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Original research article

Ecological Restoration of Degraded Concrete Waste Zones at the Nachtigal Dam Construction Site (Cameroon): A Methodological Approach for Plant Regeneration Dynamics

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ABSTRACT

The construction of large hydroelectric infrastructure often leads to significant soil degradation, particularly through the disposal of inert waste. At the Nachtigal Dam construction site in Cameroon, two concrete waste disposal sites in zones A and B were identified for ecological rehabilitation. In this study, we assessed the effectiveness of a three-layered soil remediation technique on the growth of 1,046 plants, selected based on both a survey conducted at the local community on products most commonly used and on an ecological assessment of the surrounding area, across a total area of 24,657.72 m², i.e. 8924.72m2 in zone A and 15733m2 in zone B. A mixed planting strategy incorporating 40% species producing non-timber forest products (NTFPs) and 60% woody species has been implemented to promote ecological functionality and socio-economic benefits. Post-planting monitoring through observation and counting revealed an overall survival of approximately 85%, despite localized erosion and varying survival rates within and between species. Thus, the rehabilitated areas exhibit strong regeneration potential, indicating that engineered soil profiles combined with structured planting of mixed species can effectively restore degraded concrete waste areas. This study sheds light on assisted regeneration practices relevant to large infrastructure projects in tropical forest regions.

Keywords: Assisted reforestation, conservation, inert waste, rehabilitation, soil types.

RÉSUMÉ

La construction de grandes infrastructures hydroélectriques entraîne souvent une dégradation importante des sols, notamment par le dépôt de déchets inertes. Sur le site de construction du barrage de Nachtigal au Cameroun, deux zones de dépôt de déchets en béton, A et B, ont été identifiées en vue d'une réhabilitation écologique. Dans cette étude, nous avons évalué l'efficacité d'une technique de remédiation des sols en trois couches sur la croissance de 1 046 plants, sélectionnés à la fois sur la base d'une enquête menée auprès des communautés locales sur les produits les plus couramment utilisés et d'une évaluation écologique de la zone environnante, établis sur une superficie de 24 657,72 m², soit 8 924,72 m² pour la zone A et 15 733 m² pour la zone B. Une stratégie de plantation mixte intégrant 40 % d'espèces produisant des produits forestiers non ligneux (PFNL) et 60 % d'espèces ligneuses a été mise en œuvre afin de favoriser à la fois la fonctionnalité écologique et les bénéfices socio-économiques. Le suivi post-plantation, basé sur l'observation et le comptage, a révélé un taux de survie global d'environ 85 %, malgré une érosion localisée et des variations de survie au sein et entre les espèces. Les zones réhabilitées présentent ainsi un fort potentiel de régénération, indiquant que des profils de sol reconstitués, combinés à une plantation structurée d'espèces mixtes, peuvent restaurer efficacement des zones dégradées par des déchets de béton. Cette étude met en évidence des pratiques de régénération assistée pertinentes pour les grands projets d'infrastructure en milieu forestier tropical.

Mots-clés : reforestation assistée, conservation, déchets inertes, réhabilitation, types de sols.

1. INTRODUCTION

Hydropower development contributes significantly to the reduction of greenhouse gas emissions (Berga, 2016) and plays a vital role in improving socio-economic conditions in many emerging economies, including Cameroon. Kaygusuz (2009) dealt with policies to meet increasing energy and electricity demand by using hydropower. As national electricity demand increases, large-scale energy infrastructure projects are needed to enhance production capacity, stabilize distribution networks, reduce recurrent power shortages, and ultimately improve living standards for surrounding communities (Shyu 2020; Xiong *et al*. 2024). Hydroelectric dams, in particular, are considered a renewable and reliable source of energy, capable of supporting industrial expansion, regional electrification, and long-term economic growth (Killingtveit, 2020). However, these socio-economic benefits are often derived at the expense of significant environmental disruption.

Dam construction often causes significant deforestation directly through reservoir inundation and indirectly by facilitating access to remote forests, thus creating massive biodiversity losses and carbon emissions (Andersen *et al*. 2017; Qui *et al*. 2026). Forest degradation and deforestation remain widespread, driven by factors such as agricultural expansion, unsustainable land use practices and population pressure (Ghazoul & Chazdon 2017; Bos *et al*. 2020). Moreover, large-scale infrastructure development, particularly hydroelectric dam construction, is a dominant driver of forest loss and ecological disturbance in Central Africa (Tchatchou *et al*., 2015). Such projects lead to soil erosion, loss of biodiversity, and disruption of ecosystem services, adversely affecting local communities and the environment (Tuyizere *et al*. 2025). Additionally, they often generate extensive inert waste deposits (concrete, rubble), which degrade soil layers and inhibit natural regeneration (Hamzaoui *et al*. 2024). Assisted forest regeneration using traditional knowledge of various ethnic groups has informed and improved re-afforestation with the rotation of swidden cultivation systems (Tongkoom *et al*. 2021). Challenges in achieving effective restoration in regions with complex socio-economic dynamics persist. Bill (1999) mentioned qualities required for active rehabilitation, which included a historic model—as complete as possible—with all the species present before. Therefore, a restoration strategy could contribute to ecological recovery as well as that of the local livelihoods in areas where environmental conditions allowed the safe use of NTFPs (Santini and Miquelajauregui 2022; Sze *et al*. 2022).

Therefore, ecological restoration of sites is essential for maintaining biodiversity, stabilizing soils, and restoring ecosystem services to local communities, promoting community organisation and improving rural livelihoods (Gastauer *et al*. 2020; Bos *et al*. 2020). Organic carbon restoration within soil layers may take several more years to recover aboveground grassland and biomass (Moreno-Mateos *et al*. 2012). Efforts have been recognised through global goals such as SDG 13, for urgent action against climate change and its impacts. Thus, covering the exposed concrete or rocky waste surfaces mentioned above is beneficial, as such substrates create visual pollution, prevent natural regeneration, generate heat-island effects, and increase vulnerability to erosion and extreme climatic events (Brancalion and Holl, 2020). Reconstructed soil layers and reforestation therefore provide not only functional rooting media but also contribute to landscape integration, microclimate regulation, and community food safety. These benefits align with recognized principles of restoration ecology, which emphasize the need to rehabilitate degraded substrates and to re-establish ecological processes and ecosystem functionality (Brancalion & Holl, 2020).

Forest landscape restoration is essential in enhancing ecological resilience, biodiversity, and livelihoods (Tuyizere *et al*., 2025). In the Nachtigal Hydropower Project site, two degraded areas, Zones A and B, were created as a result of concrete waste deposits during construction, leading to severe alterations of the local ecotone and limiting the natural return of forest vegetation after intense deforestation. This study assesses the restoration approach implemented across these zones, combining soil remodelling with a mixed-species reforestation strategy designed to recreate a functional forest structure within the surrounding ecosystem while enhancing the socio-economic value of the rehabilitated area. By documenting the methodology used for plant performance and regeneration dynamics, this work will contribute to the broader understanding of ecological restoration practices in large infrastructure contexts across tropical Africa.

2. MATERIAL AND METHODS

2.1. Description of the Study Areas

The Nachtigal Hydroelectric Power Plant of 420 MW is situated at the Sanaga riverbed close to the Nachtigal waterfall at 65 km northeast of Yaoundé, in Ndokoa village found in the Upper Sanaga division in the Centre Region of Cameroon. It covers a surface area of 421 ha divided into 11 zones, of which Zones A and B, located at 4.39255ºN, 11.73405ºE, originated from concrete waste dumps formed during dam construction through the deposition and levelling of heterometric concrete fragments, cement residues, gravel and inert spoil (Figure 1).

This produced highly compacted, irregular surfaces with steep lateral slopes prone to runoff concentration, very low permeability and a hostile substrate incapable of supporting natural regeneration.

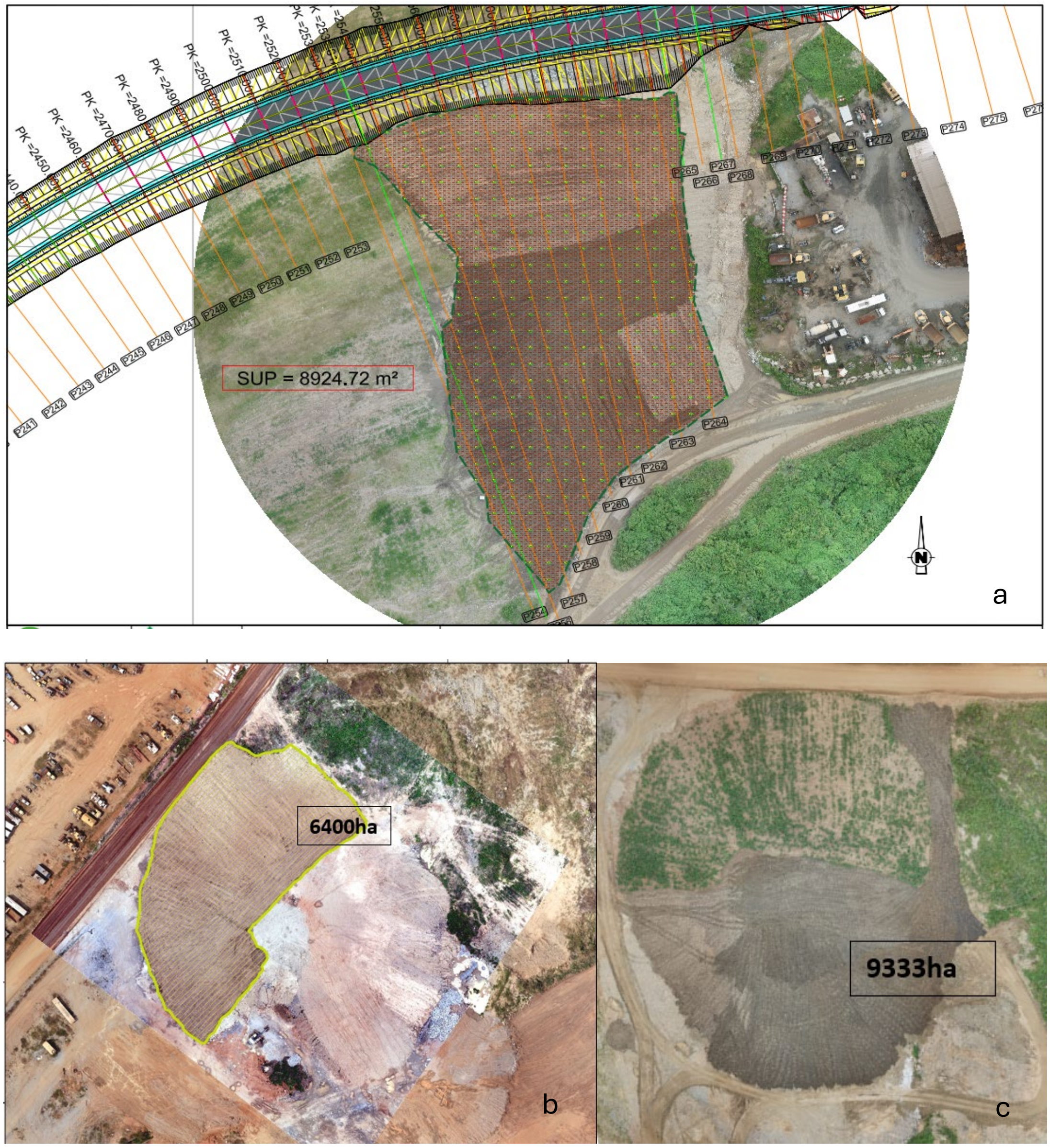

Figure 1: Overview of different zones: (a) Drone view of Zone A (Scale 1:1000); (b) and (c) Drone view of Zone B (Scale 1:1000)

2.2. Data Collection and Analysis Tools

2.2.1. Plant selection

Plant species were selected based on a multi-source data collection carried out in May 2022, combining environmental impact assessment conducted before the construction phase, a local community-derived knowledge survey on non-timber forest products most commonly used by residents in the vicinity of the Sanaga River, and field-based ecological assessments of the surrounding area. Firstly, a desk-based review of project documentation specifying the environmental and social impact assessment was undertaken to identify baseline vegetation conditions, previously existing species on the project site and their ecological interactions relevant to habitat reconstruction. All the plants mentioned in the documents were termed the 'ESIA elaboration list' as the ESIA carried out this early survey. Secondly, ethnobotanical surveys based on questionnaires and interviews were carried out in the neighboring communities of Ndji and Ndokoa villages through structured consultations with local stakeholders. From these surveys, a list of preferential plant species of socio-economic importance, used for food, medicine, cultural practices, and income generation, was established in comparison to the ESIA list.

Thirdly, various lists were also established based on the botanical field inventories conducted in the forest ecosystems surrounding the project site, i.e., in Ndji forest, Ekombite-Ndokoa forest and the forest around the dam area (Figure 2).

Figure 2: Plant inventory carried out in the Ndji forest: (a) Tree identification; (b) Tree height estimation

The plants species selected for the restoration process were thus obtained from five data sources rated 1 to 5, that is (i) project indicative list rated as 1, (ii) ESIA list as 2, (iii) Ndji community list as 3, (iv) Ndokoa community list as 4 and (v) species observed during field inventories in both Ndji and Ndokoa local forests as 5. The various species identified in the different lists were synthesised into a comparative analysis matrix compiling all proposed species according to their common and scientific names, functional category (timber/service species or NTFP-producing species), origin of citation and frequency of occurrence across the five data sources. This approach led to a well-structured and transparent prioritisation process based on three selection criteria (species cited in not less than three data sources; species unanimously requested by both communities and field-observed species requested by at least one community). The species were grouped as per the number of solicitations by list, rated from 1 to 5, and the type of species (Timber or NTFP).

2.2.2. Plant propagation in nursery

During the field botanical campaigns, not only were seed-producing trees localised with a GPS for an eventual collection of seeds in fruiting season, but also the assessment of parameters such as inter-tree distances, observation of natural regeneration patterns in addition to dendrometric measurements (plant height and diameter), assessing species distribution and regeneration potential across sites. Seeds and wild seedlings were also collected at the foot of some seed-producing trees and planted in pods to boost plant production at the nursery established in one of the zones at the dam site. Actually, two nurseries were built (Figure 3) to accommodate the plants required for the reforestation of the site. The first nursery was used for early insemination, wild seedling planting, treatment and assistance (watering, fertilisation, bio pesticide application when necessary, etc.), modified from Ngono *et al.* (2021); the other, of 300 m^2 was where the young plants were kept to grow under an established 60% shade net and monitored before being transferred to the plantation sites.

Figure 3: Nurseries used to accommodate various growing species from seeds and wild seedlings. (a) and (b) Nursery for seeds and stem cuttings; (c) and (d) nursery for fully germinated seeds and seedlings

2.2.3. Soil remodelling

To restore a functional rooting medium, the degraded domes were restructured, stabilized, and covered with a technical soil reconstruction system, remodelled by the installation of a three-layered soil profile to mask the concrete blocks and recreate a functional soil substrate. The three-layered remodelling system was made up of a 30 cm basal laterite layer (Figures 4a and 5b) distributed over the concrete sloppy dome for foundational stability. A medial layer of 70 cm deep loose soil was then spread over the basal layer (Figure 4c) to improve not only the water infiltration and drainage system but also the rooting environment. Finally, an organic topsoil layer of 30 cm deep was added (Figures 4d and 4e) for plant growth, supplying nutrients and supporting early establishment. Thus, a three-layered soil profile of 130 cm depth was designed specifically to ensure adequate rooting medium and to create a functional substrate. Figure 4 below illustrates the application of the different soil layers in zones A and B, respectively, while reshaping the domes into more regular slopes, reducing runoff velocity and improving stability. Local depressions were filled and ridges softened to avoid concentrated flow paths.

2.2.4. Planting, maintenance and monitoring

After soil remodelling, the areas were subjected to planting. Zones A and B were planted in November 2023 and April - May 2024, respectively. Four hundred and fifty (450) different plants selected as described above and grown in nurseries were introduced randomly in each hectare of land based on a modified standard procedure (Figure 5) by Ngono *et al*. (2021). Thus, for zone A, 348 plants were installed in an area of 8924.72 m^2, while in zone B of 15733 m^2, approx. 1.6 ha, 698 plants (278 and 420) were planted in two phases. The seedlings were spaced at 20 m^2 from each other in planting holes of 30 x 30 x 30 cm^3 manually excavated and half-filled with topsoil enriched with a mixture of compost + sawdust + chicken droppings in the 1:1:1 ratio. Species were placed randomly in an interwoven pattern, ensuring a 40 : 60 ratio, respectively, for NTFP-producing plants and timber species per hectare.

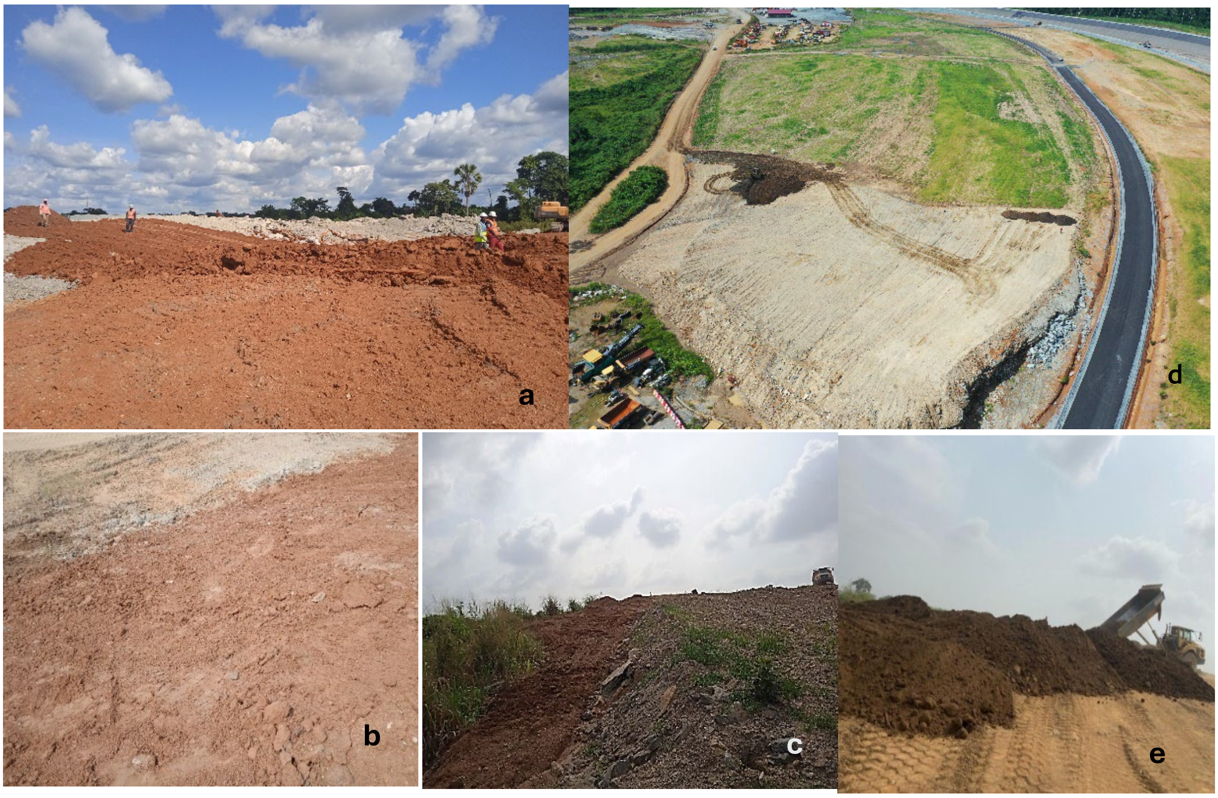

Figure 4: Remodelling of different zones: (a) Zone A with the deposition of the first layer of laterite; (b) Zone B with laterite layer installed on concrete; (c) Zone B with loose soil installed on laterite layer (d) Zone A with the addition of the dark topsoil on the loose soil and (e) Zone B with the installation of topsoil.

Figure 5: Planting disposition. (a) and (b) Measuring the spacing between future plants; (c) Dimension of the hole reserved for planting

After planting, the young plants were watered twice a week, especially during the dry season (Figure 6). In the rainy season, soil erosion control mechanisms (addition of more soil and replanting) were implemented.

Figure 6: Planting process. (a) Planting of seedlings and (b) Early watering.

Maintenance was executed once every three months during the first year of the active plantation phase and this included weeding, limiting herbaceous competition (*Mimosa diplotricha, Centrosema pubescence, Tithonia diversifolia, Chromolaena odorata*); mulching, using harvested plants organs to improve moisture retention and suppress weeds; supplemental irrigation, especially in the critical Zone A planted during the early dry-season period; slope stabilization, minor reshaping or infilling of areas affected by erosion, particularly in Zone B. Monitoring was carried out by repeated field observations over a period of 12 months. Both quantitative (seedling survival or losses) and qualitative (vigour, cover structure) metrics were evaluated, combined with the assessment of erosion impacts and the effect of invasive herbaceous species on the installed plantation in order to support evaluation of early regeneration dynamics. The survival loss was calculated as the percentage of plants alive and counted after 12 months, adapted from the formula of Motzer (2021).

$$Survival\ Percentage\ (\%) = \frac{Number\ of\ plants\ counted}{Total\ number\ of\ plants\ put\ in\ soil} x\ 100$$

3. RESULTS

3.1. Plant species selected

Figure 7 below shows the sixty-three species identified from the various lists for their use in timber and NTFP and rated from 5 to 1.

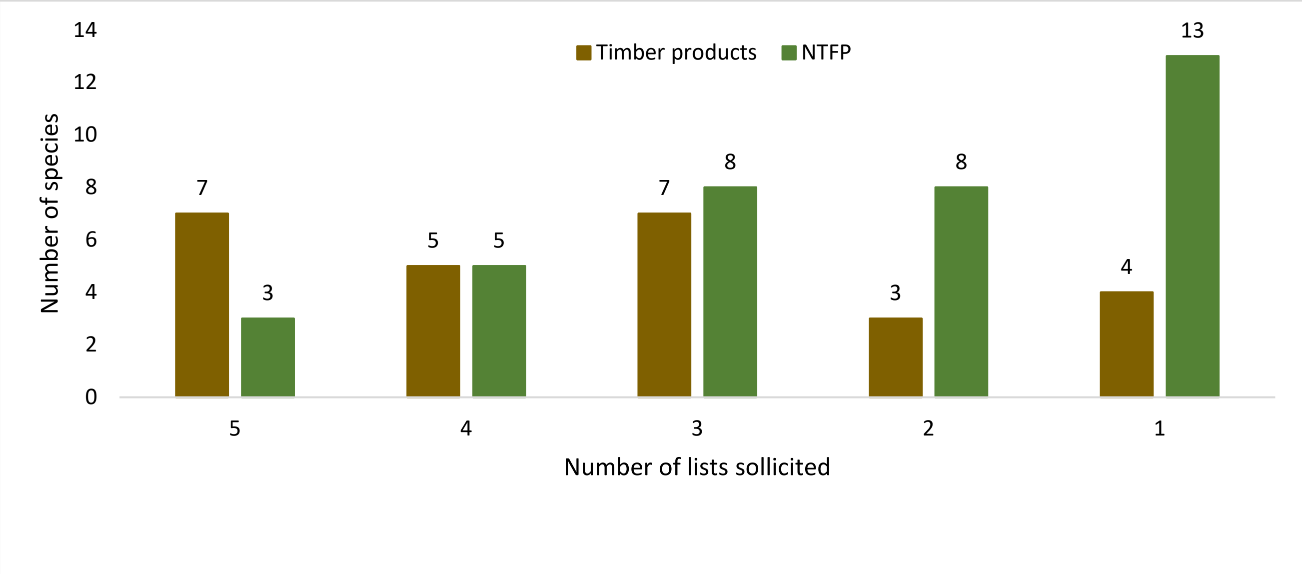

Figure 7: Number of species selected from the various rated lists and their uses (for timber or/and NTFP).

Forty (40) species retained for planting fell within the first three stages of selection criteria and comprised an equal distribution of timber/service species and NTFP-producing species (Table I).

Table I. Number of Species planted based on selection criteria

Selection stage	Criteria applied	Outcome
Stage 1	Species cited in ≥ 3 data lists	35 species retained
Stage 2	Species unanimously requested by both communities	+2 species retained
Stage 3	Field-observed species requested by at least one community	+3 species retained
Final pool	Consolidated number of plant species selected	40 species retained

The balance in species types was designed to support both ecological restoration and socio-economic benefits (Table II)

Table II: Species retained for planting in both zones, A and B

No.	Local name	*Scientific name*	Number of plants/ha
1.	Acajou de Bassam/Ngollon	*Khaya ivorensis*	9
2.	Aningré A	*Aningeria altissima*	9
3.	Bété	*Mansonia altissima*	16
4.	Dabéma/Atui	*Piptadeniastrum africanum*	9
5.	Doussié blanc/Pachi	*Afzelia pachyloba*	11
6.	Azobé	*Lophira alata*	14
7.	Eyong	*Eribroma oblongum*	14
8.	Fraké/Limba/Akom	*Terminalia superba*	16
9	Fromager/Doum	*Ceiba pentandra*	19
10.	Ilomba/Eteng	*Pycnanthus angolensis*	14
11.	Iroko/Abang	*Milicia excelsa*	24
12.	Koto/ Efok Ayus	*Pterygota macrocarpa*	9
13.	Lotofa/Nkanang	*Sterculia rhinopetala*	16
14.	Tali	*Erythrophleum ivorensis*	16
15.	Padouk	*Pterocarpus soyauxii*	9
16.	Moabi/ Adjap	*Baillonella toxisperma*	14
17.	Ayous	*Triplochiton scleroxylon*	19
18.	Sapelli/assié	*Entandrophragma cylindricum*	9
19.	Bibolo	*Lovoa trichilioides*	14
20.	Ossel Abang	*Morus mesozigia*	9
21.	Njansang/Ezezan	*Ricindendron heudelotti*	5
22.	Bush mango/Nd	*Irvingia gabonensis*	10
23.	Mango	*Mangifera indica*	15
24.	Safoutier	*Dacryodes edulis*	15
25.	Bitter cola/onié	*Garcinia cola*	10
26.	Ebak	*Brachystegia mildbraedii*	8
27.	Pawpaw	*Carica papaya*	10
28.	Ekouk	*Alstonia boonei*	10
29.	Okok	*Gnetum africanum*	10
30.	Palm tree/Alen	*Elaeis guineensis*	15
31.	Guava	*Psidium guajava*	5
32.	Eveuss	*Klainedoxa gabonensis*	5
33.	Poivre sauvage	*Piper sp.*	5
34.	Voacanga	*Voacanga africana*	8
35.	Medjanga medjagam	*Rauvolfia vomitoria*	12
36.	Assam	*Uapaca guineensis*	10
37.	Evoula	*Vitex doniana*	5
38.	Engogom	*Myrianthus arboreus*	5
39.	Zong kombe	*Solanum torvum*	7
40.	Avocado	*Persea americana*	10
TOTAL			450

3.2. Plant composition for each zone

A total of 1,046 seedlings were installed across the two zones, with 348 plants in zone A and 698 individuals in zone B, respectively (Table III).

Table III: Planting Characteristics

Parameters	Zone A	Zone B	Total
Area (m^2)	8924.72	15733	24,657.72
Number of Plants installed	348	698	1,046
NTFP/timber products ratio	40/60	40/60	40/60

The planting layout in both restoration sites (Zones A and B) is illustrated in Figure 8.

Figure 8: Display of holes on the various surface areas. (a) Zone A; (b) and (c) Zone B.

The zones are further illustrated using a standardized cartographic grid mapping system. These grids display homogeneous spacing for precise functional species distribution (Figure 9).

(a) Disposition of species planted in Zone A (red = NTFP; black = timber)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Eng	Ayo																						
2	Eba	Oko	Eko																					
3	Fra	Azo	Fro	Man	Zon																			
4	Poi	Oss	Poi	Oss	Nja	Pap	Poi																	
5	Ndo	Med	Oss	Fra	Fro	Eba	Oss	Oss	Zon															
6	Azo	Bit	Azo	Eba	Ayo	Oko	Pap	Moa	Oko	Atu														
7	Avo	Nja	Goy	Zon	Oko	Pap	Zon	Oko	Pap	Iro	Fro	Saf	Voa											
8	Azo	Moa	Med	Fro	Med	Zon	Oko	Eba	Oss	Ayo	Fra	Lot	Moa	Bet	Ayo	Saf	Man							
9	Ayo	Med	Saf	Tal	Pal	Eba	Fro	Fra	Iro	Eba	Zon	Aca	Ndo	Nja	Tal	Ass	Goy	Azo						
10	Pal	Pac	Lot	Sap	Ndo	Oko	Iro	Poi	Pap	Pal	Man	Eve	Fro	Azo	Lot	Eng	Atu	Avo						
11	Saf	Voa	Fra	Ass	Bet	Man	Moa	Ayo	Eba	Pal	Azo	Ayo	Ani	Bet	Aca	Eko	Moa	Pal	Med					
12	Bet	Med	Ndo	Saf	Atu	Iro	Aca	Ass	Ass	Oko	Eko	Lot	Med	Iro	Bit	Fra	Eve	Kot	Ass					
13	Eve	Fro	Man	Tal	Sap	Bet	Saf	Fra	Pac	Sap	Saf	Fra	Moa	Atu	Ayo	Voa	Ndo	Pac	Iro					
14	Tal	Eve	Lot	Lot	Ayo	Goy	Med	Iro	Avo	Fro	Pac	Nja	Bet	Eko	Saf	Moa	Fro	Oss	Bet	Azo				
15	Avo	Atu	Aca	Eko	Pac	Kot	Bit	Aca	Bet	Tal	Moa	Kot	Man	Voa	Fro	Lot	Tal	Pal	Man	Saf				
16	Man	Ass	Fra	Moa	Bet	Tal	Fra	Pal	Pac	Man	Pal	Saf	Bit	Tal	Ndo	Man	Med	Aca	Bit	Eko	Moa			
17	Ass	Med	Voa	Tal	Pal	Voa	Fro	Moa	Ayo	Lot	Ani	Iro	Nja	Ayo	Atu	Eko	Iro	Moa	Sap	Fra	Fro			
18	Bib	Pac	Bet	Lot	Saf	Avo	Aca	Pac	Azo	Pal	Pac	Goy	Bet	Ani	Bet	Moa	Evo	Tal	Ayo	Saf	Lot			
19	Ayo	Lot	Avo	Ayo	Fra	Fro	Eko	Man	Saf	Med	Tal	Fro	Tal	Pal	Bit	Fra	Bit	Avo	Bet	Fro	Sap	Azo		
20									Azo	Evo	Avo	Ndo	Voa	Iro	Lot	Man	Tal	Pac	Oko	Eng	Ani	Tal		
21										Kot	Eko	Bit	Lot	Sap	Eng	Ani	Kot	Lot	Man	Ani	Nja	Ndo		
22											Ayo	Pal	Fra	Pal	Saf	Ass	Atu	Ani	Azo	Ndo	Evo	Tal	Kot	Pal
23														Man	Azo	Aca	Ayo	Kot	Fro	Bit	Kot	Ani	Avo	Bet
24																Pal	Evo	Bet	Sap	Fra	Bet	Atu	Ayo	
25																			Ayo	Azo	Ass	Fro		
Number of plants Per line	19	19	18	17	17	16	16	15	16	16	16	16	16	16	16	17	17	16	15	12	10	7	3	2

LEGEND

NTFP SPECIES	Number planted
Uapaca guineensis (Ass)	9
Persea americana (Avo)	9
Garcinia cola (Bit)	9
Bridelia ferruginea (Eba)	7
Alstonia boonei (Eko)	9
Myrianthus arboreus (Eng)	4
Klainedoxa gabonensis (Eve)	4
Vitex doniana (Evo)	4
Psidium guajava (Goy)	4
Mangifera indica (Man)	14
Rauvolfia vomitoria (Med)	11
Ricinodendron heudelotti (Nja)	6
Irvingia gabonensis (Ndo)	9
Gnetum africanum (Oko)	9
Elaeis guineensis (Pal)	15
Carica papaya (Pap)	5
Piper sp. (Poi)	4
Dacryodes edulis (Saf)	14
Voacanga africana (Voa)	7
Solanum torvum (Zon)	6
TIMBER SPECIES	
Khaya ivorensis (Aca)	8
Aningeria altissima (Ani)	8
Triplochiton scleroxylon (Ayo)	18
Lophira alata (Azo)	14
Mansonia altissima (Bet)	16
Lovoa trichiliodes (Bib)	1
Piptadeniastrum africanum (Atu)	8
Eribroma oblongum (Eyo)	0
Terminalia superba (Fra)	15
Ceiba pentandra (Fro)	17
Pycnanthus angolensis (Ilo)	0
Milicia excelsa (Iro)	10
Pterygota macrocarpa (Kot)	8
Sterculia rhinopetala (Lot)	14
Baillonella toxisperma (Moa)	13
Morus mesozigia (Oss)	7
Afzelia pachyloba (Pac)	10
Pterocarpus soyauxii (Pad)	0
Entandrophragma cylindricum (Sap)	7
Erythrophleum ivorensis (Tal)	15
TOTAL	**348**

(b) Plant disposition in zone B (red = NTFP; black = timber product)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1										Moa	Fro	Sap	Voa	Fro	Fra	Fro	Azo											
2									Nja	Saf	Oko	Pal	Tal	Goy	Kot	Eba	poi	Sap										
3									Ayo	Tal	Bet	Atu	Man	Pac	Ayo	Iro	Lot	Avo	Ayo	Bib								
4								Man	Iro	Pap	Fra	Eko	Aca	Poi	Iro	Fra	Man	Pac	Fro	Iro	Fro							
5							Fro	Bib	Eng	Sap	Eba	Fro	Eyo	Pad	Bib	Bib	Azo	Eve	Bet	Oss	Iro	Pad						
6						Ayo	Med	Eko	Bet	Eve	Lot	zon	Moa	Sap	Bet	Saf	Pac	Eyo	Atu	Bib	Azo	Man						
7					Med	Goy	Iro	Kot	Voa	Lot	Oss	Tal	Bib	Pal	Med	Ani	Aca	Lot	Zon	Aca	Fra	Tal						
8					Azo	Moa	Ndo	Tal	Iro	Pal	Eko	Fro	Ndo	Evo	Tal	Ndo	Bib	Pad	Atu	Voa	Eba	Pal						
9					Avo	Bit	Eyo	Fra	Saf	Atu	Bet	Saf	Ayo	Kot	Avo	Pap	Atu	Azo	Saf	Ndo	Bet	Bib	Iro	Saf				
10				Bet	Eng	Oss	Fro	Oko	Azo	Poi	Pap	Zon	Man	Bit	Eba	Ayo	Bib	Ayo	Azo	Tal	Atu	Oss	Ayo	Fro				
11				Man	Nja	Evo	Pal	Fra	Man	Iro	Tal	Eba	Moa	Bet	Ani	Man	Eyo	Man	Eng	Pac	Eyo	Oko	Fra	Avo				
12			Eve	Fro	Azo	Atu	Kot	Eko	Ayo	Ani	Oko	Fra	Nja	Pal	Pal	Fra	Bit	Oss	Pal	Aca	Moa	Ani	Moa	Bib	Bet			
13			Moa	Eba	Lot	Med	Goy	Pac	Zon	Bit	Saf	Pac	Pad	Avo	Ayo	Pad	Moa	Ndo	Voa	Eyo	Pap	Azo	Fro	Pap	Pal			
14		Ani	Iro	Pad	Oko	Fra	Ayo	Avo	Eyo	Lot	Aca	Med	Bet	Tal	Eyo	Saf	Oko	Iro	Fra	Lot	Nja	Pac	Man	Aca	Bet	Pad		
15		Ndo	Eyo	Pal	Sap	Zon	Med	Fro	Bit	Saf	Goy	Moa	Lot	Eko	Pap	Pad	Atu	Kot	Ani	Azo	Azo	Med	Ndo	Ayo	Bit	Lot		
16		Tal	Goy	Iro	Pap	Pac	Tal	Oss	Oko	Bib	Ayo	Oko	Saf	Ayo	Evo	Voa	Bet	Eko	Sap	Pac	Avo	Man	Lot	Voa	Ani	Eko		
17		Kot	Lot	Saf	Bib	Med	Pal	Zon	Fra	Man	Saf	Med	Pal	Aca	Iro	Lot	Sap	Eyo	Man	Bit	Ndo	Fro	Fra	Ani	Ndo	Bet	Man	
18		Aca	Eko	Oss	Man	Pal	Eyo	Lot	Eve	Moa	Iro	Evo	Eyo	Bit	Eko	Iro	Ayo	Bit	Iro	Tal	Ayo	Saf	Poi	Eng	Eyo	Saf	Moa	
19		Pap	Bet	Voa	Bet	Bit	Saf	Eng	Fro	Fra	Ilo	Tal	Voa	Sap	Avo	Kot	Iro	Fro	Lot	Ilo	Lot	Iro	Kot	Bib	Eyo	Pap	Fro	
20		Oss	Sap	Eba	Ass	Pad	Zon	Bib	Bet	Iro	Pal	Ass	Bet	Man	Bet	Med	Tal	Moa	Oko	Moa	Eyo	Aca	Fro	Bet	Pal	Ayo	Fra	
21		Zon	Pad	Eve	Eyo	Fra	Pac	Ilo	Ayo	Pad	Moa	Fra	Fro	Eko	Voa	Eko	Aca	Iro	Fro	Lot	Med	Fra	Tal	Fra	Ilo	Sap	Pad	
22		Bet	Bit	Tal	Ndo	Fro	Avo	Aca	Saf	Bib	Oko	Tal	Atu	Pal	Bit	Moa	Bib	Atu	Kot	Ani	Azo	Oss	Moa	Lot	Avo	Fra	Ilo	Sap
23		Eko	Ani	Eng	Bet	Eyo	Eve	Lot	Azo	Med	Ilo	Ass	Bib	Pad	Iro	Iro	Man	Eng	Tal	Eko	Avo	Med	Ndo	Pap	Bet	Eve	Eyo	
24		Atu	Oko	Evo	Saf	Pal	Fra	Sap	Eyo	Oss	Eng	Kot	Evo	Goy	Fra	Ndo	Lot	Pal	Iro	Oss	Pap	Ayo	Fra	Saf	Aca	Lot	Bet	
25		Nja	Kot	Aca	Eyo	Sap	Kot	Moa	Man	Atu	Voa	Saf	Ayo	Lot	Evo	Bib	Avo	Ayo	Ani	Ayo	Moa	Kot	Man	Eyo	Bet	Tal		
26	Moa	Azo	Pac	Oss	Zon	Pad	Nja	Fro	Poi	Bet	Pac	Tal	Kot	Oko	Bib	Moa	Ani	Pap	Azo	Ass	Voa	Bit	Ass	Iro	Eve	Zon		
27	Avo	Pal	Saf	Iro	Fro	Nja	Azo	Ayo	Pal	Man	Goy	Med	Avo	Tal	Bet	Oss	Iro	Pad	Oko	Aca	Sap	Med	Lot	Bet	Moa			
28	Ayo	Tal	Fro	Ndo	Ani	Bib	Bit	Zon	Nja	Evo	Nja	Azo	Aca	Fro	Tal	Tal	Goy	Bib	Ayo	Eko	Saf	Fro	Bit	Oko	Eba			
29	Med	Eba	Poi	Moa	Saf	Oss	Ani	Iro	Saf	Pad	Fro	Med	Poi	Med	Lot	Eng	Voa	Evo	Pal	Lot	Kot	Ndo	Iro	Pac				
30	Azo	Lot	Avo	Eyo	Pac	Ayo	Ndo	Ass	Avo	Lot	Azo	Pal	Eko	Evo	Avo	Ayo	Oko	Iro	Fro	Iro	Fra	Bet	Man	Tal				
31	Fro	Man	Pac	Med	Ayo	Eko	Atu	Pac	Eko	Iro	Voa	Man	Saf	Pap	Lot	Evo	Fro	Fro	Med	Eko	Eba	Pac	Eba	Fra				
32	Pal	Ayo	Fra	Azo	Pal	Pac	Ayo	Azo	Pap	Poi	Ndo	Atu	Azo	Goy	Pal	Eba	Man	Eba	Pap									
33												Iro																
Number of plants per line	*7*	*19*	*21*	*23*	*26*	*27*	*28*	*29*	*31*	*32*	*32*	*33*	*32*	*32*	*32*	*32*	*32*	*31*	*30*	*29*	*28*	*27*	*23*	*23*	*17*	*13*	*8*	*1*

LEGEND

NTFP Species	Planted phase a	Planted phase b	total
Uapaca guineensis (Ass)	6	0	6
Persea americana (Avo)	7	10	17
Garcinia cola (Bit)	6	10	16
Bridelia ferruginea (Eba)	5	8	13
Alstonia boonei (Eko)	7	10	17
Myrianthus arboreus (Eng)	4	5	9
Klainedoxa gabonensis (Eve)	3	5	8
Vitex doniana (Evo)	6	5	11
Psidium guajava (Goy)	4	5	9
Mangifera indica (Man)	9	15	24
Rauvolfia vomitoria (Med)	8	12	20
Ricinodendron heudelotti (Nja)	4	5	9
Irvingia gabonensis (Ndo)	6	10	16
Gnetum africanum (Oko)	6	10	16
Elaeis guineensis (Pal)	10	15	25
Carica papaya (Pap)	6	10	16
Piper sp. (Poi)	3	5	8
Dacryodes edulis (Saf)	9	15	24
Voacanga africana (Voa)	5	8	13
Solanum torvum (Zon)	4	7	11
Timber species			
Khaya ivorensis (Aca)	6	9	15
Aningeria altissima (Ani)	5	9	14
Triplochiton scleroxylon (Ayo)	11	19	30
Lophira alata (Azo)	8	14	22
Mansonia altissima (Bet)	10	16	26
Lovoa trichilioides (Bib)	8	14	22
Piptadeniastrum africanum (Atu)	5	9	14
Eribroma oblongum (Eyo)	8	14	22
Terminalia superba (Fra)	11	16	27
Ceiba pentandra (Fro)	11	19	30
Pycnanthus angolensis (Ilo)	6	0	6
Milicia excelsa (Iro)	14	18	32
Pterygota macrocarpa (Kot)	5	9	14
Sterculia rhinopetala (Lot)	11	16	27
Baillonella toxisperma (Moa)	8	14	22
Morus mesozigia (Oss)	5	9	14
Afzelia pachyloba (Pac)	6	11	17
Pterocarpus soyauxii (Pad)	6	9	15
Entandrophragma cylindricum (Sap)	6	9	15
Erythrophleum ivorensis (Tal)	10	16	26
TOTAL	278	420	698

Figure 9: Planting grids of (a) zone A and (b) zone B

3.3. Physical parameters of Zones A and B

Table IV indicates major differences in the two study zones that influenced plant growth. Parameters such as poor soil stability led to erosion effects, and the absence of rainfall during the dry season, as planting had been scheduled during that period; however, the plants were watered twice weekly.

Table IV: Differences in Physical parameters between Zone A and B

Physical Parameters	Zone A	Zone B
Planting month	November 2023	April 2025
Planting season	Dry season	Short rainy season
Soil stability	Good	Poor due to Steep slope
Age of plantation	12 months	7 months

3.4. Plant performance at various sites

During the monitoring phase, it was observed that 84.7% of the 1046 seedlings planted were fully developed and only 15.3% were lost (Table V) due partly to soil erosion during the rainy season in certain areas of Zone B and harsh climatic conditions like dryness in Zone A during the dry season.

Table V: Survival and mortality rates of plants in Zone A and B

Characteristics	Zone A	Zone B	Combined effect
Number of plants installed	348	698	1,046
Number desiccated, eroded or missing	75	85	160
% mortality	21.6	12.2	15.3
% survival	78.4	87.8	84.7

With regards to vegetation cover and site physiognomy, at the time of completion of this study, both zones displayed a dense, evolutive plant community with some dominant species such as *Ricinodendron heudelotii* (Baill.) Pierre ex Heckel, *Ceiba pentandra* (L.) Gaertn. and *Triplochiton scleroxylon* K. Shum forming an early-phase forest structure. Figure 10 demonstrates the re-establishment of vegetative cover on the study areas.

Figure 10: Growing vegetation cover (a) at six months; (b) after 12 months in zone A; (c) at two months and d) after 12 months in zone B

3.5. Plant growth rate and early phenology

Within 12 months of monitoring, several species were found between 1.5–2.0m high. Figure 11 illustrates the height of some dominant plants (*Ricinodendron heudelotii*, *Ceiba pentandra* and *Triplochiton scleroxylon,* respectively) based on human references selected between 1.63 and 1.75 m tall.

Figure 11: Plant heights measured approximately based on human heights: (a*) R. heudelotii,* (b) *C. pentandra, and* (c) *T. scleroxylon, respectively.*

Certain species such as *Solanum torvum* Sw. and *Carica papaya* L. were already at their fructification stage (Figure 12), thus illustrating the capacity of the rehabilitated zone to offer the ecosystemic services aimed for.

Figure 12: Ongoing fructification of some species (a.) *Solanum torvum* and (b.) *Carica papaya*

3.1. Constraints and management of vegetation cover

Some hindering factors, such as soil erosion during the rainy season (Figure 13), high temperatures on bare soil, and the strong wind blowing on the sloppy landscape, were observed to inhibit normal growth of some plant individuals and hence became enabling factors for increased plant mortality rates. This phenomenon was more accentuated in zone B with steeper slopes. Additional measures such as the use of more topsoil to reshape and refill eroded areas and replacing lost plants were carried out.

Figure 13: Visible erosion effect on restored sites: (a) in zone A and (b) in zone B

4. DISCUSSION

The degraded concrete waste zones at the Nachtigal Dam construction site in Ndokoa, Cameroon, causing significant visual pollution, are now transformed into a plantation forestry using wood and sustainable practices for carbon sequestration; thus turning the old built infrastructural environment into a carbon sink. Plantation forestry generally refers to cultivated forest ecosystems established through planting or seeding of native or introduced species during the afforestation or reforestation process (FAO 2001; West 2014; Nghiem and Tran 2016). This plantation forestry is very useful for the economy, ecology, and society. Planted forests are known to play a vital role in conserving natural forests by relieving deforestation, improving and restoring degraded lands, sequestering carbon dioxide and fighting climate change (Paquette and Messier 2010; Pawson *et al*. 2013). Such plantations can be used for regulating the water cycle, reducing soil erosion and alleviating desertification (Bauhus *et al*. 2010). However, the knowledge and engagement of local communities (Ndji and Ndokoa, 2022) improved the management, implementation, and monitoring of the habitat restoration; thus, effective land restoration requires integrated scientific and local knowledge.

The engineered 130 cm depth of soil system established on a concrete waste dome at the Nachtigal Dam construction site proved to be highly effective for plant growth. A strong correlation has been observed between healthy plant responses (survival rates, plant height, leaf number, biomass production) and improved soil pore water parameters, highlighting the benefits of waste amendments; similar observations were carried out by Fernandez-Landero *et al*. (2024). With an over 80% survival rate, the engineered soil seems to portray a high level of effectiveness on plant performance. In many restoration projects, compacted substrates or concrete slabs are mechanically fragmented, scarified, or perforated to enhance infiltration and permit shallower soil reconstruction, as demonstrated by Löf *et al*. (2012) in their work on mechanical site preparation. Regrettably, at the Nachtigal site, the concrete dome was exceptionally dense, thick, and spatially extensive, making fragmentation technically unfeasible and operationally impractical. Breaking this structure would have required heavy demolition work and still would not have yielded an ecologically functional rooting layer. Thus, unlike standard restoration sites where fragmentation of the substrate is feasible (Löf *et al*. 2012), the Nachtigal concrete dome required soil capping due to its high density and level of thickness, and therefore a specific methodological approach for plant restoration was applied and proved effective.

Because mechanical fragmentation was impossible, a deep soil-capping strategy was adopted to provide adequate rooting depth, drainage, and topsoil fertility to plants. This approach aligns more closely with landfill-capping and mining-spoil remediation techniques, where reconstructed soil systems are installed over impermeable substrates as described by Fernández-Caliani *et al*. (2024) and further supported by restoration principles outlined by Brancalion and Holl (2020). Additionally, the application of thick engineered soil layers over sealed or compacted substrates is consistent with geo-environmental engineering practices, where soil covers are designed to ensure drainage, rooting capacity, and substrate stability above impervious waste layers (Liu *et al*. 2018).

The 5 m × 4 m spacing, the plant density, and mixed-species layout support rapid canopy development and functionality within a year of maintenance. Moreover, the presence of both species producing NTFP's and timber plants known and used by the local communities ensures the production of ecosystemic services that can enhance local inclusion in conservation of the developing forest resource. Furthermore, mixed-species plantations as carried out in Zones A and B are widely recognized for improving ecological resilience, productivity and functional diversity in restoration contexts (Paquette and Messier, 2010). The plantations are diverse in genotypes, species, structures and functions, and are acclaimed as more environmentally friendly and sustainable plantation systems than monocultures, especially in the case of mixing indigenous species (Manson *et al*. 2013). Also, intercropping tree species provides a tool for both restoring fertility and improving soil quality (Danise *et al*. 2021).

Plant desiccation was mostly observed in zone A, as the species were planted during the dry season but had early watering to reduce the effect. Though each zone presented operational setbacks, irrigation of zone A required maximizing water-use efficiency to support plants during the water-scarce period; zone B benefited from rainfall but faced stronger erosion due to slope steepness, and both evolved similarly considering vegetation cover and survival rates, indicating the method's adaptability. It is known that smart irrigation practices can improve water management and provide sufficient moisture for normal plant growth, especially during critical stages (Nangia *et al*. 2018; Ahmed *et al*. 2023).

Invasive species such as *Mimosa diplotricha and Centrosema pubescens* were often attached and strangling the planted seedlings, causing some changes in the ecosystems. Authors like Shuvar (2021) and Rai & Singh (2020) observed mass migration of plants, especially invasive species, leading to major drivers of biodiversity loss, thereby altering the ecosystem services and socio-economic conditions. The introduction of invasive alien plants in natural ecosystems represents the second largest threat to the loss of biodiversity of the planet, followed by loss of habitats due to human action (Alafi *et al*. 2025). However, this invasion phenomenon was controlled in both zones A and B by ensuring frequent weeding around the plants following a well-elaborated maintenance rhythm. The most common methods to control invasive alien plants involved explaining their viability and limitations in addition to compiling the risks and opportunities associated with the various strategies (Lorenzo and Morais 2023).

The study shows that the rehabilitation of an extensive portion of a degraded concrete waste zone can be successful while minimizing impacts on plant regeneration dynamics. Here, about 24,657.72 m² of degraded concrete was reforested, where it is once again a healthy, functioning, and self-sustaining ecosystem. It goes beyond just planting trees; the young forest supports biodiversity, improves soil health, and provides environmental benefits. Moreover, limited constraint due to species representability is observed, as there were over 1,000 mixed-species trees established on the engineered soil caps and all demonstrating good growth with an overall survival rate of over 85%; therefore, replicable across large-scale construction sites.

5. CONCLUSION

The restoration of Zones A and B at the Nachtigal construction site demonstrates that severely degraded concrete waste surfaces can be successfully rehabilitated using a deep engineered soil profile and a structured mixed-species planting design. Despite the inability to fragment the dense concrete substrate, 1.30 cm of soil system provided sufficient rooting depth and water retention for plant growth, enabling the establishment of 1,046 seedlings across 24,657.72 m². A survival rate above 85% along with rapid vegetation cover and early functional recovery confirm the effectiveness of the approach, with localised erosion and dry-season stress manageable through targeted maintenance. The results show that, under appropriate design and management, engineered soil capping combined with mixed species composition can rapidly transform inert waste domes into stable, regenerating forest plots. This programme provides a practical and replicable model for ecological restoration on concrete waste platforms in large tropical infrastructure projects.

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