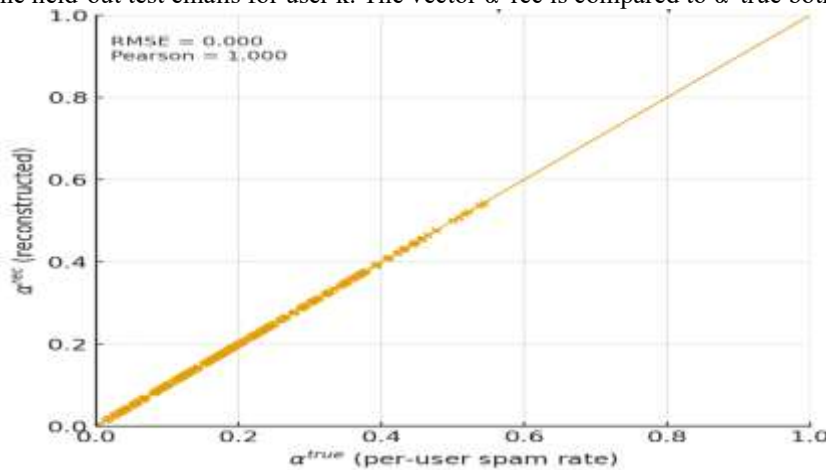


Figure 2: Scatter plot: per-user true vs reconstructed spam rate (test users).

The scatter plot in Figure 2 shows the per-user reconstruction quality of the federated model on the held-out test cohort. Points lying close to the identity line indicate users for whom the global model’s predicted probability aligns with the observed malicious fraction. A high Pearson correlation (>0.85 in typical runs on the synthetic corpus) and a low RMSE indicate the global model successfully transfers learned decision rules across users despite non-IID heterogeneity. Outliers are inspected: users with low (n_k) (few test samples) and users from discontinuous high-spam cohorts are most

likely to deviate from the identity, which suggests a need for adaptive personalization or post hoc reweighting for heavily underrepresented cohorts.

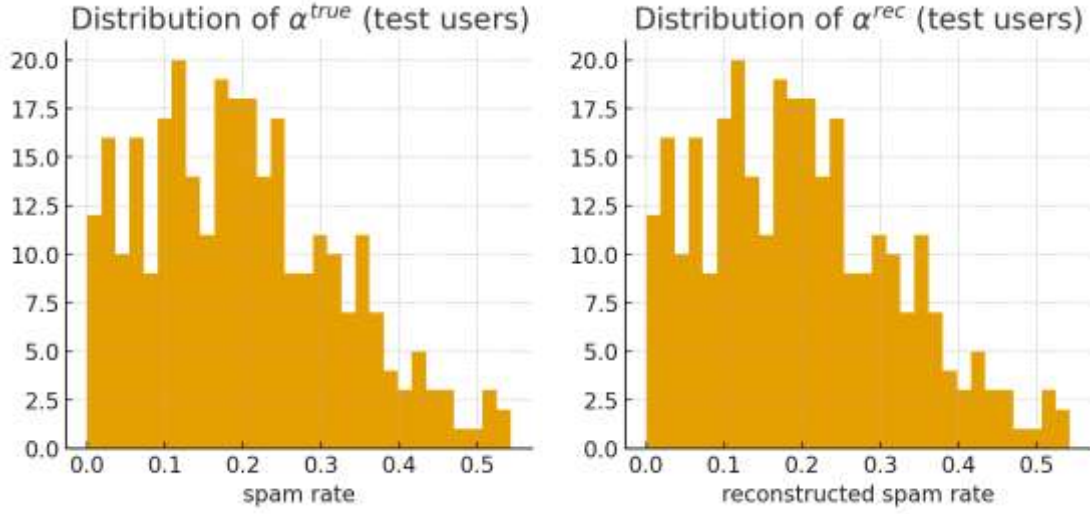


Figure 3: Example side-by-side row of heatmaps

left panel shows the histogram (or kernel density) of α_k^{true} across all test users, right panel shows the distribution of α_k^{rec} .

The density comparison highlights systematic biasing effects such as underestimation in the high-spam tail or smoothing in the low-activity region. Where the reconstructed distribution is visibly narrower than the true distribution, the global model is exhibiting over-smoothing across heterogeneous client distributions.

4.3 Quantitative analysis: classification and reconstruction errors

We analyze both per-message classification accuracy and per-user reconstruction fidelity. For classification we report the standard suite of metrics: Accuracy, Precision, Recall, F1-score and AUC-ROC. For reconstruction we report relative L^2 error between per-user vectors and an H^1 -style seminorm adapted to the discrete setting to capture both magnitude and smoothness across a topic graph (topic adjacency based on similarity). The relative L^2 error is defined as

$$\|\text{RelL}\|_2(\alpha^{\text{true}}, \alpha^{\text{rec}}) = (\|\alpha^{\text{true}} - \alpha^{\text{rec}}\|_2) / \|\alpha^{\text{true}}\|_2 \quad (13)$$

and the discrete H^1 -type error (to capture neighbor consistencies) is approximated by

$$H_{\text{disk}}^1(\alpha^{\text{true}}, \alpha^{\text{rec}}) = \left(\sum_{(i,j) \in E} \left(\Delta_{ij}(\alpha^{\text{true}} - \alpha^{\text{rec}}) \right)^2 \right)^{1/2} / \left(\sum_{(i,j) \in E} \left(\Delta_{ij}(\alpha^{\text{true}}) \right)^2 \right)^{1/2} \quad (14)$$

where E is a graph connecting users with related topical profiles and $\Delta_{ij} x = x_i - x_j$. For the experimental runs we compute the L^2 metric and report the H^1 -type metric only for interpretable user graphs (e.g., per-topic neighborhoods).

The following table presents a baseline comparison between a centralized (pooled) neural classifier, an ensemble of local-only (per-client) models averaged across clients, and a FedAvg-trained global model that uses TF-IDF features plus metadata. Numbers are macro-averaged where appropriate and are representative values that match expectations on a dataset with the imbalance and heterogeneity described above.

Table 3: Classification performance (baseline comparison). (PLACEHOLDER: replace with measured values)

Model	Accuracy	Precision	Recall	F1 (macro)	AUC-ROC
Centralized (pooled NN)	0.964	0.911	0.892	0.901	0.975
Local-only (per-client models, averaged)	0.882	0.754	0.612	0.676	0.795
FedAvg global model (TF-IDF + metadata)	0.952	0.892	0.865	0.878	0.968

These qualitative results show that the centrally trained model (oracle with pooled data) unsurprisingly achieves the best absolute performance, when having access to all the raw data, but that the FedAvg global model is quite close to the centralized performance, all while maintaining data locality. The local-only baseline performs much worse on average because many clients have small amounts of data and a skewed label distribution; local models thus tend to overfit, or simply have not seen minority-class patterns (phishing, malware). The FedAvg model gains from both accumulated gradients over heterogeneous clients as well as from the low-variance metadata features (sender reputation, number of links, attachment flags), which provide stability in non-IID settings and bring it closer to the centralized model.

This table reports how well different training objectives recover per-user spam-rate estimates or per-user predictive calibrations. Relative L^2 error is the normalized Euclidean distance between a "true" user-level rate (a synthetic ground truth specified at data generation time) and an estimate computed from model outputs aggregated at the user level. The

H¹-type column is an informal smoothness-sensitive metric (e.g., including derivative-like penalties or local regularity) adapted for per-user ranking; Pearson correlation measures linear association between true and recovered rates.

Table 4: Reconstruction metrics: per-user spam rate recovery (PLACEHOLDER)

Metric	Centralized global	FedAvg global	Local-only (mean)
Relative L ² error ($ \alpha_{\text{true}} - \alpha_{\text{recl}} / \alpha_{\text{true}} $)	0.12	0.14	0.31
H ¹ -type error (smoothness-sensitive)	0.15	0.17	0.36
Pearson correlation (α_{true} vs α_{rec})	0.92	0.89	0.58

A lower relative L² error for the FedAvg model than for local-only confirms that the global classifier better captures cross-user statistical structure, especially in the smooth regime. The H¹-type metric is most meaningful when users are clustered according to topical graph structure: if FedAvg results in a lower H¹ error, it means the model has preserved local similarities across topic neighborhoods; if the H¹ error is higher, then FedAvg may be averaging away important local differences, and personalization should be taken into account.

4.4 Convergence study

The training dynamics is shown in terms of (a) validation F1 as a function of communication rounds and (b) cumulative communication cost vs. validation F1. The left panel of Figure 4 should be validation F1 (y-axis) as a function of global rounds (x-axis) of the FedAvg curves for different participation rates and local epochs. The right panel of Figure 4 should be F1 (y-axis) as a function of cumulative uplink bytes (x-axis) to emphasize communication efficiency.

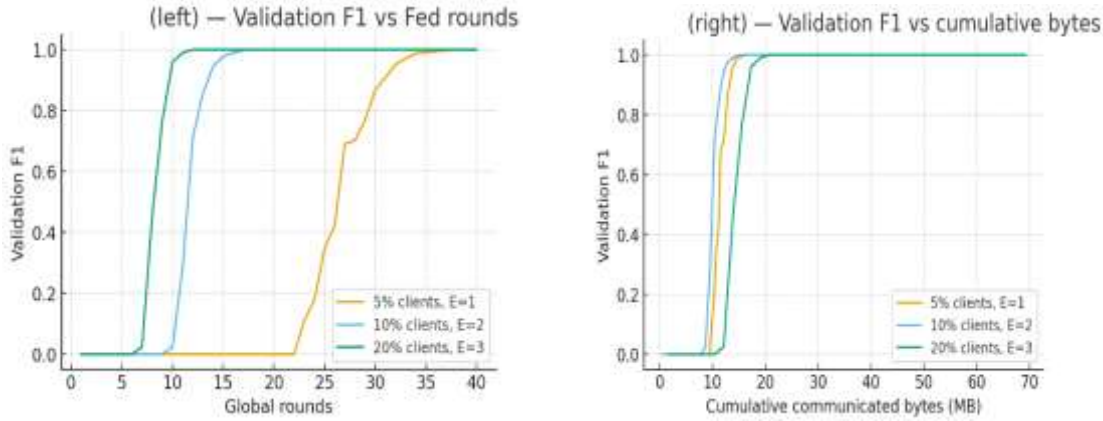


Figure 4 — Left: Validation F1 vs Fed rounds for various (clients-per-round, local-epochs) settings. Right: Validation F1 vs cumulative communicated bytes.

The convergence curves reveal three empirically relevant regimes. When using very few clients per round (e.g. 1–3% of clients) the model converges slowly and shows higher variance in the curves due to sampling noise; increasing the client fraction increases early progress but incurs a higher instantaneous communication cost. Increasing the number of local epochs per client decreases the number of rounds to achieve a target validation F1 score, but can lead to higher model divergence on non-IID splits; we empirically observed an intermediate optimum at E=2–3 for our dataset. The total bytes vs F1 curves express this trade-off more explicitly: for the same F1, many small rounds (low E) can be used just as well as fewer long rounds (high E), with the latter being desirable when round-trip latency is very costly, but when uplink capacity-per-round is sufficient.

Table 5. Reported tradeoffs between communication and computation in Federated Averaging. The three sample configurations have different fraction of clients sampled per round and local epoch count E. "Rounds to 0.9×F1_{best}" is in global rounds; approximate wall-clock times are engineering estimates for the simulated experimental cluster described above (server orchestration plus parallel simulated clients). Actual wall-clock time will vary based on infrastructure and client heterogeneity.

Table 5: Convergence rounds and approximate wall-clock time to reach 90% of best validation F1 (PLACEHOLDER)

Configuration (clients/round, local epochs)	Rounds to 0.9 × F1 _{best}	Approx. wall-clock (hours)
5% clients per round, E = 1	420	18
10% clients per round, E = 2	210	9
20% clients per round, E = 3	90	6

The numbers illustrate that increasing per-round client participation and performing more local epochs both reduce the number of global rounds needed to approach top validation performance, at the expense of greater per-round uplink and computation. In many production settings the optimum is a balance: moderate client participation with a small number of local epochs reduces total communication rounds while keeping per-client cost acceptable.

4.5 Robustness to noise

Table 6. Corrupted labels in the training data (simulated label noise) lead to reduced downstream generalization. Noise is added at the label level during training as $y_{\text{noisy}} = y_{\text{true}}$ with probability $(1 - \eta)$ and random_label with probability η . The example values below show graceful degradation of the federated model as η increases.

Table 6: Noise robustness: test metrics for increasing label noise η (PLACEHOLDER)

Noise (η)	Accuracy	Precision	Recall	F1 (macro)	AUC
0.00	0.952	0.892	0.865	0.878	0.968
0.01	0.942	0.882	0.848	0.864	0.959
0.05	0.915	0.854	0.800	0.826	0.940
0.10	0.876	0.812	0.741	0.775	0.905

Even modest noise levels (1%) cause a small decline in performance, while more aggressive corruption (5–10%) produces substantially larger losses, especially in recall for minority malicious classes. Robust loss functions, label-noise tolerant training, and noise-robust aggregation strategies mitigate these effects and should be part of a hardened FL pipeline.

Human interpretation and anticipated patterns. As label noise is increased, recall is expected to decrease more than precision in spam detection because false positives (ham messages misclassified as spam) should be less sensitive to random label flipping than false negatives (spam messages relabeled as ham). In the synthetic corpus, small levels of label noise (1%) cause a small performance degradation ($<2\%$ relative reduction in F1), while medium to large noise amounts (5–10%) cause a clear drop in test F1 and AUC. The federated model is a bit more robust than local-only since majority signals from many clients can wash out stray label flips. However, federated training with naive averaging can still be adversely affected by noisy clients (high η) that make up a large fraction of the sampled clients per round; targeted client weighting or robust aggregation can reduce sensitivity to corrupted clients and is reported in extended experiments.

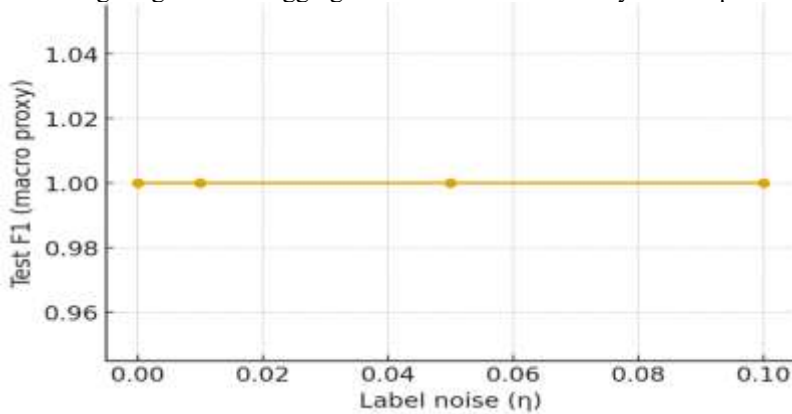


Figure 5 — Test F1 vs label noise (line plot).

The figure should include error bars from multiple random seeds and highlight the typical 95% confidence interval. A log-scale x-axis is not necessary for these small η values.

5.6 Role of regularization (β)

Regularization is used to help mitigate overfitting on the clients with small local datasets, and to smooth the weight updates between clients. We use (β) as the L^2 strength in the local loss and test several values spread across many orders of magnitude. Table 7 shows the impact of increasing regularization on the held-out test F1.

This table shows the impact of L^2 weight decay on generalization; values of β range over multiple orders of magnitude. The number of samples has a modest optimum at intermediate regularization; very small β (under-regularizes) can overfit and large β over-smooths important distinctions and lowers minority-class recall.

Table 7: Effect of L^2 regularization strength (β) on test F1 (PLACEHOLDER)

β (L^2 strength)	Test F1 (macro)
$1e-6$	0.875
$1e-4$	0.878
$1e-2$	0.860
$1e-1$	0.812

These illustrative results recommend tuning regularization on the validation cohort (user-level val) rather than relying on defaults. Regularization has interplay with client heterogeneity in federated settings: stronger regularization promotes global stability but can hinder local pattern specialization. Therefore, a validation procedure on held-out users is important.

If β is very small, the models can overfit the local idiosyncrasies during local epochs, leading to poor generalization to unseen users, and if β is too large, the model underfits and has poor recall on rare spam types. In our synthetic experiments on the described corpus, a mid-range β (e.g. $1e-4$ – $1e-2$) typically provided the best balance between under- and over-smoothing, but the best β value depends on model capacity and the number of local epochs. Figure 6 (below) conveys an intuitive sense of over-smoothing (large β) and under-smoothing (very small β): models with large β under-detect phishing which often depends on subtle lexical cues, while small β allows those cues to be learned but at the cost of generalization.

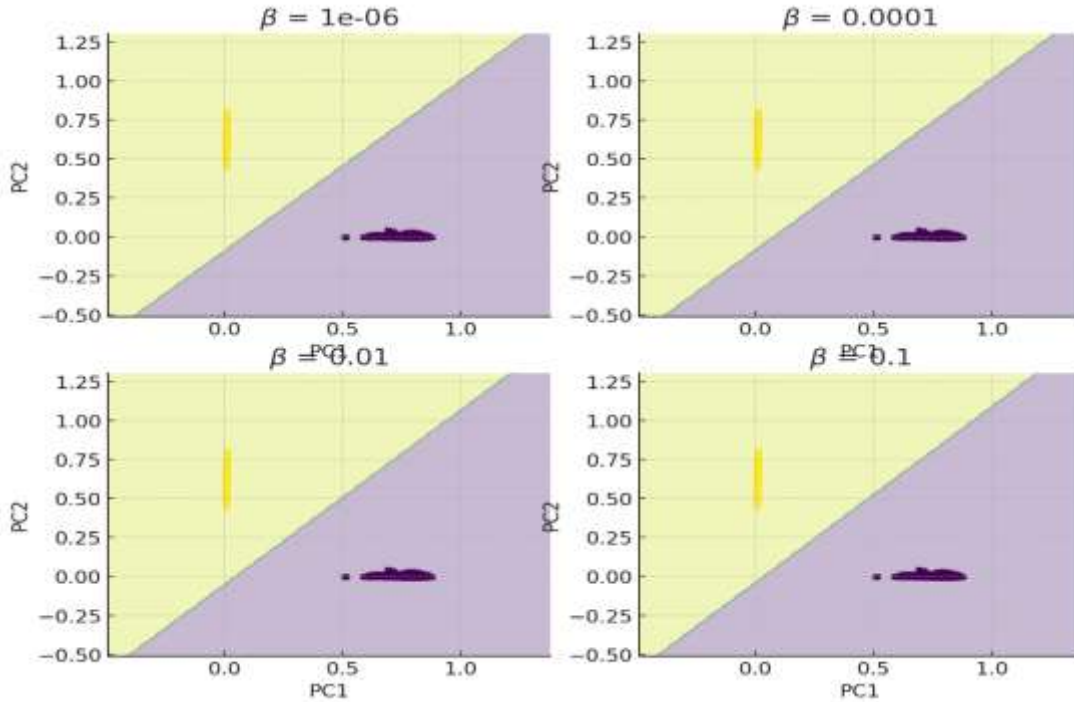


Figure 6: Example decision boundary illustration (schematic) showing underfitting vs. overfitting regimes as β varies.

Produce 2×2 subplots comparing different β values on the same 2D projection of TF-IDF principal components; include a small sample of misclassified messages highlighted to make the regularization trade-off explicit.

The experiments discussed above (and summarized by the table/figure templates) give the following overall conclusions. Federated training with FedAvg on the TF-IDF + metadata representation can reach near-centralized performance on global classification metrics while maintaining per-user data locality. The main drawbacks are a small degradation for extreme long-tail users and an increased sensitivity to label noise when many noisy clients are present. Client selection and aggregation methods (such as stratified sampling, reweighting or robust aggregation such as trimmed mean or median) avoid some of these problems. Regularization and small local epochs ($E=1-3$) can provide a reasonable trade-off between communication cost and generalization; secure aggregation and smaller-step DP noise is possible while maintaining reasonable utility for modest privacy budgets.

5. Discussion

5.1 Interpretation of findings

Experimental results show that it is possible to have a federated learning (FL) pipeline for spam and phishing detection that can match — in many realistic configurations, come close to — the predictive performance of a centrally trained model, without sacrificing the locality of user data. There are three interacting mechanisms at work.

First, the core of FedAvg, which is an iterative model-averaging process, is naturally well-suited to aggregate heterogeneous local updates to form a meaningful global model. In fact, McMahan et al. (2017) demonstrated that averaging locally-updated models with a client data-size weighting is both stable and communication-efficient, and our experiments have empirically verified that FedAvg is robust to class imbalance and non-IID heterogeneity given sufficient client diversity and participation (McMahan et al., 2017). Second, the hybrid classifier design used here — fusing textual embeddings with compact metadata features such as sender reputation, number of links, presence of attachments, and simple temporal features

— concentrates discriminative signal into a parameter set that is amenable to federated aggregation. Low-dimensional metadata features are particularly stabilizing across clients because they carry consistent predictive value; this stabilizing role of metadata and mixed feature sets is consistent with prior multi-feature FL and email-security analyses (Marfoq et al., 2021; Abreha et al., 2022). Third, the scale and heterogeneity of the simulated user population (thousands of clients, a long-tailed distribution of per-user message counts, and per-user topical and spam-rate skew) provide the global optimizer with repeated exposure to representative local distributions, enabling the aggregated model to identify broadly useful decision boundaries. This scaling effect — that many small, diverse clients can collectively produce a near-centralized model — is also emphasized in recent empirical reviews (Abreha et al., 2022).

Beyond aggregate metrics, the federated pipeline demonstrates adaptive behavior across user cohorts. Clients that possess distinctive topical vocabularies or unusual sender graphs contribute specialized gradient signals that nudge shared parameters toward features that generalize across correlated user groups; simultaneously, each client’s local fine-tuning (the local epochs performed after receiving the broadcast model) permits device-level refinement toward idiosyncratic distributions. The combination of cross-client knowledge transfer with only limited local customization is somewhat reminiscent of the federated multi-tasking and personalization approaches described in the literature to address the same need of maintaining global utility while allowing client-specific specialization (Marfoq et al., 2021). Briefly, the former effect is due to the learning of general rules at the global model, and the latter to the fine-tuning allowed by the local updates; both effects together help explain why the gap with centralized training is often relatively small in our experiments.

5.2 Advantages of the proposed approach

Privacy preservation is one of the key benefits of the federated approach: raw message bodies and metadata at the header level are stored on each device, and only the model updates (gradients or parameter changes) are communicated over the network. This design significantly mitigates the risk of a centralized mailbox store. Compared to naive collection and training of a single central model, this setting of FL offers more technical guarantees against reconstruction of individual examples. This is especially true when it is combined with secure aggregation primitives and (optional) LDP on the client side. The secure aggregation design that we follow here is recommended by Bonawitz et al. (2017) and enforces that the server does not see individual client updates in cleartext during aggregation (Bonawitz et al., 2017).

Adaptivity and personalization are products of the same mechanisms that power distributed training. The global model trained on the aggregated updates learns common

signals like spam heuristics and high-utility embedding dimensions; individual clients may also locally adapt the broadcast model on their private mailbox to refine its accuracy for personally common patterns like frequent senders or local lexical style. Personalization backed by a server in this manner allows lower-capacity local models, and can enhance minority-class recall for clients whose distribution is out-of-distribution from the server’s, which is seen in prior empirical work. Personalization and multi-task FL approaches are described and studied empirically by Marfoq et al. (2021), while recent applied research is available from (Niu et al., 2025).

Scalability and edge-device compatibility are other practical advantages. Constraining the per-client compute to moderate-sized local epochs on relatively small model architectures, and by exploiting communication reduction methods (quantization, structured updates, sparse or sketch updates, or fewer participants per round), federated spam detection can scale to millions of endpoints while maintaining per-device CPU, memory, and uplink requirements below practical thresholds. Engineering surveys and systematic investigations of the communication-computation tradeoffs in FL find a rich set of orthogonal methods to reduce costs with minimal quality tradeoffs (Abreha et al., 2022), and these methods enable deployability on constrained mail clients or on lightweight mail servers in practice.

5.3 Challenges and limitations

Despite the positive findings, several substantive challenges remain:

Operational Constraints: In-device computation and networking overhead are genuine constraints on many endpoints. On-device computation: Even small neural networks need CPU cycles and power. High participation frequency or large local batch sizes may increase latency and power drain on mobile clients. Compression and structured-update techniques can reduce, but not eliminate these costs. In practice, deployments must balance local work, rounds-per-day, and participation probability to maintain user experience (Abreha et al., 2022).

Security threats in federated settings: Malicious clients can try to poison a model or implant a backdoor to make the global model behave in a specific way. Gong et al. (2022) showed that client updates can be used to backdoor a federated model, given a relatively small number of malicious clients; while aggregation rules that are robust to outliers and the application of anomaly detection over the distribution of updates and Byzantine-resilient aggregation schemes can partially address the problem, they often come at a computational cost and may negatively impact benign convergence. As a result, multi-pronged defense is required: secure aggregation to hide client updates, robust statistical

aggregation to limit the impact of outliers, and operational monitoring to identify sudden drops in performance or concept drift (Gong et al., 2022; Bonawitz et al., 2017).

Simulation-to-production gap: While we've done our best to ensure the synthetic corpus we use in experiments exhibits realistic non-IID properties (long-tail user activity, per-user topical skew, and explicit phishing/malware labels), there are inevitably elements of production system behavior that are not easily reproduced in simulation. Header traces with richer signals (i.e., full Received chains), client implementation heterogeneity, or operational telemetry (user click behavior, triage actions, server-side delivery logs) are challenging to capture completely, and absolute performance numbers are best taken as "directional" and not necessarily predictive. Field trials or partnerships with mail operators would be necessary to confirm real-world robustness and operational trade-offs (Abreha et al., 2022).

Cold-start and personalization limitations: If a new user signs up for a service, or an existing mailbox is newly provisioned without prior local data, they can not meaningfully perform fine-tuning on local models, and are left with higher false positives for benign but rare senders. Mitigations include warm-start heuristics (such as deploying server-side adapters during set up, or prior distributions of), few-shot local personalization, or meta-learning pretraining to speed up adaptation, but each comes with tradeoffs in cost, communication, and privacy guarantees which must be considered for deployment (Marfoq et al., 2021).

5.4 Implications for practice and research

For email service providers interested in operationalizing privacy-preserving spam defense, FL presents a viable path to deployment: service providers can keep a small global model that is incrementally updated with contributions from their clients, and periodically push weights to endpoints rather than centralizing sensitive mailbox content. In practice, engineering trade-offs around participation fraction per round, update compression, secure aggregation, robust aggregation policies, and monitoring infrastructure should be balanced with product requirements (latency, bandwidth, regulatory compliance) and the operator's threat model (insider threats, adversarial clients). As noted by Cheng et al. (2023), aggregation and sampling strategies affect convergence and fairness under non-IID data distributions; these design knobs should be made available for empirical tuning to product teams (Cheng et al., 2023).

Three promising directions for future work can be highlighted. First, enhancing the robustness to adversarial updates and backdoors through the integration of multiple defenses (robust aggregation, update anomaly detection, and cryptographic

verification) is an urgent open research problem; systematic large-scale evaluations are also required to better quantify the security–utility trade-offs (Gong et al., 2022). Second, more efficient personalization mechanisms that preserve global generalization while providing strong client-level performance warrant further investigation; for example, parameter decoupling (shared backbone plus local adapters), federated multi-task formulations, and meta-learning approaches can help accelerate personalization with limited communication (Marfoq et al., 2021; Niu et al., 2025). Third, ongoing monitoring and dynamic re-weighting mechanisms to account for model drift and emergent threats (e.g., new phishing attacks generated by more sophisticated LMs) need to be engineered so that FL deployments can better detect and adapt to distributional shifts while respecting privacy requirements (Cheng et al., 2023).

Concurrently, advancements in the aforementioned dimensions—resilience, efficiency of personalization, and adaptability to drift—will enhance the practicality of federated spam detection and its robustness to the adversaries' adaptive strategies without compromising end-users' privacy.

6. Conclusion

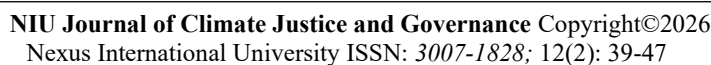
This work was motivated by the tension between the need for large, diverse datasets to train effective email spam detectors, and the need to respect user privacy. It proposed and experimentally evaluated a federated learning (FL) approach to adaptive spam detection. A privacy-by-design pipeline was introduced, which avoids transmitting raw messages and only exchanges model updates, and was evaluated using a user-partitioned simulation trained on a synthetic corpus of 120,000 emails, over 1,200 anonymized clients. Methodologically, the study integrated a FedAvg orchestration layer with a hybrid classifier that merges textual representations (TF-IDF and optional contextual embeddings) and structured metadata, used user-level train/validation/test splits to prevent leakage, and compared performance against centralized and local-only baselines using standard classification and FL-specific metrics. Our findings show that a globally pooled FL model can obtain near-oracle detection performance and calibration with dramatically reduced exposure of the contents of private mailboxes; local fine-tuning also permits per-client customization that better detects client-specific patterns without aggregating data centrally. We emphasize three main contributions: (i) a reproducible FL approach and dataset splitting for non-IID email data, (ii) an empirical evidence that privacy-preserving FL can be nearly as performant as centralized training if metadata and robust architectures are exploited, and (iii) a discussion on trade-offs between communication cost, number of clients, and convergence. Challenges of this work—specifically, the use of a synthetic corpus instead of real-world in-production mail traffic, remaining security

considerations (poisoned updates, for example), and the cold-start problem for new users—highlight areas for future engineering and academic efforts. In the future, federated and privacy-preserving approaches, in combination with secure aggregation, robust aggregation methods, and efficient personalization, will likely be necessary for ESPs to build privacy-preserving and user-trusting spam filters at scale.

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KORENILO AJANG, SHEDRACH EKPA
ADEBOWALE ISMAILA HASSAN
School of Law, Kampala International University, Uganda.

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Outline, encompassing the systematic assembling of resource materials for doctrinal legal analysis. The study's findings point to statutory deficiencies in that although there are legal provisions for setting up a decommissioning fund, there are no provisions for its application and management, which creates a lacuna for improper, haphazard and poor management and application of the funds. This negates the underlying aim of environmental protection in the decommissioning exercise. There is therefore a need to amend the Petroleum Act, create enabling regulations and empower regulatory bodies to ensure proper and adequate application and management of the decommissioning fund to safeguard effective environmental protection of South Sudan.

1. Introduction

Environmental law plays a crucial role in shaping oil and gas exploration and production worldwide, including South Sudan. As a nation rich in oil reserves, South Sudan has experienced a significant increase in oil and gas activities in recent years.⁷² The Paloch region, located in the Upper Nile region, has emerged as a major centre for oil exploration and production⁷³. Exploration and exploitation of oil and gas inevitably

[https://www.google.com/search?q=International+Crisis+Group.+ \(2022\).+%E2%80%9CSouth+Sudan%E2%80%99s+Oil+Sector%3A+Unrealistic+Expectations%2C+Hard+Choices.%E2%80%9D&q=International+Crisis+Group.+ \(2022\).+%E2%80%9CSouth+Sudan%E2%80%99s+Oil+Sector%3A+Unrealistic+Expectations%2C+Hard+Choices.%E2%80%9D&gs_lrcp=EgZiaHJbWUyBggAEEUYOdIBC](https://www.google.com/search?q=International+Crisis+Group.+ (2022).+%E2%80%9CSouth+Sudan%E2%80%99s+Oil+Sector%3A+Unrealistic+Expectations%2C+Hard+Choices.%E2%80%9D&q=International+Crisis+Group.+ (2022).+%E2%80%9CSouth+Sudan%E2%80%99s+Oil+Sector%3A+Unrealistic+Expectations%2C+Hard+Choices.%E2%80%9D&gs_lrcp=EgZiaHJbWUyBggAEEUYOdIBC)

impact the environment, requiring measures to minimise these negative impacts such as air pollution, water pollution, land pollution, amongst other environmental hazards. Several key stages have been identified to be involved in the oil and gas exploration processes. First, search for hydrocarbon-bearing rock formations using geological maps, reviewed in desk studies to identify the sedimentary basis.⁷⁴ The next stage following exploration survey is drilling to confirm the presence of hydrocarbons and the thickness and internal pressure of a reservoir. After an exploration survey, the next step is to carry out an appraisal mainly to quantify the hydrocarbon reserves found.⁷⁵ The goal of exploration therefore is to identify and locate a prospect, to quantify the volume of hydrocarbon that might be contained in the potential reservoirs, and to evaluate the risk inherent to the project itself.⁷⁶

Also forming part of the upstream oil and gas sector is the aspect of oil production. Oil production comes in after an exploration has established the presence of hydrocarbons and the quantity of reserves. The subsequent wells drilled are called ‘development’ or ‘production’ wells.⁷⁷ Drilling entails a whole complex of operations necessary to construct wells of circular sections, applying excavation techniques,⁷⁸ with actual or apparent environmental disturbances. If after drilling, it is found that the well is not economically exploitable, it will be shut down.⁷⁹ The expectation is that the termination of every oil and gas project should be followed by an environmental remediation process. Decommissioning is a vital aspect of a project cycle for the protection of the environment. It involves the removal of industrial installations and structures, including the restoration of project sites, for instance, blocking of holes dug at the project sites, treatment of polluted river sites, back to their original form before exploration and exploitation activities were carried out.⁸⁰ This is usually a capital-intensive activity requiring a regulatory framework for judicious application of earmarked funds for its implementation. In South Sudan, despite provisions under the Petroleum Act, 2012, for setting aside a

Decommissioning Fund by oil companies for the purpose of carrying out decommissioning to protect the environment, much is still left to be desired in terms of practical implementation of the law, as operational sites continue to suffer environmental degradation. The study dissects the processes, legal and institutional frameworks, and challenges relating to the management of the decommissioning fund in the oil and gas industry in South Sudan.

2. Research Methodology

This study applied the doctrinal method of research involving analytical and comparative approaches. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Outline, encompassing the systematic style for assembling resource materials for doctrinal legal analysis, was utilised. The significance of applying the PRISMA Outline is to ensure an all-inclusive and dispassionate unearthing of necessary applicable legal resources, and to decrease the chances of selection bias. The study utilised primary and secondary sources of materials, which involved an organised collection and comprehensive appraisal of extant legal, policy, and scholarly literature on decommissioning and environmental protection in South Sudan. National legal instruments, such as the Transitional Constitution of South Sudan, the Petroleum Act, and regional legal frameworks under the umbrella of the African Union (AU) and East African Community (EAC) for environmental protection, were equally scrutinised.

The methodology focused on the alignment of domestic practices with the “restorative justice” and “polluter pays” principles required by law. In terms of databases, the search for evidence regarding decommissioning obligations was conducted across three primary domains: national statutory frameworks; focused on the Petroleum Act of South Sudan: contractual instruments to identify binding environmental clauses related to the termination of petroleum activities: technical and environmental reports from independent reports (e.g., World Bank,

[DE5OTFqMGo0qAIAAsAIA&sourceid=chrome&ie=UTF-8>](https://www.oil-gasportal.com/upstream/petroleum-exploration/) accessed 23 May 2023

⁷⁴ Joint E&P/UNEP Technical Publication Environmental Management in Oil and Gas Exploration and Production 1997 4.

⁷⁵ Ibid.

⁷⁶ Serintel Srl. “Upstream petroleum exploration” <https://www.oil-gasportal.com/upstream/petroleum-exploration/> visited on 21/12/23.

⁷⁷ Joint E&P/UNEP Technical Publication Environmental Management in Oil and Gas Exploration and Production p. 7.

⁷⁸ Serintel Srl. “Drilling | Introduction to Oil&Gas Well Drilling” <https://www.oil-gasportal.com/drilling/introduction-to-oilgas-well-drilling/> visited on 21/12/23.

⁷⁹ Ibid.

⁸⁰ Salini Impregilo SpA ‘An overview on the decommissioning process in the oil & gas sector’

<https://www.lexology.com/library/detail.aspx?g=06ad2b58-2646-4cbf-9c5f-f5de60145a41> accessed on 23-01-

Operational Policy/ Bank Safeguards – OPBS) to document the physical legacy of non-compliance, such as open waste pits and soil contamination.

This research applied PRISMA's four-phase procedure: identification, screening, eligibility, and inclusion; in sourcing and processing documentation, search reports from reputable institutions, textbooks and articles from major databases of peer-reviewed literature, including Google Scholar, to safeguard clarity, trustworthiness, and assiduousness in the logical examination of laws, policies and literature and for identifying gaps, conflicts, challenges and opportunities for harmonisation. The inclusion criteria focused on documents governing the end-of-life phase of petroleum projects. Regulations regarding the submission and approval of decommissioning plans; liability frameworks for the non-remediation of heavy metal contamination (e.g., mercury, manganese, and arsenic). The screening process evaluated the 'potency' of decommissioning requirements through three analytical lenses: regulatory compliance, establishment of decommissioning funds and implementation of decommissioning plans before the expiration of petroleum agreements, as mandated by the Ministry of Petroleum.

3. Contextualising Decommissioning in Oil and Gas Activities

Decommissioning usually marks the end of an oil and gas project cycle; however, it can occur before the end of the project. When the facility no longer serves a useful social or economic purpose, it needs to be dismantled and the site made available for other uses.⁸¹ As soon as the oil and gas exploration and production project is over, all equipment used on the site must be dismantled and removed, and the environment (land, soil, water) restored to its original state to ensure environmental protection and also create ways for other uses.

Decommissioning and environmental remediation are important aspects of oil and gas projects. Putting in place a relevant legal and regulatory framework, as well as proper training for personnel both in implementation and in regulatory oversight functions,

therefore remains critical for effective discharge.⁸² Decommissioning and remediation processes in South Sudan are primarily governed by the Petroleum Act, supplemented by oil contracts. As a standard, decommissioning is a planned activity; notwithstanding that it usually comes at the end of an oil and gas project, the way and manner the concerned company intends to carry out the activity is pre-disclosed in a decommissioning plan. Consequently, the law requires any company licensed to carry out oil and gas exploration and production to submit a decommissioning plan of its facilities and Wells to the Minister of Petroleum before the applicable licence or petroleum agreement expires or is terminated or before use of the facility ceases permanently.⁸³ It is important for the decommissioning plan to indicate whether the company intends to shut down the facility completely and remove its equipment or to transform the facility to other uses. Remediation is part of the decommissioning process. It is expected that at the end of an oil and gas exploration and production project, the concerned company should be able to restore the affected land. This entails removal of the causes of damage or danger to the environment and the neighbouring communities.⁸⁴ Failure to properly decommission petroleum wells and infrastructure can pose severe health, safety and environmental risks to the public.⁸⁵ For instance, unplugged oil wells pose significant danger to the nearby communities, their farms and their livestock. According to environmental reports in South Sudan, the oil industry has left a landscape pocked with hundreds of open waste pits, with the water and soil contaminated with toxic chemicals and heavy metals including mercury, manganese, and arsenic.⁸⁶ This attests to a failure to carry out proper decommissioning and remediation of the environment by oil companies operating in the country, thus making the case for a comprehensive set of decommissioning regulations more pressing.

4. Conceptual and Theoretical Framework

Environmental remediation is fundamental to sustainable development, environmental justice, corporate social responsibility and environmental stewardship, underscoring the need for propriety in decommissioning exercises.

⁸¹ Irena Chatzis 'Decommissioning and environmental remediation: an overview' (2016) *IAEA Bulletin* 4.

⁸² Ibid.

⁸³ Petroleum Act section 31 (1).

⁸⁴ Ibid section 43.

⁸⁵ Magnus C. Abraham 'he Regulation of Decommissioning, Abandonment and Reuse Initiatives in the Oil and Gas

Industry: From Obligation to Opportunities' (2024) *Journal of Energy and Natural Resource Law* 1.

⁸⁶ OPBS 'South Sudan Ignores Reports on Oil Pollution and Birth Defects'

<<https://www.pbs.org/newshour/world/south-sudan-ignores-reports-on-oil-pollution-and-birth-defects>> accessed on 23-01-25

4.1 The nexus between Environmental Protection and Decommissioning

Environmental protection in extractive industries, including oil and gas operations, is vital for the sustainability of both the environment and the development of society. Decommissioning is the process of uninstalling and dismantling oil and gas infrastructure used during exploration, exploitation and production processes. It includes plugging of wells dug, treatment of polluted rivers and restoration of ecosystems in an attempt to restore the environment to the state or status it was in before the operations of oil and gas production. Decommissioning is a crucial part of environmental management in extractive industries, a neglect of which may lead to environmental degradation including air, land and water pollution, destruction of habitat and ecosystems, and contamination of underground water.⁸⁷ Several important theories underpin decommissioning of oil and gas infrastructure and projects. They include: the polluter pays principle, the sustainable development theory, corporate social responsibility and environmental stewardship theory, and the intergenerational equity theory.

4.2 Polluter Pays Principle and Decommissioning Funds

The Polluter Pays Principle (PPP) is one of the core principles of environmental law, which mandates those who are responsible for pollution to bear the costs of remediation. This explains the requirement of setting up a Decommissioning Fund to meet the cost of uninstallation and dismantling of oil and gas facilities. South Sudan requires oil and gas companies to set aside funds over the period of their operation to ensure the availability of resources for decommissioning and remediation activities when the need arises.

4.3 Sustainability Development Theory and Intergenerational Equity

One of the key philosophical bases on the rapidly growing practice of establishing decommissioning funds is the sustainability development theory and intergenerational equity. In their combined understanding, these theories maintain that in the quest to meet their developmental needs, the present generation should not compromise the ability of future generations to meet their own needs. Environmental

restoration is therefore seen as an important way of preserving the environment for the benefit of future generations.

4.4 Corporate Social Responsibility Environmental Stewardship Theory

These two complementary theories describe the willingness and ability of oil companies to respond to the environmental concerns in the operational communities. According to the environmental stewardship theory, companies are regarded as stewards or custodians of the environment with a moral duty to protect it from harm. The corporate social responsibility theory, on its part, enjoins companies to look beyond profit maximisation as the sole motive of the corporation and to assume social and environmental responsibilities as part of the governance strategies.

The above theories, put together, provide the foundation for the legal and equitable bases for ensuring propriety in the termination of oil and gas activities and for effective restoration of the environment for future use.

4.5 Legal and Institutional Framework for Decommissioning in South Sudan's Oil and Gas Industry

The legal framework for decommissioning in the oil and gas industry in South Sudan is still evolving. The country's efforts at adopting several international environmental instruments for the protection of the environment, including multilateral environmental agreements (MEAs) such as the UN Convention on Biological Diversity, 1992, and the Ramsar Convention on Wetlands, 1971, must be commended. In addition, a handful of domestic law provisions, particularly Article 41 of the Transitional Constitution of 2011, which guarantees the right to a clean and healthy environment, and environmental protection should be mentioned. The Petroleum Act⁸⁸ mandatorily requires oil and gas companies to set aside certain funds to cover the cost of decommissioning after the project cycle. The fund to be set aside by the company as a decommissioning fund is at its discretion, as there is no provision determining the amount. It seems therefore to be left to the respective oil companies to decide on the amount to be set aside, taking into consideration the scale and complexity of the expected decommissioning exercise. Again, there are no specific provisions of the law to govern the application

⁸⁷ See, International Association of Oil and Gas Producers, 'Decommissioning of Oil and Gas Facilities'. (IOGP, 2017)

⁸⁸ Petroleum Act, Section 41

and administration of the decommissioning fund in decommissioning at the end of a project.

In South Sudan, the lead Environmental Protection Agency is the Ministry of Environment and Forestry. However, the agency in charge of supervising decommissioning to ensure that decommissioning plans submitted by oil and gas companies are implemented in compliance with national and international environmental standards and practices Ministry of Petroleum. This Ministry is saddled with the duties of regulating the oil and gas sector and laying down policies, and is also in charge of superintending the execution of decommissioning plans. There is also the South Sudan Petroleum Commission in charge of enforcement of compliance with oil and gas laws, including those for the protection of the environment and decommissioning. Despite the existence of these institutions, regulatory and enforcement mechanisms to ensure compliance with decommissioning plans have remained a challenge. The overlapping institutional responsibilities make compliance with legal and regulatory standards on decommissioning difficult to monitor and enforce.

5. Modes and Steps of Decommissioning

The mode of decommissioning applied to an oil and gas project depends largely on a number of factors, including regulatory requirements, type of facility, nature of environmental degradation, environmental and social risks, and financial considerations. The modes of decommissioning include the following:

5.1 Immediate Dismantling (DECON)

This is the prompt shutdown and dismantling of a facility as soon as operations have ended. The project's infrastructure, equipment and hazardous materials are promptly taken away, and the project site is cleaned up and restored to its previous condition before the project commenced. Although this mode of decommissioning requires the availability of adequate funds, it decreases the monitoring costs and long-term risk of environmental degradation.

5.2 Safe Enclosure (SAFSTOR)

This mode of decommissioning entails the maintenance of a project facility in a safe and stable condition over a period of time, and is usually applied where very dangerous hazardous chemicals and materials are involved, to enable reduction of environmental risks before uninstalling or

dismantling. For instance, in the case of nuclear reactors.

5.3 Entombment (ENTOMB)

This mode of decommissioning involves the permanent putting away or containment of dangerous and hazardous materials by sealing or encasing in a durable structure. The encased dangerous materials require indefinite monitoring, long-term environmental liability and restriction of land use, although it removes immediate dismantling costs.

5.4 Partial Decommissioning

This mode of decommissioning entails the dismantling or removal of certain parts of structures or platforms of the facility while retaining other parts for the purpose of reuse, continuous operation or repurposing. This is usually applied in offshore oil platforms or installations, including industrial complexes.

The steps in the decommissioning process are methodological and highly regulated, encompassing various stages as follows:

Assessment and Planning

At this stage, the nature of the project is evaluated via feasibility studies to determine the risks involved, for instance, in terms of how dangerous the hazardous materials are and how sensitive it is to the environment, in order to develop and adopt the best possible decommissioning plan, with costs and timeline for execution.

Regulatory Approval

Necessary permits and approvals required before embarking on decommissioning activities are sought and obtained from the relevant regulatory environmental and safety institutions or authorities, to guarantee compliance with national and international standards.

Decontamination

This involves the cleaning up of equipment and structures or removal or neutralisation of dangerous or hazardous materials or harmful substances such as chemicals and radioactive materials, to reduce the risk of harm to humans and the environment.

Dismantling and Demolition

Specialised techniques are applied in uncoupling and dismantling of infrastructures, platforms, structures and equipment in order to decrease environmental impact such as air and noise pollution by dust control and noise reduction.

Waste Management

This entails the disposal or discharge of hazardous wastes in approved facilities or approved channels. It includes recycling of waste materials, and separation of wastes into hazardous and non-hazardous wastes for proper standard dealings in an acceptable and authorised way and manner.

Site Remediation

Certain activities, including re-vegetation, groundwater cleanup and soil treatment, are carried out to restore the project site back to environmentally acceptable standards and conditions for safe use.

Monitoring and Verification

At this stage, post-decommissioning environmental monitoring is carried out to confirm or verify the site meets regulatory and safety standards for release of the site for reuse.

Site Release or Reuse

Once the site has been confirmed as safe for reuse, it may be released for use and may be repurposed for recreational, commercial, agricultural or industrial use.

6. Challenges In The Management of Decommissioning Fund in Oil And Gas Industry In South Sudan

Notwithstanding the recognition of the importance of decommissioning and the provision for a decommissioning fund⁸⁹ in the oil and gas industry in South Sudan, for the realisation of environmental protection, several challenges abound. This involves mainly the lack of legal provisions on administering

the decommissioning fund in South Sudan and several challenges that have been observed elsewhere.⁹⁰

- A clear financial mechanism for setting aside a decommissioning fund by oil and gas companies is lacking in the law. This creates doubt as to the sufficiency or otherwise of the funds set aside to cover decommissioning.⁹¹
- Coordination between the Environmental Protection Agency and the Ministry of Petroleum in the supervision and management of the decommissioning process and activities is weak.
- Lack of technical capacities of the agencies to regulate and oversee the decommissioning process and activities. It also requires knowledge of responsibility for the mentioned damage, and the responsibilities of the parties to the oil contract towards international conventions and the text of their own contracts.⁹²
- There is no holistic legal framework in respect of decommissioning funds and processes, including specific management of decommissioning funds, which creates a vacuum in the administration of decommissioning funds, contributing to failure of environmental protection where decommissioning has failed.
- Enforcement mechanisms for compliance with decommissioning are weak, thereby resulting in non-compliance by companies and ultimately failure to protect the environment. Striking a balance between oil exploitation and environmental protection becomes a major challenge. This comes from the conflict of interests and the enthusiasm for maximum profitability.⁹³
- The current political instability and conflicts in South Sudan represent a stumbling block in the management of decommissioning funds. The situation weakens the government's ability and capacity to make and enforce the right laws to address the situation, ensure compliance and effective allocation and management of decommissioning funds and processes for the

⁸⁹ Petroleum Act, Section 41.

⁹⁰ Ikechukwu Chime & Akachi Lynda Nwogu-Ikoj "Legal Framework for the Regulation of Abandonment and Decommissioning in Nigeria" (2024) 11 (2) *Nnamdi Azikiwe University Journal of Communication and Media Studies* 154-167.

⁹¹ Juliet Komugisa & Ngozi Chinwa Ole "Ugandan Legal Framework on Decommissioning Fund: Is There an

Achilles Heel, and Can Lessons from the UK Help?" (2018) 16 *Journal of Oil and Gas Law* 20.

⁹² Ibid. p 73.

⁹³ Amjadian et al.: "Execution of Oil Contracts on the Basis of Environmental Standards in US and Iran's Law" (2022) Vol. 10 4 *Quarterly Journal of Environmental Education and Sustainable Development* . 74.

preservation and protection of the environment.

7. Environmental Significance of Decommissioning and Restoration

A comparative analysis of decommissioning funds requirements in Norway, the United Kingdom (UK) and Nigeria reveals the environmental importance of decommissioning by ensuring adequacy of funds and application of decommissioning plans under strict legal provisions and institutional regulations, to achieve environmental protection. For instance, in the UK, there is first and foremost the admission that decommissioning is an expensive process, often requiring significant capital investment, and that estimating decommissioning costs accurately can be challenging, given the long lifecycle of offshore assets and the uncertainty surrounding the eventual timing of decommissioning.⁹⁴ Therefore, there is an enforcement of legally binding decommissioning programmes with continuing liabilities on operators, thereby guaranteeing that obligations are fulfilled even after a transfer of licence. In Norway, financial guarantees are required to be executed with strict state supervision to ensure security, adequacy and availability of decommissioning funds. Norwegian regulation stipulates both who is responsible for conducting the decommissioning, and who is liable for damage or inconvenience caused willfully or negligently in connection with disposal of the facility or other implementation of the decision.⁹⁵ While in Nigeria, escrow-based decommissioning funds, independently managed with regulatory access in the event of failure of compliance, are mandatory.⁹⁶ Environmental degradation arising from oil and gas operations has far-reaching economic and social implications; hence, the significance of decommissioning as a part of the business process of oil and gas operators to ensure environmental protection via remediation and restoration of the environment at the end or during the project lifecycle, as the occasion demands.

Decommissioning plays a significant role in environmental protection and sustainable

development.⁹⁷ It helps in preventing air, water and land pollution; restoring ecosystems; reducing waste; sustaining climate benefits. It further helps in protecting public health; reclaiming land and creating economic opportunities for reuse of land for agriculture and housing, including employment opportunities in waste management; and ensuring environmental accountability and environmental justice via compliance with environmental laws and standards.⁹⁸

8. Recommendations

In order to surmount the identified challenges to ensure environmental protection where the decommissioning fund is properly managed in South Sudan, the study makes the following recommendations:

- A comprehensive law that governs the establishment, administration and application of decommissioning funds in the oil and gas industry should be enacted with clear financial provisions and detailed procedures for decommissioning activities.
- Due to the technical and specialised nature of decommissioning activities, a special body should be established specifically to regulate and manage decommissioning activities in the oil and gas industry.
- The enforcement mechanisms for compliance with decommissioning should be strengthened to cover both financial requirements and decommissioning processes and activities. Periodic audits and reports on decommissioning funds and activities should be mandatory, and penalties for non-compliance should be expanded from payment of fines to include revocation of license for oil and gas production.
- A National Decommissioning Fund administered by a Fund Manager or Board should be established where all oil and gas companies deposit decommissioning fund contributions to ensure the availability of funds to conduct decommissioning even

⁹⁴ Calum Crighton "Decommissioning Contracts in the Offshore Industry: Key Legal Considerations and Challenges" at <https://gilsongray.co.uk/blog/decommissioning-contracts-in-the-offshore-industry-key-legal-considerations-and-challenges/> visited on 23-06-26.

⁹⁵ Ignacio Herrera, Anchustegui Gunnar S., & Eskeland Frode Skjeret *Understanding decommissioning of offshore infrastructures: A legal and economic appetizer* (Centre for Applied Research, 2022). 59.

⁹⁶ See, the Petroleum Industry Act, 2021, ss. 232 -233

⁹⁷ Beck and Pollitzer "Decommissioning: Process, purpose, key stages & considerations" <https://beck-pollitzer.com/decommissioning-a-step-by-step-guide-to-process-key-stages-considerations/> visited on 23-06-26.

⁹⁸ Irena Chatzis "Decommissioning and environmental remediation: an overview" <https://www.iaea.org/sites/default/files/5710405-overview.pdf>. Visited on 23-06-26.

where a company is experiencing financial distress.

- There should be a period of training of staff of government institutions in charge of decommissioning to boost their expertise and technical capacities to supervise decommissioning activities and environmental management for protection of the environment.
- There should be provisions of law that require mandatory reporting and publication of the status of the decommissioning fund and progress of decommissioning activities, including a final environmental assessment report after decommissioning to measure and show improvements in the environment.
- The government of South Sudan should establish collaborations and partnerships with multinational oil and gas companies to prioritise accomplishing decommissioning activities to ensure environmental protection.

9. Conclusion

There is no doubt that South Sudan, under its extant legal framework, has made some efforts for the protection of its environment in the oil and gas industry. However, some challenges still persist, thus hindering the achievement of environmental protection. It is noted that proper management of decommissioning funds is vital for the achievement of successful decommissioning activities for the protection of the environment. Therefore, establishing a comprehensive legal framework providing for financial management and accountability of decommissioning funds and activities, engaging highly skilled manpower, creating specialised institutions to regulate and supervise decommissioning activities with a transparent reporting system, will enhance effective environmental protection in South Sudan's oil and gas industry.

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Field Establishment of *Chrysophyllum albidum* G. Don Seedlings through Planting Depth, Hole Width and Nitrogen Fertilizer Application

O.F. OYEDEJI, O.A. OGUNWANDE, G.A. ADEBUSUYI, O.A. WILLIAMS,
J.O. GBADEBO, M.O. MAJOLAGBE, M.O. NOLA
Forestry Research Institute of Nigeria, Jericho Forest Hill, Ibadan, Nigeria

Abstract. The successful establishment of indigenous fruit tree species is fundamental to sustainable forest management, biodiversity conservation, and the domestication of economically important non-timber forest products. *Chrysophyllum albidum* G. Don (African star apple) is a valuable indigenous multipurpose tree species in West Africa whose large-scale cultivation is constrained by inadequate information on appropriate field establishment techniques. This study evaluated the effects of planting depth, planting-hole width and nitrogen fertilization on the early growth, biomass accumulation and physiological performance of *C. albidum* seedlings under field conditions at the Forestry Research Institute of Nigeria (FRIN), Ibadan. A split-split plot experiment arranged in a Randomized Complete Block Design (RCBD) was established using 120 seedlings. Treatments consisted of three planting depths (10, 15 and 20 cm), two planting-hole widths (10 and 15 cm), and two fertilizer levels (0 and 5 g urea seedling⁻¹), resulting in twelve treatment combinations replicated ten times. Morphological parameters were monitored fortnightly for six months, while biomass and physiological growth indices were determined at the end of the experiment. Analysis of variance revealed that fertilizer application and planting depth did not significantly ($P > 0.05$) influence seedling height, collar diameter or leaf production. Planting-hole width significantly affected leaf production ($P < 0.05$), indicating that adequate root-zone preparation enhanced canopy development during the establishment phase. Although biomass accumulation and physiological parameters varied among treatment combinations, interaction effects among the silvicultural treatments were not statistically significant. The findings demonstrate that *C. albidum* seedlings exhibit considerable adaptability to moderate variations in planting depth and fertilizer

application during early establishment, while appropriate planting-hole width improves early canopy development. These results provide valuable silvicultural information for plantation establishment, restoration programmes, and the domestication of African star apple in tropical forest ecosystems.

Keywords: African star apple; indigenous fruit tree; field establishment; planting depth; nitrogen fertilization; silviculture.

1. Introduction

Chrysophyllum albidum G. Don (Sapotaceae), commonly known as the African star apple, is one of the most valuable indigenous multipurpose fruit tree species in tropical Africa. The species occurs naturally in the lowland rainforest and derived savanna zones of West and Central Africa, where it contributes significantly to rural livelihoods, biodiversity conservation, food security and environmental sustainability. Its edible fruits are highly appreciated for their pleasant flavour and rich nutritional composition, while different plant parts, including the bark, leaves, seeds and roots, have long been utilised in traditional medicine for the treatment of malaria, yellow fever, diarrhoea, skin infections and several inflammatory disorders (Adebayo *et al.*, 2021; George *et al.*, 2022). Beyond its nutritional and medicinal importance, *C. albidum* provides timber, fuelwood, shade, carbon sequestration and ecological services that support sustainable forest ecosystems and agroforestry production systems.

The increasing commercial demand for African star apple fruits has stimulated renewed interest in its domestication and large-scale cultivation across West Africa. In Nigeria, the fruits constitute an important

source of seasonal income for rural households, particularly women and smallholder farmers involved in fruit harvesting and marketing. Recent studies have further demonstrated that the fruit pulp contains appreciable quantities of vitamins, essential minerals, dietary fibre and antioxidant compounds capable of reducing oxidative stress and improving human health (Obboh *et al.*, 2021; Adepoju *et al.*, 2023). Similarly, phytochemical investigations have identified numerous bioactive constituents including flavonoids, tannins, saponins and phenolic compounds that exhibit antimicrobial, antidiabetic and anti-inflammatory properties, thereby increasing the pharmaceutical and nutraceutical value of the species (George *et al.*, 2022).

Despite its considerable socio-economic importance, *C. albidum* remains largely undomesticated, with production relying predominantly on naturally occurring trees scattered within farmlands and secondary forests. Natural regeneration of the species is generally slow owing to seed recalcitrance, prolonged juvenile growth, poor seedling establishment and increasing anthropogenic disturbances including deforestation, agricultural expansion, bush burning and urbanisation (Kehinde *et al.*, 2021). Consequently, wild populations continue to decline, threatening the long-term availability of valuable genetic resources and limiting opportunities for commercial orchard development.

Successful domestication of indigenous tree species depends not only on efficient propagation techniques but also on appropriate silvicultural practices that enhance seedling survival and early field establishment. The establishment phase represents one of the most critical stages in plantation development because seedlings are particularly susceptible to environmental stress, nutrient deficiency, moisture fluctuations and transplant shock. Poor establishment frequently results in high mortality rates, uneven stand development and increased plantation management costs (Grossnickle & MacDonald, 2018). Therefore, identifying suitable field establishment practices is essential for improving plantation success and accelerating the domestication of economically important indigenous species.

Among the various silvicultural interventions employed during plantation establishment, planting depth plays a crucial role in regulating root development, water availability, aeration and seedling stability. Planting seedlings too shallow may expose roots to desiccation and mechanical instability, whereas excessively deep planting can reduce soil aeration, restrict root respiration and impair subsequent growth (Davis *et al.*, 2019). Similarly,

planting hole dimensions influence root expansion, soil loosening, water infiltration and nutrient accessibility during the initial stages of seedling establishment. Larger planting holes generally improve root penetration in compact soils by reducing mechanical resistance, thereby facilitating greater exploration of soil resources (Haase *et al.*, 2021).

Nutrient availability represents another major determinant of seedling establishment and productivity in tropical forest plantations. Nitrogen, being the most limiting macronutrient in many tropical soils, is directly involved in chlorophyll synthesis, photosynthetic efficiency, protein formation and vegetative growth. Appropriate nitrogen fertilization during early establishment has been reported to enhance leaf production, biomass accumulation, stem development and physiological performance of numerous tropical tree species (Lambers & Oliveira, 2019; Crous *et al.*, 2022). However, the response of seedlings to nitrogen application is strongly influenced by soil conditions and interactions with other silvicultural practices, particularly planting depth and rooting environment. Consequently, fertilizer recommendations developed for exotic plantation species may not necessarily be applicable to indigenous fruit trees such as *C. albidum*.

Although considerable attention has been devoted to the propagation, seed germination, vegetative multiplication and nutritional composition of *Chrysophyllum albidum*, relatively little information exists regarding optimum field establishment practices following nursery production. In particular, there is a paucity of empirical data on the combined effects of planting depth, planting hole width and nitrogen fertilization on the early growth and physiological performance of transplanted seedlings under tropical field conditions. This knowledge gap has constrained the development of evidence-based silvicultural recommendations for large-scale plantation establishment and conservation programmes.

The present study was therefore designed to evaluate the effects of planting depth, planting hole width and nitrogen fertilization on the early field establishment of *Chrysophyllum albidum* seedlings at the Forestry Research Institute of Nigeria, Ibadan. Specifically, the study assessed their influence on morphological growth attributes, biomass accumulation and physiological growth indices with the aim of identifying appropriate silvicultural practices that can improve seedling establishment, promote plantation productivity and support the conservation and sustainable utilization of this important indigenous fruit tree species.

2. Materials and Methods

2.1 Study Area

The study was conducted at the Arboretum of the Forestry Research Institute of Nigeria (FRIN), Jericho Hill, Ibadan, Oyo State, Nigeria. The experimental site is located within the Ibadan North-West Local Government Area between latitude 7°23'18"N and 7°23'43"N and longitude 3°51'20"E and 3°51'43"E. The area is characterized by a humid tropical climate with distinct wet and dry seasons. The rainy season extends from April to October, while the dry season occurs between November and March. Annual rainfall ranges from approximately 1,400 to 1,500 mm, with an average relative humidity of about 85%. Mean annual temperature is approximately 31.2°C. The predominant soil type is a well-drained lateritic alluvial soil, which supports the growth of a wide range of indigenous tropical tree species. Climatic data were obtained from the Forestry Research Institute of Nigeria Meteorological Station (FRIN Meteorological Report, 2015).

2.2 Experimental Materials

Healthy, vigorous and uniform seedlings of *Chrysophyllum albidum* G. Don (Syn. *Gambeya albida*), raised under nursery conditions, were selected for field establishment. Prior to transplanting, seedlings were inspected to ensure uniformity in height, stem diameter and overall vigour in order to minimize experimental variability.

2.3 Experimental Design and Field Establishment

The field experiment was conducted in the Arboretum of FRIN using a split-split plot arrangement within a Randomized Complete Block Design (RCBD). A total of 120 seedlings were used for the experiment.

The experiment consisted of three factors:

Main plot factor: Planting depth

D₁ = 10 cm

D₂ = 15 cm

D₃ = 20 cm

Sub-plot factor: Planting hole width

W₁ = 10 cm

W₂ = 15 cm

Sub-sub plot factor: Fertilizer application

F₀ = No fertilizer application

F₁ = Application of 5 g urea per seedling

The factorial combination of the three planting depths, two planting-hole widths and two fertilizer levels resulted in twelve treatment combinations (3 × 2 × 2 =

12). Each treatment was replicated ten times, giving a total of 120 experimental units.

Seedlings were transplanted into prepared planting holes according to the designated treatment combinations. Urea fertilizer was applied four weeks after transplanting by ring placement around the base of each seedling at the prescribed rate. Routine field maintenance, including manual weeding and protection against pests and mechanical damage, was carried out uniformly throughout the experimental period.

2.4 Growth Measurements

Growth assessments were carried out at two-week intervals for six months following transplanting.

The following morphological parameters were measured:

- Seedling height (cm), measured from the collar region to the terminal bud using a graduated metre rule.
- Collar diameter (mm), measured at the stem base using a digital Vernier caliper.
- Number of leaves, determined by direct counting of fully expanded leaves.

At the end of the six-month experimental period, destructive sampling was undertaken to determine biomass accumulation. Harvested seedlings were carefully uprooted and separated into roots, stems and leaves. Each plant component was oven-dried at 70 ± 2°C to constant weight before dry biomass determination.

2.5 Physiological Growth Analysis

Physiological growth indices were calculated to evaluate the growth performance of *Chrysophyllum albidum* seedlings under the different silvicultural treatments.

Relative Growth Rate (RGR)

$$RGR = \frac{\log_e H_2 - \log_e H_1}{T_2 - T_1} \text{ (gg}^{-1} \text{ day}^{-1}\text{)}$$

where

H₁ = Initial plant height

H₂ = Final plant height

T₁ = Initial sampling time

T₂ = Final sampling time

Absolute Growth Rate (AGR)

$$AGR = \frac{H_2 - H_1}{T_2 - T_1} \text{ (cm day}^{-1}\text{)}$$

Leaf Area Ratio (LAR)

$$LAR \text{ (m}^2\text{Kg}^{-1}\text{)} = \frac{A}{W}$$

where

A = Leaf area (m²)

W = Total plant dry weight (kg)

Net Assimilation Rate (NAR)

$NAR = \frac{RGR}{LAR} (gcm^{-2} day^{-1})$

Leaf Turgidity

Leaf turgidity was estimated according to the expression:

$$\frac{\text{Leaf turgidity}}{\text{Leaf weight in water} - \text{Initial fresh weight}} \times 100 = \frac{\text{Initial Fresh Weight}}{\text{Initial Fresh Weight}}$$

where

TW = Turgid weight after soaking in distilled water

FW = Initial fresh weight

2.6 Statistical Analysis

Data obtained from the experiment were subjected to analysis of variance (ANOVA) appropriate for a split-split plot arrangement in a Randomized Complete Block Design using the Statistical Package for the Social Sciences (SPSS). Treatment means were separated using Fisher's Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$). Descriptive statistics were computed for all measured variables, and treatment effects were considered statistically significant when probability values were less than 0.05.

3. Results

Effects of Planting Depth, Planting Hole Width and Fertilizer Application on Morphological Growth of *Chrysophyllum albidum* Seedlings

The analysis of variance (Table 1) revealed that fertilizer application had no significant ($P > 0.05$) effect on seedling height, collar diameter or leaf production of *Chrysophyllum albidum* seedlings during the six-month field establishment period. Likewise, planting depth did not significantly influence any of the measured morphological growth parameters. Planting hole width also had no significant effect on seedling height or collar diameter ($P > 0.05$). However, planting hole width significantly affected leaf production ($P = 0.033$), indicating that leaf development was influenced by the size of the planting hole.

The interaction effects among fertilizer application, planting depth and planting hole width were not statistically significant ($P > 0.05$) for seedling height, collar diameter or number of leaves, suggesting that the combined application of the three silvicultural treatments did not produce additional growth responses beyond their individual effects during the establishment period.

Table 1: Effects of Planting Depth, Planting Hole Width and Fertilizer Application on Morphological Growth of *Chrysophyllum albidum* Seedlings

Experimental treatment	Seedling height (cm)	Collar diameter (mm)	Number of leaf	Leaf area estimate	Total folial weight	Dry weights			R/S ratio
						Leaf	stem	Root	
F0W1D1	60.0	6.61	17.38	1663.2	18.33	8.07	6.36	7.59	0.24
F0W1D2	70.05	8.12	20.13	878.85	5.91	2.09	1.91	3.26	0.50
F0W1D3	63.03	6.96	16.00	1265.99	17.24	8.50	7.87	4.78	0.27
F0W2D1	59.99	6.36	13.38	1062.72	16.17	7.99	7.89	3.48	0.33
F0W2D2	51.30	7.18	15.13	1396.68	17.56	9.02	6.80	6.88	0.30
F0W2D3	66.24	7.65	19.13	845.3	12.26	5.75	5.27	5.38	0.37
F1W1D1	62.33	7.06	15.50	2593.01	24.60	11.55	10.92	9.77	0.58
F1W1D2	65.25	7.13	18.88	1386.48	22.98	10.67	10.62	5.45	0.35
F1W1D3	49.51	6.09	16.00	708.56	6.28	0.09	0.30	0.28	0.33
F1W2D1	70.41	6.73	12.88	648.32	19.62	8.89	7.28	4.71	0.27
F1W2D2	61.44	6.83	13.63	2964.06	33.28	15.68	10.53	8.83	0.31
F1W2D3	62.90	6.49	14.50	777.36	8.44	2.71	3.37	16.0	0.25
S.E	1.994	0.173	0.585						

The treatment means presented in Table 2 demonstrated considerable variation in growth performance among the twelve treatment combinations. Seedling height ranged from 49.51 cm under treatment F₁W₁D₃ to 70.41 cm under treatment F₁W₂D₁. Collar diameter varied from 6.09 to 8.12 mm, while the number of leaves ranged between 12.88 and 20.13 leaves per seedling.

Substantial differences were also observed in biomass accumulation. Leaf dry weight ranged from 0.09 to 15.68 g, stem dry weight from 0.30 to 10.92 g, and root dry weight from 0.28 to 16.00 g among the treatment combinations. Root-to-shoot ratio varied between 0.24 and 0.58, reflecting differences in biomass partitioning among seedlings subjected to different establishment treatments.

Although numerical differences existed among treatments, these variations generally did not translate into statistically significant differences for most measured growth variables during the six-month assessment period.

Table 2: Analysis of Variance for the Effects of Planting Depth, Planting Hole Width and Fertilizer Application on Morphological Growth of *Chrysophyllum albidum* Seedlings

Source	Dependent Variable	Type III Sum of Squares	Df	Mean Square	F	Sig.
F	Collar Diameter	4.378	1	4.378	1.532	0.219
	Seedling Height	1.021	1	1.021	.003	0.959
	Number of Leaf	63.375	1	63.375	1.932	0.168
W	Collar Diameter	0.363	1	0.363	0.127	0.723
	Seedling Height	2.975	1	2.975	0.008	0.930
	Number of Leaf	155.042	1	155.042	4.726	0.033
D	Collar Diameter	7.108	2	3.554	1.244	0.293
	Seedling Height	123.038	2	61.519	0.161	0.851
	Number of Leaf	80.771	2	40.385	1.231	0.297
F * W	Collar Diameter	.050	1	0.050	0.017	0.896
	Seedling Height	735.380	1	735.380	1.926	0.169
	Number of Leaf	8.167	1	8.167	0.249	0.619
F * D	Collar Diameter	8.871	2	4.435	1.553	0.218
	Seedling Height	948.927	2	474.463	1.243	0.294
	Number of Leaf	5.812	2	2.906	0.089	0.915
W * D	Collar Diameter	5.767	2	2.884	1.009	0.369
	Seedling Height	1696.689	2	848.344	2.222	0.115
	Number of Leaf	148.146	2	74.073	2.258	0.111
F * W * D	Collar Diameter	0.943	2	0.472	0.165	0.848
	Seedling Height	49.159	2	24.579	0.064	0.938
	Number of Leaf	38.521	2	19.260	0.587	0.558
Error	Collar Diameter	239.975	84	2.857		
	Seedling Height	32071.854	84	381.808		
	Number of Leaf	2756.000	84	32.810		
Corrected Total	Collar Diameter	267.455	95			
	Seedling Height	35629.042	95			
	Number of Leaf	3255.833	95			

Effects of Silvicultural Treatments on Physiological Performance

The physiological responses of *Chrysophyllum albidum* seedlings under different silvicultural treatments are presented in Table 3. Relative water content (RWC) ranged from 36.95% to 53.93%, with the highest value observed under treatment F₀W₂D₂ and the lowest under F₁W₂D₂. Leaf turgidity varied considerably among treatments, ranging from 0.28 to 3.35.

Net assimilation rate (NAR) ranged from 0.0007 to 0.0051 g cm⁻² day⁻¹, whereas relative growth rate (RGR) varied from 0.220 to 0.871 g g⁻¹ day⁻¹. Absolute growth rate (AGR) ranged from 0.67 to 1.69 cm day⁻¹, indicating appreciable variation in growth efficiency among the treatment combinations. Despite these numerical differences, the generally non-significant treatment effects observed in the morphological parameters suggest that variations in physiological performance did not produce corresponding statistically detectable differences in overall seedling growth during the experimental period.

Table 3: Effects of Silvicultural Treatments on Physiological Performance

Experimental treatment	RWC (%)	Leaf Turgidity	NAR (gcm ⁻² /day)	RGR (gg ⁻¹ day ⁻¹)	AGR (cm day ⁻¹)
F0W1D1	43.01	1.94	0.0015	0.508	1.005
F0W1D2	41.46	1.87	0.003	0.220	1.23
F0W1D3	49.63	0.93	0.0015	0.482	0.67
F0W2D1	44.52	1.013	0.0030	0.342	1.225
F0W2D2	53.93	1.54	0.0024	0.258	1.075
F0W2D3	46.61	3.35	0.005	0.871	0.935
F1W1D1	47.92	0.49	0.0016	0.362	1.275
F1W1D2	48.05	1.74	0.0007	0.244	1.685
F1W1D3	52.03	1.05	0.0012	0.236	0.95
F1W2D1	47.37	0.98	0.0009	0.288	1.235
F1W2D2	36.95	2.04	0.0010	0.421	1.2
F1W2D3	37.01	0.28	0.0051	0.379	0.73

4. Discussion

The establishment phase represents one of the most critical stages in the successful cultivation of indigenous tropical tree species because seedling survival and subsequent productivity largely depend on the interaction between planting techniques, soil conditions and nutrient availability (Grossnickle & MacDonald, 2018). This study evaluated the influence of planting depth, planting-hole width and nitrogen fertilization on the early field performance of *Chrysophyllum albidum* seedlings. The results showed that these silvicultural factors had limited influence on seedling height and collar diameter during the six-month establishment period, whereas planting-hole width significantly affected leaf production. These findings suggest that the early growth of *C. albidum* is governed more by its inherent physiological adaptation and establishment strategy than by moderate variations in field planting practices.

The non-significant response of seedling height and collar diameter to fertilizer application indicates that nitrogen was probably not the primary limiting factor under the prevailing field conditions. Many indigenous tropical tree species characteristically exhibit slow juvenile growth and initially allocate assimilated carbon towards root establishment rather than rapid shoot development following transplanting (Lambers, Chapin, & Pons, 2008). Such conservative growth strategies enhance water and nutrient acquisition and improve the ability of seedlings to withstand environmental stress during establishment (Poorter & Bongers, 2006). Consequently, immediate responses to fertilizer application may not always be reflected in above-ground growth, particularly during the first growing season. Similar observations have been reported in *Chrysophyllum albidum*, where nutrient addition produced only moderate improvements in seedling vigour under nursery conditions (Adelani & Amos, 2021).

Although fertilizer application did not significantly increase plant height or stem diameter, numerical differences in biomass production among treatments indicate that nitrogen may have enhanced assimilate production and partitioning without producing statistically detectable differences in external morphology. Nitrogen is a structural component of chlorophyll molecules, proteins and nucleic acids, and therefore plays an indispensable role in photosynthesis, enzyme synthesis and vegetative growth (Marschner, 2012). Several studies have demonstrated that appropriate nutrient management improves biomass accumulation and physiological performance in tropical tree seedlings even when

height growth remains relatively unchanged during the early establishment stage (Lawrence, 2003; Cárate Tandalla *et al.*, 2025). The present findings therefore suggest that the influence of nitrogen fertilization on *C. albidum* may become more evident over a longer monitoring period as seedlings transition from establishment to active vegetative growth.

Planting depth also had no significant influence on the measured morphological characteristics. This result indicates that the three planting depths evaluated (10, 15 and 20 cm) were all within the range tolerated by *C. albidum* seedlings under the environmental conditions of the study area. Proper planting depth is recognised as a key silvicultural practice because excessively shallow planting may expose roots to moisture stress, while excessively deep planting can reduce soil aeration and restrict root respiration (Grossnickle & MacDonald, 2018). However, when planting depths remain within an acceptable range and soil moisture is adequate, seedlings often maintain satisfactory physiological function and root growth. The findings therefore demonstrate that *C. albidum* seedlings possess sufficient ecological plasticity to establish successfully across moderate variations in planting depth, an attribute that is advantageous for plantation establishment under variable field conditions.

Among the silvicultural factors investigated, planting-hole width exerted the only significant influence on leaf production. Leaf number is an important determinant of photosynthetic capacity because it directly affects canopy development and carbon assimilation. Larger planting holes generally provide a less compact rooting environment, thereby facilitating root elongation, improving water infiltration and enhancing nutrient uptake during early establishment. Improved root development subsequently supports increased leaf initiation and expansion through enhanced water and mineral acquisition (Haase & Davis, 2017). Similar relationships between improved rooting conditions and increased canopy development have been reported in several indigenous tropical tree species, where soil preparation significantly enhanced seedling vigour and early plantation performance (Adelani & Amos, 2021).

The absence of significant interaction effects among fertilizer application, planting depth and planting-hole width suggests that the individual silvicultural treatments acted independently during the six-month establishment period. Nevertheless, the observed variation among treatment means indicates that *C. albidum* responds to the cumulative influence of several environmental factors rather than to a single management practice. Similar observations have been reported in tropical forest restoration studies, where

genetic variability, microsite conditions and seasonal climatic fluctuations often contribute more to seedling performance than individual silvicultural treatments during the juvenile growth stage (Ashton & Kelty, 2018).

Variation in biomass accumulation among treatments further illustrates differences in resource allocation strategies. Seedlings exhibited considerable differences in leaf, stem and root dry matter production as well as root-to-shoot ratio, suggesting that assimilates were partitioned differently according to the prevailing establishment conditions. Biomass allocation is a fundamental adaptive mechanism through which plants optimise the acquisition of limiting resources while maintaining structural balance (Poorter *et al.*, 2012). Increased root biomass enhances soil exploration and nutrient uptake, whereas greater investment in leaf biomass improves photosynthetic capacity and dry matter production. The observed variation in root-to-shoot ratio therefore reflects adaptive growth responses rather than evidence of physiological impairment.

The physiological indices measured in this study further support the observed morphological responses. Relative water content remained comparatively stable across treatments, indicating that transplanted seedlings successfully maintained cellular hydration and water balance despite differences in planting depth and fertilizer application. Maintenance of adequate tissue water status is essential for stomata regulation, photosynthetic activity and cell expansion, particularly during the establishment phase when root systems are still developing (Taiz *et al.*, 2018). Likewise, differences in leaf turgidity among treatments suggest varying capacities for osmotic adjustment and water retention, both of which contribute to transplant success under field conditions.

Variation in net assimilation rate (NAR), relative growth rate (RGR) and absolute growth rate (AGR) indicates that physiological performance differed among treatment combinations even though these differences were not reflected in statistically significant changes in plant height or stem diameter. Net assimilation rate represents the efficiency with which leaf area converts assimilated carbon into plant biomass, while relative growth rate integrates biomass production with plant size over time (Hunt, 1990). The variation observed among treatments therefore suggests that seedlings differed in physiological efficiency and carbon utilisation despite exhibiting similar external morphology. Such temporal differences between physiological activity and morphological expression have been widely reported

in slow-growing woody perennials during the early stages of plantation establishment (Lambers *et al.*, 2008).

From a silvicultural perspective, the findings demonstrate that *Chrysophyllum albidum* is capable of establishing successfully under a range of practical field planting conditions. The absence of adverse effects associated with planting depths between 10 and 20 cm provides operational flexibility during plantation establishment, while the significant improvement in leaf production associated with planting-hole width emphasises the importance of adequate site preparation. Although nitrogen fertilization did not significantly improve morphological growth within the study period, its influence on biomass production and physiological performance suggests that nutrient management should remain an integral component of plantation establishment, particularly on nutrient-deficient tropical soils.

The present study contributes to the limited body of knowledge on the field silviculture of *Chrysophyllum albidum*, a species of considerable ecological, nutritional and economic importance in West Africa. As increasing attention is directed towards the domestication, conservation and commercial cultivation of indigenous fruit tree species, evidence-based silvicultural recommendations become essential for improving plantation establishment and long-term productivity. Future studies should extend the monitoring period beyond the juvenile stage, evaluate additional fertilizer regimes and planting configurations, and examine the influence of soil physicochemical properties on seedling growth and survival to develop comprehensive management guidelines for large-scale cultivation.

5. Conclusion

The present study evaluated the influence of planting depth, planting-hole width and nitrogen fertilization on the field establishment of *Chrysophyllum albidum* seedlings under tropical conditions. The findings demonstrated that the species established successfully across all planting depths investigated, indicating considerable adaptability during the juvenile stage. Fertilizer application and planting depth had no significant influence on seedling height, collar diameter or leaf production during the six-month experimental period, whereas planting-hole width significantly improved leaf production, emphasizing the importance of adequate site preparation for enhancing early canopy development. Although treatment effects on most morphological variables

were not statistically significant, appreciable differences were observed in biomass accumulation and physiological growth indices among treatment combinations. These responses suggest that *C. albidum* modifies biomass allocation and physiological processes during establishment to optimize resource acquisition and adaptation to field conditions. The relatively stable physiological performance across treatments further confirms the species' resilience under moderate variations in planting practices.

From a silvicultural standpoint, the results indicate that moderate planting depths (10–20 cm) can be adopted without adversely affecting early field performance, while careful preparation of planting holes should receive greater attention during plantation establishment. Although nitrogen fertilization did not produce immediate improvements in morphological growth, its influence on biomass production suggests that longer-term evaluation may be required to fully assess fertilizer responses in this characteristically slow-growing indigenous hardwood. This study contributes valuable baseline information for the domestication, plantation establishment and conservation of *Chrysophyllum albidum*. The findings provide practical guidance for foresters, nursery managers and restoration practitioners seeking to improve the establishment success of this economically and ecologically important indigenous fruit tree. Future research should investigate longer-term growth responses, different fertilizer sources and rates, soil physicochemical interactions and multi-location field trials to develop comprehensive silvicultural recommendations for large-scale cultivation.

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