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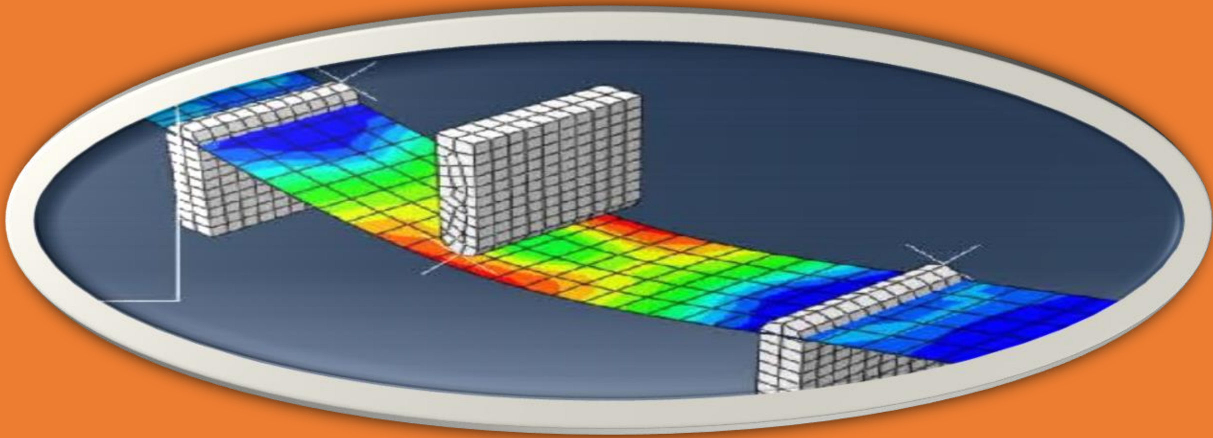

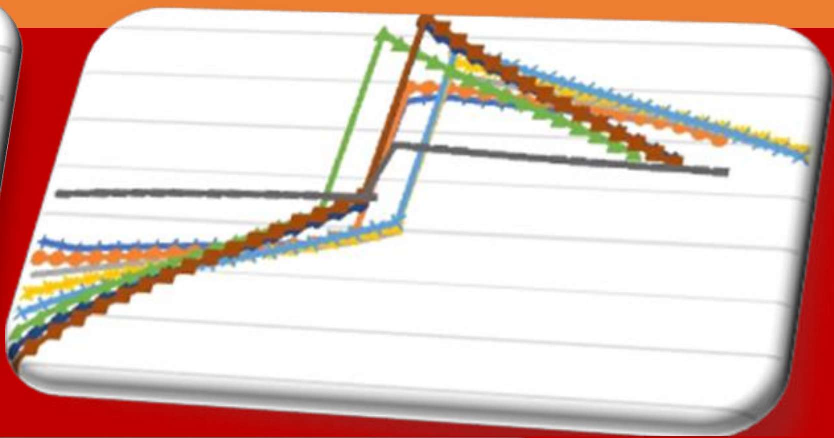

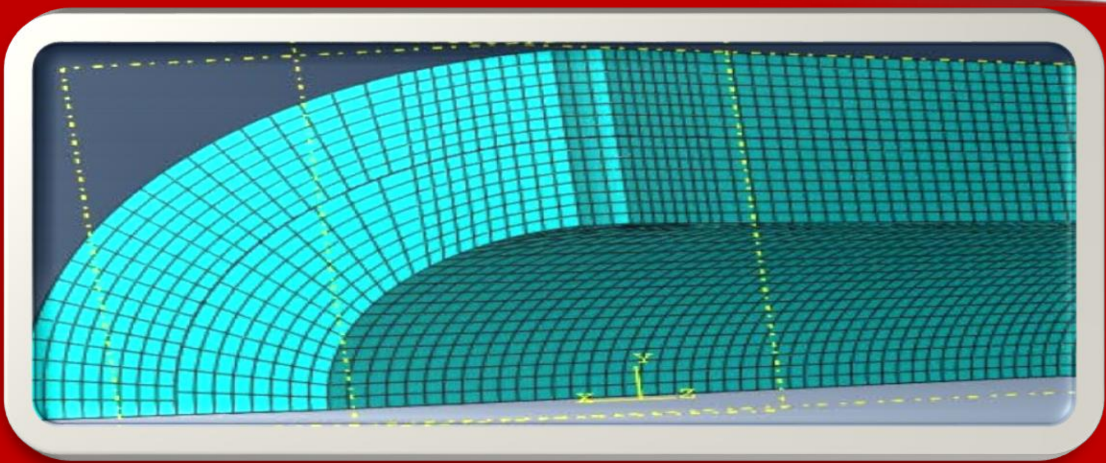

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Evaluating Shear Properties and Structural Performance of Custom I-shaped Engineered Timber for Sustainable Construction

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Abstract

The construction industry faces significant environmental challenges, particularly from resource depletion and waste generation. In response, engineered timber, specifically Cross Laminated Timber (CLT), has emerged as a sustainable alternative construction material. CLT, made from layers of wood planks arranged crosswise, offers exceptional strength and stability for various applications, including mass timber buildings. However, CLT is prone to shear failure, especially in complex structures. This research investigates the potential of custom I-shaped CLT panels to mitigate shear issues in floor construction. The study establishes the shear properties of standard block configurations and evaluates the shear characteristics of newly developed custom I-shaped panels. It compares the structural performance of eucalyptus and grevillea wood species in these engineered panels. Laboratory tests focused on shear and bending strength, utilizing properly seasoned timber while excluding tree age considerations prior to logging. Key findings reveal that I-Section eucalyptus panels exhibit a 20.46% higher Modulus of Elasticity (MOE) and a 26.61% higher Modulus of Rupture (MOR) than I-Section grevillea panels, indicating increased stiffness and load-bearing capacity. Eucalyptus also shows 7.1% greater shear strength than grevillea, making it suitable for applications requiring enhanced shear resistance. However, grevillea offers better compression strength and hardness for specific construction scenarios. Overall, custom I-shaped panels significantly improve shear resistance compared to standard block configurations, reducing the risk of shear failure in CLT-based structures.

Keywords: Cross Laminated Timber (CLT), Shear resistance, Eucalyptus, Grevillea, Modulus of Elasticity (MOE), Modulus of Rupture (MOR).

1. Introduction

Cross Laminated Timber (CLT) is an engineered wood product constructed by bonding multiple layers of timber boards at right angles. It is increasingly favored for its strength, sustainability, and ability to replace traditional building materials like steel and concrete. CLT is environmentally friendly, as it utilizes renewable resources and reduces carbon emissions (Barbhuiya, 2023). These factors align with the growing demand for eco-conscious construction practices. CLT is used in walls, floors, and entire building structures, and its large panels enable efficient, rapid construction. This reduces labor costs and time, making it an attractive solution for modern construction projects (Bechert et al., 2021).

The strength and performance of CLT are key reasons for its growing use in tall buildings and complex architectural designs. For instance, the Brock Commons Tallwood House in Canada and the Mjøstårnet in Norway, two of the tallest timber structures globally, demonstrate the structural versatility and potential of CLT. These buildings highlight CLT's high strength-to-weight ratio and the ability to integrate CLT elements with concrete and steel for enhanced performance (Ilgin& Karjalainen, 2022)

2. Literature Review

Shear failure in CLT structures is a significant challenge. Shear forces, particularly out-of-plane, can cause excessive deflection and rolling shear failure, compromising the structure's integrity (Ayanleye et al., 2022). Poor installation practices, inadequate panel connections, and exceeding design loads exacerbate this issue. In the absence of standardized design codes tailored to CLT, engineers must adapt existing codes, often overlooking CLT's unique characteristics (Aloisio et al., 2022).

Research has expanded to study factors such as adhesive type, panel thickness, and boundary conditions that affect CLT's shear properties. By optimizing these factors, CLT can better resist shear forces, reducing the risk of failure (Angelucci et al., 2022). Shear failure is particularly concerning in CLT due to wood's orthotropic nature, meaning its properties vary along its three axes: longitudinal, tangential, and radial (Johansson, 2016). Understanding these properties is crucial when designing structures to withstand shear stress, especially as wood exhibits a viscoelastic nature, combining elastic and plastic behaviors.

Custom structural panels, especially I-shaped CLT panels, offer an innovative solution to the shear failure issue. Engineers design these custom shapes to optimize load distribution and improve shear resistance, akin to pre-engineered steel sections. The slenderness of the flange and web in these sections plays a crucial role in improving shear resistance and stability (Qureshi, 2018). Custom-shaped timber elements not only enhance structural efficiency but also contribute to sustainability by reducing material usage and carbon emissions (Shuttleworth, 2023).

Beyond structural benefits, custom CLT panels allow for greater design flexibility, offering architects the opportunity to create visually appealing and innovative designs (Monarch et al., 2020). These panels align with sustainable building practices, as their manufacturing process is energy-efficient compared to concrete and steel. The responsible sourcing of timber for CLT ensures adherence to sustainable forest management principles, preserving ecosystems and reducing the environmental impact (Jensen & Craig, 2019).

CLT's environmental benefits extend beyond construction, as its energy-efficient manufacturing reduces emissions during production and transportation. Additionally, CLT structures inherently generate less onsite waste than traditional materials (Ding et al., 2022). The long-term durability of CLT, especially when customized for specific environmental conditions, minimizes the need for replacements, further reducing environmental impact (Pierobon et al., 2019).

Despite CLT's advantages, the construction industry faces a research gap in addressing shear failure, especially in complex buildings. While existing research has primarily focused on standard CLT block configurations, little attention has been given to the development of custom I-shaped sections. These sections hold promise for enhancing shear resistance and structural integrity, especially in floor constructions, by redistributing and efficiently transferring shear forces. Developing innovative solutions to counteract shear deformation can significantly improve the safety and longevity of CLT-based structures (Mayencourt& Mueller, 2020.

3. Methodology

3.1. Material sourcing

Eucalyptus and Grevillea timber were sourced from Gikomba Market. Structural timber sections, including block and I-sections, were assembled using Polyvinyl Acetate adhesives, which are widely available in the Kenyan market

3.2. Experimental Program

Experimental analysis of structural timber sections of block and I-sections using Polyvinyl Acetate adhesives on Eucalyptus and Grevillea were performed. Timber was inspected for defects, cut into segments, and strategically laminated with adhesive applied both along and across the grain. The laminated elements were tightly bound with manila string and subjected to cold pressing at room temperature, applying 200 tons of top force and 100 tons of side force. After overnight curing, the laminated sections were tested according to BS EN 384:2016+A2:2022 and BS EN 408:2010+A1:2012 for structural timber and glued laminated timber.The various samples sizes for testing are as shown in figure 3.1.

Figure 3.1. Samples sizes for testing

3.3. Laboratory Tests

Compression tests were performed with standard specimens (2 cm x 2 cm x 6 cm) parallel to the grain per BS EN 384:2016+A2:2022, loading at 0.025 in/min until failure to determine compressive strength.

Compression tests perpendicular to the grain applied loads between parallel plates in radial and tangential directions, also at 0.025 in/min, recording maximum load and strain at 0.1 in. Shear tests followed BS EN 408:2010+A1:2012 using 2 cm cubes, loading at 0.025 in/min until failure. For Static bending tests as shown in figure 3.2, specimens (2 cm x 2 cm x 30 cm) underwent central loading at 0.26 in/min per BS EN 408:2010+A1:2012, measuring mid-length deflection until failure. Janka hardness tests assessed workability using 10 cm x 2 cm x 2 cm specimens, loading at 0.025 in/min until failure. Lastly, moisture content tests adhered to BS

EN 13183-1, where timber weights were recorded before and after 24-hour oven drying to calculate moisture content as a percentage difference, ensuring optimal machining and strong glue joints.

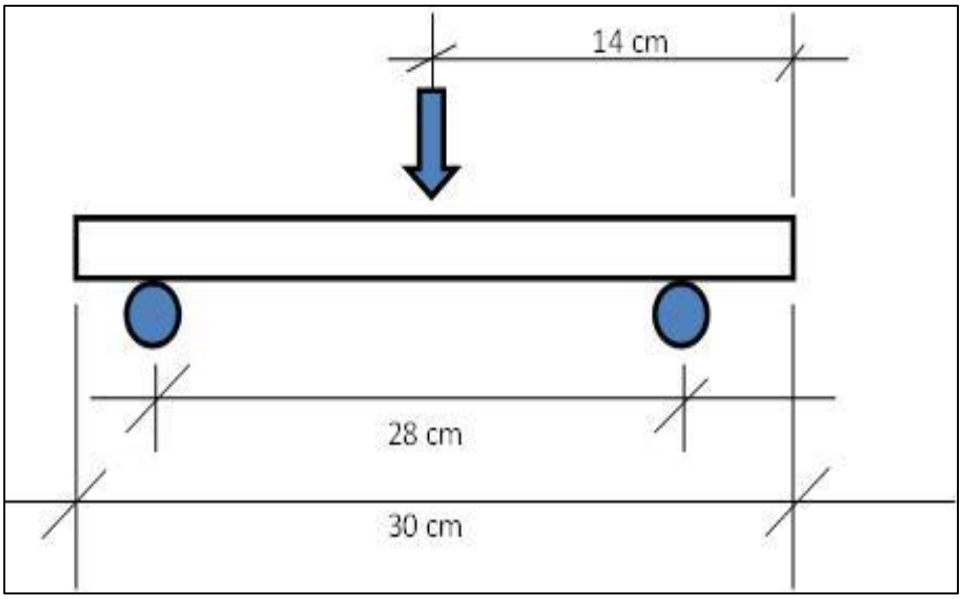

Figure 3.6: Static bending test setup dimensions

4. Results, Analysis and Discussion

4.1. Results

The results presented in table 3.1 highlights the engineering properties of eucalyptus and grevillea timber, comparing their performance in normal, block CLT, and I-section forms.

Table 3.1. Summary of Mechanical Properties of Timber Samples

SUMMARY	MOE (N/mm²)	MOR (N/mm²)	Compression strength (N/mm²)	Density (g/cm³)	MC %	Shear strength (Mpa)	Average Hardness
Normal Grevillea	4,825.47	16.17	30.59	0.54	34.78	18.65	2.56
Normal Eucalyptus	6,123.18	23.09	30.92	0.62	40.31	22.00	4.04
Block CLT Grevillea	3540.26	10.76	18.55	0.54	23.92	14.02	2.54
Block CLT Eucalyptus	4365.71	16.97	25.2051	0.66	20.74	16.63	4.5
I-Section Grevillea	39,921.75	119.63	68.55	0.67	6.53	49.34	4.99
I-Section Eucalyptus	68,081.67	151.47	40.78	0.29	63.47	63.78	3.94

Eucalyptus consistently outperforms grevillea in terms of density, compressive strength, flexural strength (MOR), modulus of elasticity (MOE), and Janka hardness. I-section specimens exhibit the highest values in MOE, MOR, compressive strength, and shear strength, indicating superior load-bearing capacity emerging as the most promising for construction use due to its enhanced strength and stiffness. The Static bending and the overall performance metrics of various specimen is as shown in figure 4.1 and 4.2 respectively.

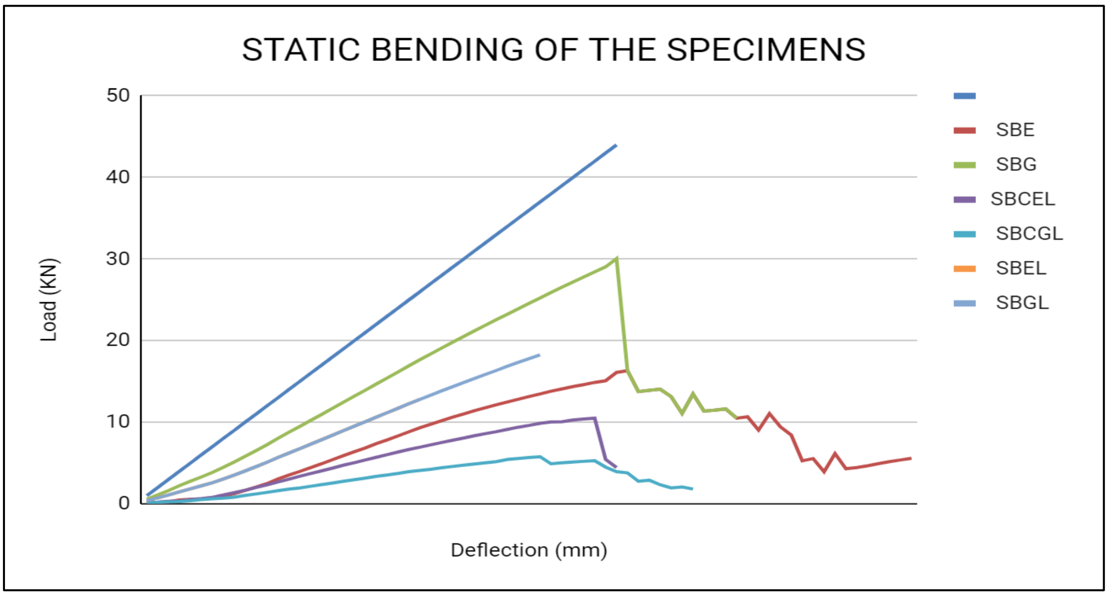

Figure 4.1: Static bending of various specimen

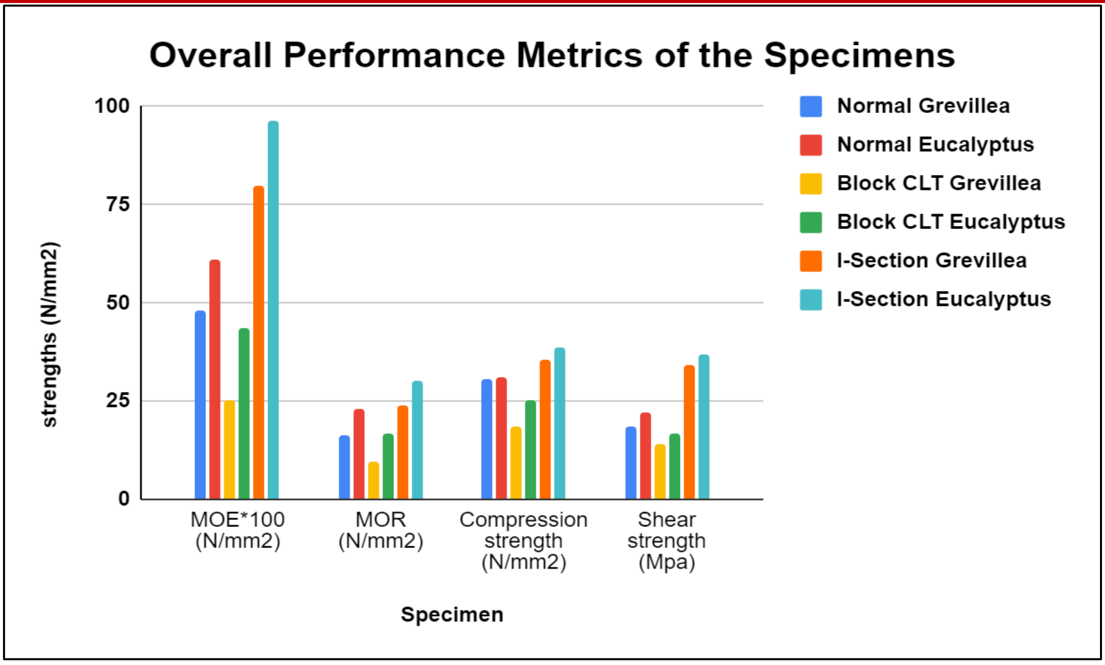

Figure 4.2: Specimen Overall Performance Metrics

4.2. Discussion

4.2.1. Engineering Properties of Normal Timber

The investigation into the engineering properties of eucalyptus and grevillea timber provides vital insights into their construction suitability, particularly for structural applications like floors and walls. Eucalyptus has a higher density (0.62 g/cm³) than grevillea (0.54 g/cm³), suggesting greater strength and making it preferable for load-bearing applications. Both species show similar compressive strengths, with eucalyptus at 30.92 N/mm² and grevillea at 30.59 N/mm². However, eucalyptus significantly surpasses grevillea in flexural strength, indicated by its Modulus of Rupture (MOR) of 23.09 N/mm² compared to grevillea's 16.17 N/mm², making it more suitable for resisting bending forces in structural elements like beams and joists. The Modulus of Elasticity (MOE) further emphasizes eucalyptus's advantages, as it is stiffer with a MOE of 6123.18 N/mm² versus grevillea's 4825.47 N/mm², indicating greater resistance to deformation under load. Eucalyptus also exhibits higher hardness (4.04 N) compared to grevillea (2.56 N), enhancing its durability for frequently used surfaces. In shear strength, eucalyptus outperforms grevillea (22.00 MPa vs. 18.65 MPa), underscoring its suitability for applications with significant shear forces, such as connections and joints. Despite these strengths, both species have high moisture content (20.16% for eucalyptus and 17.39% for grevillea), which can adversely affect mechanical properties and dimensional stability, highlighting the importance of effective drying and treatment processes.

4.2.2. Shear Properties in Standard Block CLT Panels

The shear strength values for both Grevillea and Eucalyptus are notably lower than their Modulus of Elasticity (MOE), Modulus of Rupture (MOR), and compressive strength, indicating a relative weakness in resisting shear forces despite their strengths in bending, stiffness, and compression. Specifically, Block CLT Eucalyptus has shear strength of 16.63 MPa, while Block CLT Grevillea shows a strength of 14.02 MPa. Eucalyptus's shear strength is approximately 29.33% higher than that of Grevillea, making it a better choice for applications where shear resistance is critical. However, the lower shear strength of these CLT panels necessitates careful consideration in engineering applications, particularly in areas where shear forces are predominant. This may involve using alternative materials with higher shear resistance to maintain structural integrity. Engineers must design structures with these shear properties in mind, ensuring that CLT panels are configured to minimize exposure to excessive shear forces. Although both Grevillea and Eucalyptus CLT panels exhibit strong mechanical properties in stiffness, bending, and compression, their lower shear strength underscores the importance of careful consideration in structural applications.

4.2.3. Shear Strength in Custom I-Shaped Laminated Panels

The development of custom I-shaped laminated panels aimed to enhance mechanical properties beyond those achievable with standard block configurations. The evaluation of these custom panels revealed significant improvements in shear properties. The I-shaped laminated panels demonstrated remarkable shear strength compared to their standard block counterparts. I-Section Eucalyptus exhibited shear strength of 36.78 MPa, while I-Section Grevillea showed 34.34 MPa shear strength. When compared to the standard Block CLT panels, the shear strength of I-Section panels significantly increased, as detailed in Table 4.2.

Table 4.2: Percentage increase Shear strength

Shear strength (Mpa)	**Block CLT**	**I-Section**	**% increase**
Grevillea	14.02	34.34	144.96%
Eucalyptus	16.63	36.78	121.14%

The substantial improvement highlights the effectiveness of the I-shaped design in enhancing the shear properties of CLT panels. The I-shaped configuration likely provides better distribution of shear forces and improved resistance to sliding failures, making it an excellent choice for applications demanding higher shear performance.

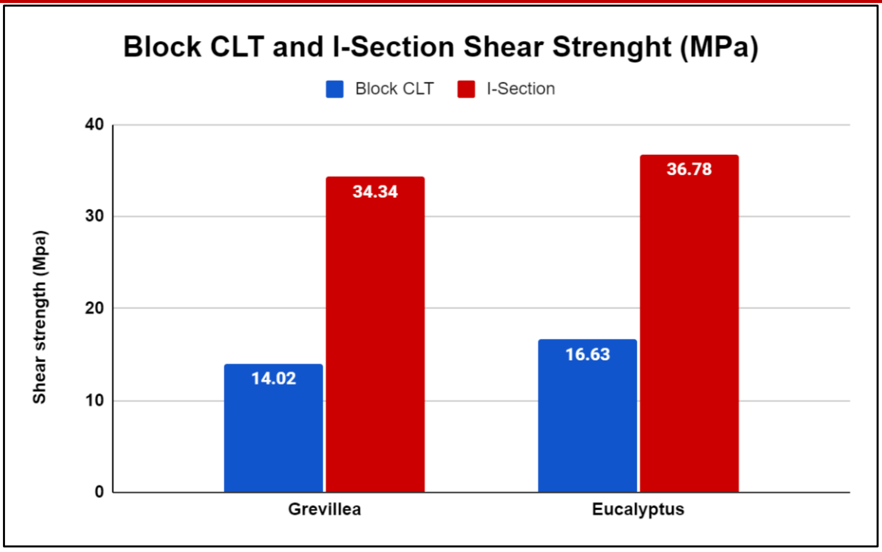

Figure 4.2: Shear strength of Block CLT and I-Section

As illustrated in Figure 4.2, I-sections exhibit higher shear strength compared to ordinary block configurations due to their optimized structural design. The geometry of the I-section significantly increases the moment of inertia, efficiently distributing material away from the neutral axis to enhance overall strength and stiffness. The I-shape effectively places material where it is most needed, providing greater resistance to shear and bending forces with minimal material use. The horizontal flanges at the top and bottom of the I-section resist bending moments and distribute loads more evenly, while the vertical web connects the flanges and handles shear stress. This design ensures even load distribution, reducing stress concentrations and the risk of shear failure. In conclusion, I-sections offer a higher strength-to-weight ratio, supporting more load without a proportional increase in material usage, thereby enhancing structural efficiency and stability. The I-section's design inherently provides higher shear strength due to its optimized geometry, efficient material distribution, and ability to distribute loads evenly. These factors contribute to the enhanced structural performance of I-sections compared to ordinary block configurations.

4.2.4. Comparing the Structural Performance of Eucalyptus and Grevillea Wood Species in Custom I-Shaped Engineered Timber Panels

The structural performance analysis, as shown in Table 4.3 and Figure 4.3, indicates that I-Section Eucalyptus panels outperformed I-Section Grevillea panels in key areas. Eucalyptus exhibited a 20.46% higher Modulus of Elasticity (MOE) (96.16 N/mm^2) and a 26.61% superior Modulus of Rupture (MOR) (30.29 N/mm^2), highlighting its increased stiffness and load-bearing capacity. This enhanced performance can be attributed to Eucalyptus's denser cellular structure, which typically contributes to greater strength and rigidity compared to Grevillea.

Eucalyptus demonstrated a 7.1% greater shear strength (36.78 MPa) compared to Grevillea (34.34 MPa), indicating better resistance to sliding forces. However, Eucalyptus had a 15.92% higher moisture content (20.16% vs. 17.39%), which may affect its mechanical properties in moisture-sensitive applications. In contrast, Grevillea excelled in compression strength, showing 9.11% higher strength (35.55 N/mm² vs. 38.78 N/mm² for Eucalyptus), and was 26.58% harder (4.99 compared to 3.94). While Eucalyptus is denser (0.62 g/cm³ vs. 0.54 g/cm³ for Grevillea).

Table 4.3: Comparison of Eucalyptus and Grevillea I-Sections

Property	Comparison
MOE	Eucalyptus is 20.46% better
MOR	Eucalyptus is 26.61% better
Compression Strength	Eucalyptus is 9.11% better
Density	Eucalyptus is 14.81% denser
Moisture Content	Eucalyptus has 15.92% higher moisture content
Shear Strength	Eucalyptus is 7.1% better
Average Hardness	Grevillea is 26.58% harder

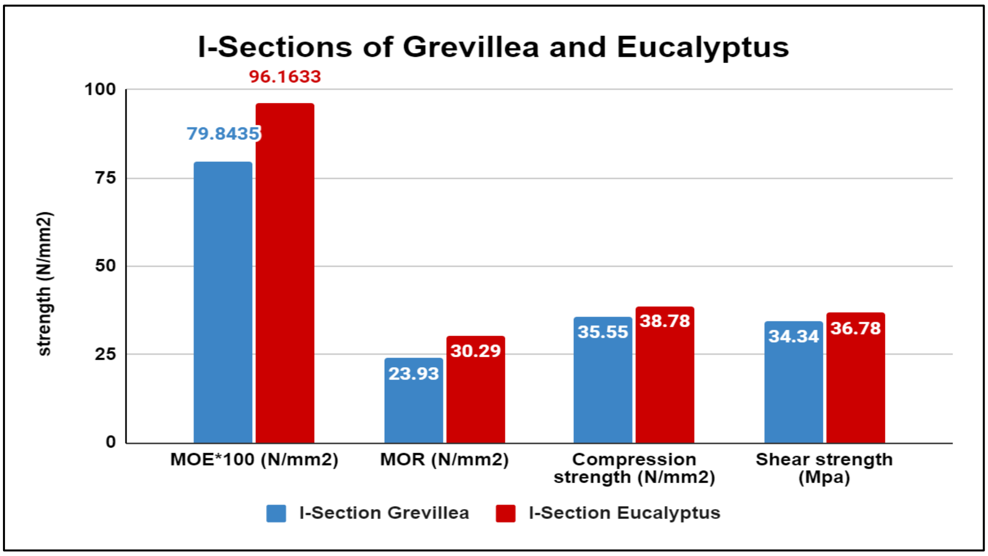

Figure 4. 3: Performance of the Specimens' I-Sections

As shown in Figure 4.8, the comparison between the two wood species in I-section panels reveals that while Eucalyptus excels in stiffness, load-bearing capacity, and shear strength, Grevillea exhibits better compression strength, hardness, and lower moisture content. These characteristics make each wood species suitable for different structural applications depending on the specific mechanical properties required for the design.

5. Conclusions and Recommendations

5.1. Conclusions

1) Material Suitability: Eucalyptus demonstrates superior mechanical properties such as higher MOE, MOR, and shear strength, making it well-suited for structural applications requiring stiffness and load-bearing capacity. Grevillea, with its higher compression strength and hardness, offers advantages in specific construction scenarios.

2) Shear Challenges: Standard blocks CLT panels, whether Eucalyptus or Grevillea, exhibit lower shear strength relative to their other mechanical properties. This highlights the need for careful engineering consideration to mitigate potential weaknesses in shear resistance.

3) Advancements with I-Sections: Custom I-shaped laminated panels significantly enhance shear strength compared to standard block configurations. The I-section design optimizes material distribution and load-bearing efficiency, offering improved structural performance and stability under complex loading conditions.

5.2. Recommendations

5.2.1. Recommendations from this Study

1) Enhance Treatment Processes: Improve methods for treating Eucalyptus and Grevillea timbers to optimize moisture content and density.

2) Assess the feasibility of using custom I-shaped laminated panels in construction to leverage their mechanical advantages.

3) Work with industry stakeholders to create standardized guidelines for Cross-Laminated Timber (CLT) use in structural applications.

4) Set up programs to monitor the durability and resilience of CLT structures in real-world conditions.

5.2.2. Recommendations for Further Study

1) Investigate the fire resistance of CLT panels made from various timber species.

2) Explore modern manufacturing techniques for CLT production to enhance efficiency.

3) Study the sound insulation capabilities of Eucalyptus and Grevillea CLT panels in building applications.

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Pedestrian Traffic Generation Modelling for Middle Income Residential Estates: A Case of Nyayo Highrise Estate, Nairobi, Kenya

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Abstract

Pedestrians are often given little or no consideration when planning for large residential estates and yet walking is the dominant mode of transport within such housing developments. One such example is Nairobi's Nyayo Highrise Estate, which is a gated residential neighborhood housing the lower middle-income category of the society, and catering for a total of 1,987 households (Kenya National Bureau of Statistics, 2009). This study aims to model pedestrian traffic generation within Nyayo Highrise. Pedestrian traffic volume counts were undertaken near the high pedestrian activity locations for a period of three days, where it was observed that there were two peaks occurring in the morning periods and in the evening periods. In addition, the study collected household characteristics from 250 households by way of questionnaires, which were randomly administered. Using multiple regression techniques, relationships were established between the household characteristics and the pedestrian volumes, resulting in two models where the independent variables (i.e., household characteristics) accounted for 93.4% prediction of pedestrian traffic volumes. These calibrated models offer a new approach for transportation planners to take into consideration in the planning, design and operation of pedestrian facilities in high density residential neighborhoods, provided the socio-economic and demographic characteristics are known.

Key Words: Pedestrian traffic generation modelling, pedestrian trip generation, Residential estates, Household characteristics, Pedestrian volumes.

1. Introduction

Pedestrian trip generation is a component of transportation engineering that estimates the number of pedestrian trips that originate in a specific location such as a home, a workplace, a shopping center, and so on. Pedestrian trip generation forms the foundation upon which planners and designers make appropriate provisions for pedestrian facilities in residential neighborhoods. The focus of this study is to come up with pedestrian trip generation models for high density residential neighborhoods that simplify the process of estimating pedestrian trips from such residential neighborhoods. According to Transportation Research Board (2010), peak pedestrian volume is the highest 15 minutes pedestrian volume across the day. In the study, peak pedestrian volumes served as the dependent variable, while household characteristics served as the independent variables. Pedestrian volume counts were undertaken at the points of highest pedestrian activity at the last stretch of the access road to the main gate. The target access road is 700m long from the main gate up to the farthest point of the estate.

Provision of pedestrian facilities in high density residential neighborhoods in Kenya is going to be a major challenge as government shifts its focus to provide low cost housing around the country. In 2017, the government came up with a plan of building 500,000 homes over a four year period (State Department of Housing & Urban Development, 2018) in Kenya's major cities that can be purchased by low-income families (Gardner, et al., 2019) in order to address the annual housing deficit of about 250,000 houses (The Exchange, 2023). This deficit is set to increase as more and more people migrate to urban areas with a projection of approximately 46% of the population by 2030 (National Council for Population and Development, 2016). With increasing urbanization as well as successful implementation of high-rise, high-density housing developments, pedestrian facilities are becoming more challenging to provide. It is common to see pedestrians sharing the road carriageway with vehicles and putting their safety to risk. This process therefore requires a solution to the challenges experienced by pedestrians. This study will make a contribution towards assisting planners and designers to project pedestrian trip volumes within project neighborhoods.

Nyayo Highrise is located on Mbagathi Road in Nairobi and has high pedestrian volumes especially during the morning and evening peaks. It is located at latitude 1°18'56.4"S and longitude 36°48'20.2"E, approximately4.8 kilometers from the Nairobi central business district and adjacent to the Nairobi Dam.

In 2017, the Kenyan government released a four-year development plan titled "The Big Four." The foundation of the development agenda was the Kenya Vision 2030, which aims to move Kenya to a middle-income economy by 2030. One of the four pillars of 'the Big Four' agenda was Affordable Housing, which aimed to provide 500,000 dwellings over a four-year period (State Department of Housing & Urban Development, 2018) and devised a plan to engage the private sector to achieve this goal. To make housing affordable, high-rise, high-density residential structures were to be built.

According to the State of the Kenya Population Report, an examination of urbanization trends in Kenya reveals that approximately twelve million people (31% of the total population) reside in urban areas. This represents a significant increase from the 5.3%, or 285,000 people, in 1948. Urbanization is expected to reach roughly 46 percent of the population by 2030 (National Council for Population and Development, 2016). With such a significant increase in urbanization and the successful implementation of high-rise, high-density residential dwellings, the challenges associated with providing pedestrian and public transportation utilities have also increased significantly. In the construction of high-density residential dwellings, the obstacles become even more pronounced. In residential estates, it is common to see pedestrians sharing roads with motorized traffic, and in the majority of cases, this results in conflicts between motorists and pedestrians. When vehicles exceed the speed limit, pedestrians' safety is frequently at risk.

There is a wide disparity in the sophistication of pedestrian planning in Kenya, with transportation modeling limited to motorized modes, leaving out pedestrians. As a result, many urban settings do not have advanced methods of modeling for pedestrians, nor are there considerations for non-motorized modes in the national design manuals. The lack of available data, and several other issues contribute to pedestrians being left out of the modeling mix. For instance, pedestrians are not always confined to roadway space, however, they enjoy mobility that makes them difficult to observe from any counting station. The outcomes of this study will be the development of a regression model that will aid transportation planners to predict pedestrian traffic generation in high density, residential estates.

2. Literature Review

2.1. Introduction

In this section, the author looked for and analyzed available literature on pedestrian trip generation modeling in Kenya and around the world. There are multiple pedestrian trip generators such as residential areas, malls, workplaces, social places, and so on but the approach to pedestrian traffic modeling is essentially similar. The review of literature enabled the author to appreciate the work so far undertaken, how they relate or contrast with the current study and to establish the gaps in the body of knowledge. This process was critically done to ensure that only quality information was relied upon.

Deborah & Sumila (2019) studied Kenyan city travel demand and found that walking and matatus are the main modes of transport and that most commuters can choose to either walk or ride in matatus. However, even though pedestrians make up a significant proportion of travelers in Nairobi's urban areas, local authorities currently disregard the significance of walking. The streets in densely populated areas were designed with vehicles in mind while pedestrians were neglected (Otieno, 2018). This is set to get worse as was observed in China by Yi, et al. (2018) that is currently experiencing rapid urbanization, but urban planning has been abandoned, leading to unsustainable land utilization and insufficient pedestrian infrastructure in many urban developments. Other factors that affect pedestrian facilities include provisions for the physically challenged, width of facility, lighting, safety, vendors on the facility (Majanja, 2013), security, continuity, connectivity, and visual appearance (Oginga, 2017). The literature review revealed that limited research has been done on pedestrian traffic especially in developing countries as was observed by Fiona, et al. (2018).

2.2. Issues Affecting Pedestrians

Although walking is considered the most environmentally friendly mode of transportation, it is seldom considered a substantive mode of transportation (Wigan, 1995) and is often an overlooked means of transport (Olszewski, 2007) as demonstrated by ARUP (2016) who noted that vehicle-dominated development includes communities lacking sidewalks, public spaces filled with parked automobiles, and urban roadways that separate neighborhoods to service growing suburbs. The built environment and social environment both influences how people move (Baran, et al., 2009) and certain aspects of urban development, such as better street connectivity and job-housing balance, can increase people's propensity to walk (Yi, et al., 2018). Key issues that encourage pedestrian activity include pedestrian facility quality (Noorul, et al., 2019) and (Otieno, 2018), security of pedestrians (Olszewski, 2007), (Oginga, 2017), safety of pedestrians (Wigan, 1995), lighting (Aromal & Naseer, 2022) and (Oloo, 2015), human activity (Ahmed & Islam, 2020), (Oginga, 2017) and (Otieno, 2018), facility maintenance (Majanja, 2013) and continuity (Osama & Sayed, 2017). It was established that when pedestrians have alternative modes of transport, these issues are likely to affect the reliability of pedestrian trip generation models. Basically, even though population and household characteristics may indicate a high volume of pedestrian traffic generation using generation models, they may prefer to drive or use public transport because of impediment posed by the issues highlighted.

2.3. Planning for Pedestrians in Developing Countries

Many developing nations lack complete and organized planning initiatives for pedestrians, posing challenges for planning and implementation agencies (Aromal & Naseer, 2022) and yet the norms and amenities for pedestrians used in the developed world do not apply to developing nations (Prabhu & Sarkar, 2016). The author searched for all available literature seeking to find any relevant ones on modeling for pedestrian trips in Kenya and other developing nations. The finding was that some work was done by Otieno (2018) who modeled pedestrian traffic in an urban road based on the time of the day. The scope of this model is limited as it does not relate pedestrian traffic generation with characteristics of the generators such as residential neighborhoods.

2.4.Pedestrian Trip Generation Modelling

When using household-based models, modelling is the process of connecting the dependable variable, such as the number of trips a household produces, to the related independent variables that are described by the household characteristics. Modeling the volume of trips made by zone residents is complex and is heavily reliant on the integrity and availability of data (Tillema, et al., 2004). Regression turns to be more appropriate for modeling pedestrian trip production (Kim & Susilo, 2013). Garber & Hoel (2009) undertook a study using two independent variables in a multiple regression analysis and came up with the following relationship:

$$T=0.82 + 1.3P + 2.1A \quad \text{Equation 1}$$

Where:

T = number of daily trips per household P = number of individuals per household A = number of vehicles per household

Kim & Susilo (2013) compared four distinct regression models for estimating of pedestrian demand at the regional level and determined that Poisson regression is the most suitable model taking into account the National Household Travel Survey (NHTS) 2001 information for the modeling of pedestrian trip generation in terms of the X2 ratio test and Pseudo R2. The Baltimore metropolitan region, which contains around 2,500,000 households, was the subject of their study, which included a sample of 66,000 households. This study was built on the work done by Pushkarev & Zupan (1971) who predicted pedestrian demand in densely populated regions using current land-use data as well as pedestrian volume counts and forecasted total pedestrian numbers per block using linear regression analysis. Other relevant work was done by Behnam & Patel (1977) who utilized a similar regression approach. In their regression equations, both research teams utilized pedestrian counts per hour per block as the dependent variable. Parking space, storage space, residential space, vacant space, commercial space, office space, manufacturing space, cultural and entertainment space, and maintenance space were the independent variables. Though the area of interest in all these works is in pedestrian trip generation modeling, their work covered large geographical spreads which had varying household characteristics. Additionally, their independent variables revolved around land use and socio-economic characteristics. The studies were undertaken in the United States whose land use and transport characteristics are literally worlds apart when compared with those of Kenya.

Tian & Ewing (2017) proposed a home-based model for generating walk trips in Portland, Oregon. They aimed to develop models that could forecast the probability of households creating home-based walk journeys and the amount of home-based pedestrian trips for the portion of households making such trips. Their findings indicated that sociodemographic factors are strong predictors of pedestrian trip generation; specifically, household size, income, and the number of household workers impact the probability of a household making any walk trips. The author further observed that the size of the household and the number children who lived in the household influenced the number of walking journeys made by the subset of households that walked. Except that the study was conducted in a developed nation, the concept is the closest to the current study. However, the study was qualitative and did not go to the extent of proposing pedestrian trip generation models. Additionally, it did not consider the homogeneity of residential estates within the study area. In their conclusion, they noted that the built environment of the surrounding area had a greater influence on non- motorized journeys.

Gruyter, et al. (2021) sought to comprehend the spectrum of site characteristics associated with multimodal trip generation rates in residential developments. Information was obtained from the database of the Trip Rate Information Computer System for 933 dwellings in the United Kingdom and Ireland, estimating trip generation separately for pedestrians. There was a total of 65 independent variables included in the analysis, representing a variety of site characteristics related to location and housing characteristics, public transportation quality, parking spaces, and travel plan measures. Thereafter, site characteristics were regressed against trip generation rates by mode and time period to examine their relationship with pedestrian trip generation. Findings revealed that pedestrian trip generation rates in residential developments were related to a variety of site characteristics, including to varying degrees, spatial and housing characteristics such as: high-rise developments and dwelling size; density of population; vehicle ownership; distance to nearby amenities such as convenience stores; train or bus service efficiency; on-site parking spaces, and several travel plan initiatives such as secure, well-lit; and covered bicycle parking. They concluded that pedestrian-friendly characteristics should be incorporated whenever practicable into new residential developments. Gruyter, et al. (2021) provided an insight that was useful in understanding pedestrian travel behavior.

In Kenya, some pedestrian trip generation modeling work was done by Otieno (2018) where he used multiple linear regression models to contrast the results with actual findings from traffic count surveys at different places in his study area. His study came up with models for various urban road links that attempted to explain the hourly pedestrian volume variation. Kim & Susilo (2013) noted that there is currently no accepted method for accurately predicting the demand for pedestrian travel.

In summary, a review of the literature establishes that while efforts have been made to help quantify pedestrian trip making, there is a need to develop better methods to estimate pedestrian trip generation rates, particularly in Kenyan urban settings/ high density residential developments. This indeed is the focus of this research. This study explores statistical methods to develop such models.

3. Methodology

The Nyayo Highrise estate was used as a case study. This estate has a population of about 6,000 people living in 1,987 households. Despite such a high population, pedestrian facilities were not given consideration. Household characteristics were collected from 250 households by way of questionnaires administered randomly within the estate. The targeted population was arrived at using the guidance made by Kadiyali (2007) who recommended that for a population of less than 50,000 people, a target sample size of at least 1:10 should be used. The targeted household characteristics included number of adults, household income, vehicle ownership, number of school going children and number of income earning adults. To guarantee a high quality of data collected, the researcher used multiple contacts within the estate to ensure close interaction with respondents and support any challenges experienced whilst filling the questionnaires. The data obtained was then manipulated using the Statistical Package for the Social Sciences (SPSS) software.

The study undertook pedestrian volume counts for three days between 6.00am and 9.00pm. According to Garber & Hoel (2009), pedestrian volume counts should be undertaken at intersections and crossings when the weather is favorable. American Society of Planning Officials (1965) discourages undertaking the volume counts during holidays, when schools are closed and other distortions to travel patterns. The counts were aggregated to 15-minute intervals (Mingo, et al., 1988) with the key interest being the morning and evening peaks. From the volume counts, the researcher obtained peak 15-minute pedestrian volume counts that would be used as the dependent variable in the model.

At all stages of the study, including literature review, sample selection, data collection and analysis, and conclusion drawing, obtaining valid and reliable data was of paramount importance. The validity of a study's findings is entirely dependent on the quality of the study methodologies and procedures used (Kumar, 2011). A stakeholders awareness campaign was conducted, and the views collected were incorporated into the study. At the data collection stage, the researcher took care to avoid sample selection bias, ensuring that most of the people in the target group filled out the questionnaire. This included making certain that the questionnaire did not have any ambiguities that could potentially compromise the reliability of the findings. The idea of using the local opinion leaders to share the questionnaires brought in the element of trust from the respondents, thus ensuring the validity of the results.

The researcher established whether the findings of this study have external validity. This refers to the application of the study's findings to other similar settings or environments with the expectation of obtaining accurate and reasonable results. According to the literature review, the level of a country's economy greatly influences household characteristics. Similarly, pedestrian traffic generation modelling is context specific, thus, there are wide disparities in methods of pedestrian modeling in developed versus developing countries, to quantify latent pedestrian demand at the neighborhood level.

The researcher also evaluated the validity of the statistical conclusions drawn from the study's findings (Marczyk, et al., 2005). Findings revealed that the independent variables had a strong correlation with the dependent variable, eliminating the possibility of low statistical power. Additionally, all the respondents had formal education hence the chances of measurement unreliability was considerably reduced.

4. Data Analysis

4.1. Pedestrian Volume Counts

Pedestrian volume counts were conducted in order to determine peak pedestrian volumes for the main access to the estate (See figure 1).

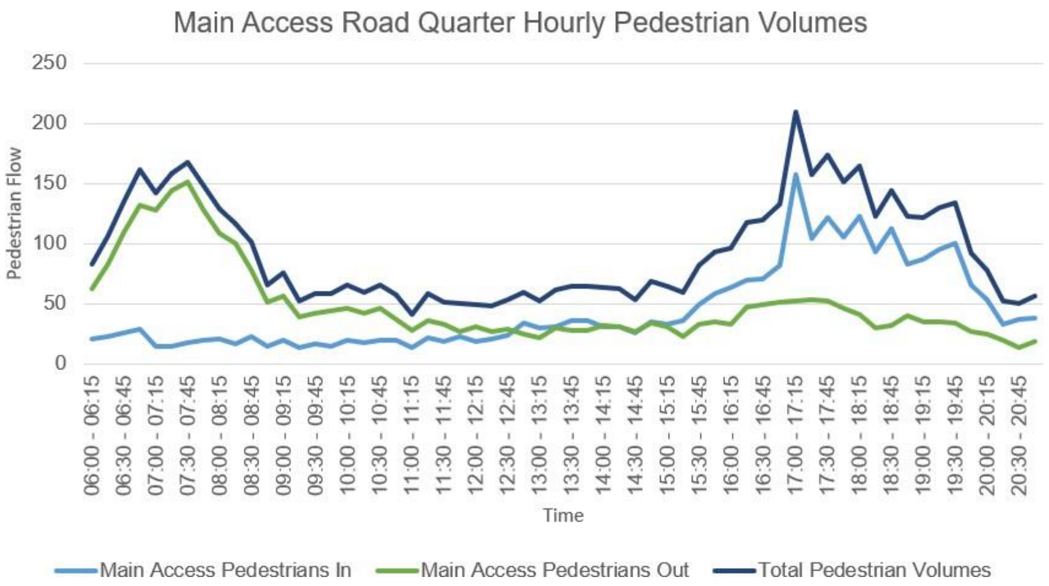

Figure 1: Quarter Hourly Pedestrian Volumes.

The study observed that the main access road has two distinct peak pedestrian volumes occurring in the morning period and in the evening period, respectively. The former was observed between 7.30am and 7.45 am with a peak volume of 168 pedestrians while the latter was observed between 5.00pm and 5.15pm with a peak of 209 pedestrians. It is seen that the morning peak is caused pedestrians getting out of the residential estate while the evening peak is caused by pedestrians returning to the estate. This is an indication of the residents leaving in the morning to go to work and school and returning in the evening. A closer look at the chart in Figure 1 shows that the morning peak lasts about 2 hours while the evening one extends up to 4 hours. A key inference here is that after the lapse of the official working time at 5.00pm, a large number of the residents go on to do other activities which may include shopping and social activities.

The following equation was developed by modeling the data using the polynomial equation of order 6:

$$Y=-0.0000003x^6+0.00006x^5-0.0047x^4+0.1993x^3-4.0232x^2+28.811x+75.598 \quad \text{Equation-2}$$

The R^2 was 79.4% meaning that this equation was able to predict the quarter hourly pedestrian volumes through the day at a 79.4% accuracy. This equation is shown in figure 2.

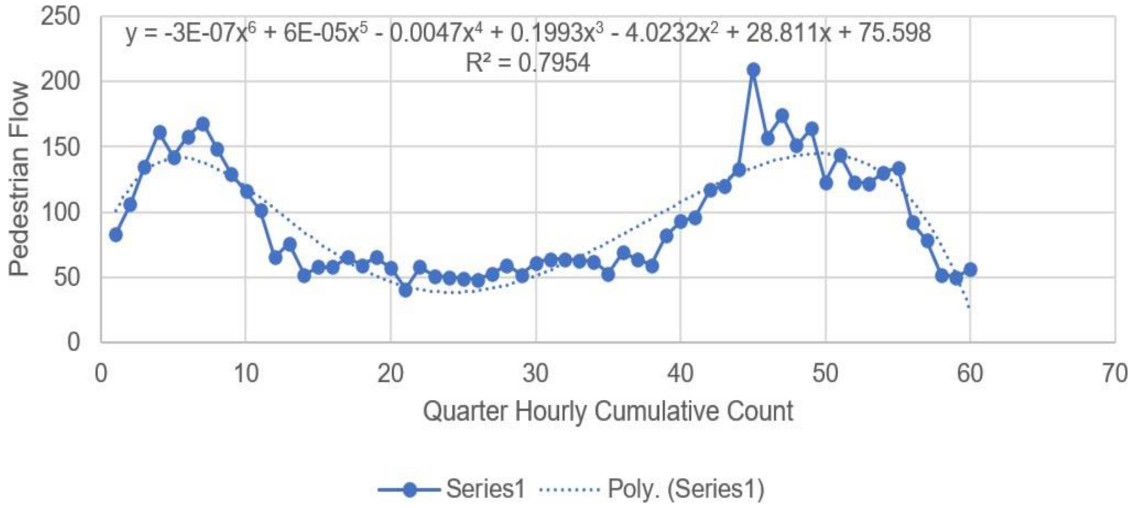

Figure 2: Quarter Hourly Pedestrian Volumes Model.

Individual households contribute to the flow of pedestrians and what differentiates them is their characteristics. According to the literature review, each household characteristic has a contribution to the generation of pedestrian trips. The household surveys yielded the results in Tables 1 to 4 and Figure 3.

Table 1: Number of Adults in the Households.

	Frequency	**Percentage (%)**
One	80	32.0
Two	127	50.8
Three	30	12.0
More than four	13	5.2
Total	**250**	**100.0**

From Table 1, it is observed that 32% of the households had one adult, 50.8% had two, 12% had three and 5.2% had more than four.

Table 2: No. of Adults Earning Income.

	Frequency	**Percentage (%)**
Zero	37	14.8

One	80	32.0
Two	115	46.0
Three	16	6.4
More than four	2	0.8
Total	**250**	**100.0**

From Table 2, it is observed that 14.8% of the households had no income earning adults, 32% had one, 46% had two, 6.4% had three and 0.8% had more than four.

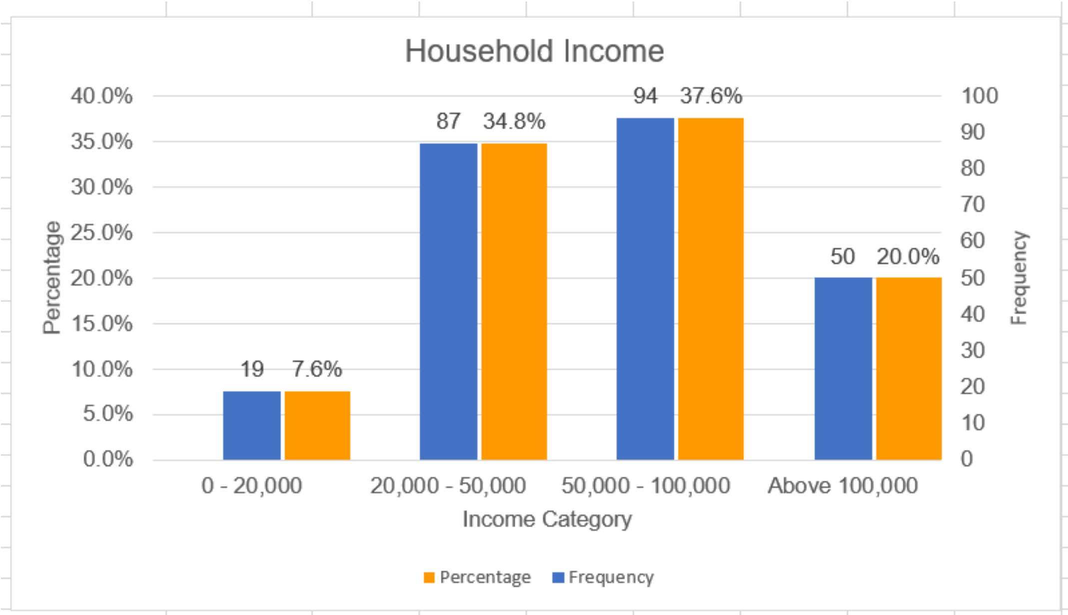

Figure 3: Household Income.

From Figure 3, it is observed that 7.6% of the households had a household income of Kshs. 20,000, 34.8% had between Kshs. 20,000 and Kshs. 50,000, 37.6% had between Kshs. 50,000 and Kshs. 100,000 and 20% had above Kshs. 100,000.

Table 3: Ownership of Vehicles.

How many vehicles does the household own?		
Counts	**Frequency**	**Percentage (%)**
None	116	46.4
One	92	36.8
Two	37	14.8
Three	4	1.6
Four & above	1	0.4
Total	**250**	**100.0**

From Table 3, 46.4% of the households did not have a vehicle, 36.8% had one vehicle, 14.8% had two, 1.6% had three and 0.4% had four.

Table 4: No. of Children Going to School.

Counts	Frequency	Percentage (%)
None	96	38.4
One	73	29.2
Two	52	20.8
Three	24	9.6
Four & above	5	2.0
Total	**250**	**100.0**

From Table 4, 38.4% of the households did not have school going children, 29.2% had one, 20.8% had to, 9.6% had three and 2% had four and above.

According to Alsobky (2022), trip generation modeling is unusual since the input-output relationship is often nonlinear and unclear. The above data was analyzed using the Statistical Package for Social Sciences (SPSS) using multiple regression test. The outcomes in Table 5 were obtained through a multiple regression test that examined different pairings of the independent variables.

Table 5: Summary of the Models.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.951[a]	0.905	0.905	0.15394	0.905	16611.36	1	1747	0.000	
2	.962[b]	0.925	0.925	0.13665	0.020	471.055	1	1746	0.000	
3	.965[c]	0.932	0.932	0.13022	0.007	177.566	1	1745	0.000	
4	.966[d]	0.934	0.934	0.1285	0.002	47.919	1	1744	0.000	
5	.966[e]	0.934	0.934	0.12848	0.000	1.536	1	1743	0.215	1.625

a. Predictors: (Constant), No. of adults

b. Predictors: (Constant), No. of adults, No. of income earning adults

c. Predictors: (Constant), No. of adults, No. of income earning adults, Total household income

d. Predictors: (Constant), No. of adults, No. of income earning adults, Total household income, Vehicle Ownership

e. Predictors: (Constant), No. of adults, No. of income earning adults, Total household income, Vehicle Ownership, No. of school going children

f. Dependent Variable: No. of pedestrian trips

The adjusted R squared values show that all the five models have a good fit with model 5 giving the best fit.

The ANOVA test was then done which showed that Models 4 and model 5 were highly significant, and there was a very small possibility that the results were by chance. The other three models were found to be insignificant.

From the regression equations in Table 5, the regression coefficients are provided in Table 6.

Table 6: Coefficients Table.

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
4	(Constant)	.020	.007		2.790	.005
	No. of adults	.215	.032	.193	6.803	.000
	No. of income earning adults	.427	.030	.390	14.020	.000
	Total household income	.347	.029	.305	12.078	.000
	Vehicle Ownership	.100	.014	.098	6.922	.000
5	(Constant)	.014	.008		1.669	.095
	No. of adults	.215	.032	.193	6.819	.000
	No. of income earning adults	.425	.031	.387	13.882	.000
	Total household income	.346	.029	.304	12.049	.000
	Vehicle Ownership	.098	.015	.097	6.774	.000
	No. of school going children	.019	.015	.009	1.239	.215

The coefficients in Table 6 show how each independent variable affects the dependent variable. By substituting the B values in Model 4, we get the model in Equation 3.

$$Y = 0.02 + 0.215X_1 + 0.427X_2 + 0.347X_3 + 0.1X_4 + e \qquad \text{Equation-3}$$

By also substituting the B values in Model 5, we get the model in Equation 4.

$$Y = 0.014 + 0.215X_1 + 0.425X_2 + 0.346X_3 + 0.098X_4 + 0.019X_5 + e \qquad \text{Equation-4}$$

5. Conclusion & Recommendation

5.1. Conclusion

Based on the findings of the above analysis, the following pedestrian trip generation models provide the best fit for generation of pedestrian traffic at the Nyayo Highrise estate:

$$Y = 0.014 + 0.215X_1 + 0.425X_2 + 0.346X_3 + 0.098X_4 + 0.019X_5 + e \quad \text{........ ……Equation-5}$$

$$Y = 0.02 + 0.215X_1 + 0.427X_2 + 0.347X_3 + 0.1X_4 + e \quad \text{………………………. Equation-6}$$

The independent variables in the two models accounted for 93.4% prediction of the pedestrian trips at the estate.

5.2. Recommendation

This study has strongly supported the hypothesis that there is a strong relationship between household characteristics and pedestrian trip generation. The author looked for the best combination among the household characteristics relied upon in this study but what comes out is that there can be countless combinations that yield significant results. There is therefore room for further research using other household characteristics in order to broaden the body of knowledge on pedestrian trip generation.

The study came up with two models where the household characteristics accounted for 93.4% prediction of pedestrian trips generated at the Nyayo Highrise Estate. This shows that the models can actually be relied upon to predict pedestrian trip generation with a high level of accuracy for residential neighborhoods with similar socio-economic settings. It is therefore recommended that the models be adopted for predicting pedestrian traffic generation in residential neighborhoods similar to Nyayo Highrise estate as they would be helpful especially for designers of large residential estates when designing pedestrian facilities.However, as established from the literature review, care should be taken to ensure that the physical state of the infrastructure and the environment encourage pedestrian activity.

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Integrated Development and Productive Use of Energy for Off-Grid Electrification in Kenya

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Abstract

Kenya has set ambitious goals for achieving full electrification as part of its national development objectives. Programs like The Last Mile Connectivity Project and the Kenya National Electrification Strategy (KNES) aimed to extend electricity access across the whole country. However, despite the success of the country's electricity access rollout in recent years these targets remain unmet prompting a revised timeline for achieving universal access by 2026. To reach this goal, extensive scientific literature emphasizes the crucial role of mobilizing both private investment and household contributions. Recent Integrated Development (ID) strategies in many Sub-Saharan African (SSA) countries have proven to be the most effective way to achieve this financial mobilization. Notably, countries have found success through Business Model Innovations (BMIs) which provide electricity ac cess integrate services such as agro-processing, food cold storage, water irrigation, internet connectivity and e-mobility. These models provide added value to consumers and boost profitability for energy providers through productive use (PU) of energy, highlighting the critical role of private investors in achieving successful electrification expansion and significantly improve living conditions in rural areas. This paper critically evaluates the current off-grid policy framework in Kenya focusing on its ability to support and stimulate market conditions favorable for the adoption of these innovative solutions. The analysis uses publicly available policy documents as well as drafts of policies not yet approved, obtained through contacts within the country's energy regulatory framework. A detailed matrix was developed to categorize and evaluate the presence and comprehensiveness of policy instruments relevant to off-grid electrification including those facilitating PU and integrated development. The results of this analysis, discussed with stakeholders encompassing a wide range of off-grid energy expertise (including private companies, academia, and regulatory bodies), reveal a significant policy gap in supporting the productive use of off-grid energy and a general lack of strategies to drive productive use of energy and comprehensive growth through off-grid energy solutions. To address this gap the paper employs a modeling strategy focusing on a real cluster of mini grids proposed in the Kenya Off-grid Solar Access Project (KOSAP). The study explores the consequences of enhancing the productive use of the electricity generated by these mini grids, to assess the potential benefits for both developers and local populations. The conclusions drawn from this analysis provide critical insights into the necessary policy adjustments needed to foster productive use of energy through an innovative environment for off-grid energy solutions, and what consequences such adjustments would bring.

Keywords: Off-Grid, Kenya, Energy Policy, Integrated Development, Electrification, Productive Use

1. Introduction

In Sub-Saharan Africa (SSA) faces significant challenges in achieving universal access to electricity, as outlined in Sustainable Development Goal 7 (SDG7), which aims to provide reliable, affordable, and sustainable modern energy to all by 2030. Despite ongoing efforts, a large portion of SSA’s population, particularly in rural areas, remains without access to electricity. Over 567 million people in the region are still unserved, which has been exacerbated by rapid population growth that has outpaced electrification initiatives (1). While some countries, such as Kenya and Ethiopia, have made notable progress in recent years, rural areas remain significantly underserved due to the high costs and logistical difficulties of grid extensions. Off-grid solutions, such as mini-grids and stand-alone systems, have emerged as viable alternatives to traditional grid expansion in reaching remote and rural communities (2). However, the success of these off-grid energy projects hinges largely on mobilizing substantial financial investments. The financing gap is stark: SSA requires an estimated $25 billion annually to meet its electrification goals, but current investments fall far short of this target (2). Much of the funding for these projects has traditionally come from public sources and development finance institutions, but this approach alone is insufficient to meet the growing demand. There is a growing recognition of the need for private sector involvement, as well as household contributions, to fill this financing gap (3).

One of the key obstacles to attracting private investment in off-grid energy projects is the high cost of capital, which is driven by factors such as high interest rates, inflation, and the perceived risks associated with operating in emerging markets (4). These challenges are further compounded by debt sustainability concerns in many countries, which limit their ability to finance infrastructure projects. In SSA, the cost of financing for energy projects is significantly higher than in more developed markets, making it difficult to secure investment for small, high-risk projects like off-grid systems. Early-stage financing, essential for activities such as feasibility studies and pilot projects, is particularly hard to come by, further delaying the development of bankable projects that could attract larger investments (5).

In response to these challenges, new financing mechanisms are being explored. Concessional finance, which includes grants, low-interest loans, and risk guarantees, is playing an increasingly important role in reducing the perceived risk of off-grid energy investments and making these projects more appealing to private investors (5). Other innovative financing models, such as results-based financing, fintech solutions, and public-private partnerships, have also gained traction as tools to attract private capital. These models allow for more flexible, efficient, and accountable financing, ensuring that investments are closely tied to tangible outcomes, such as the number of new electricity connections or improvements in community access to energy services (6).

Private sector involvement in off-grid energy projects is essential for bridging the investment gap and ensuring the long-term sustainability of electrification efforts (7)(8). Business Model Innovations (BMIs) have emerged as a critical strategy in this context, particularly those that go beyond the provision of basic electricity services to include additional value-added services, such as agro-processing, cold storage, internet connectivity, and electric mobility. These models not only improve the economic viability of off-grid energy projects but also attract private investment by providing a diversified revenue stream. In doing so, BMIs align with the broader goals of rural development by boosting local economies and improving the quality of life in off-grid communities (9).

However, the challenge remains in scaling these business models across SSA. The demand for productive use of energy is often low in off-grid areas, particularly in regions where the local economy is underdeveloped, and there are few businesses or industries to drive electricity consumption. One promising approach to overcoming this challenge is the "Big Pull" strategy, which aims to simultaneously build energy infrastructure and create demand for electricity by promoting productive economic activities (10). This approach mirrors the “Big Push” development theory but focuses on attracting resources and investments from the bottom up, rather than relying solely on top-down interventions. By fostering demand for electricity through business activities like agricultural processing, small-scale manufacturing, and services, off-grid energy providers can ensure more stable and predictable revenue streams, which in turn makes the projects more attractive to investors.

Several case studies have demonstrated the effectiveness of this integrated development approach. For instance, appliance financing programs in countries like Nigeria and Kenya have shown that providing businesses and households with affordable, income-generating appliances, such as grain mills or woodworking equipment, can significantly increase electricity demand (11). This demand boost improves the financial viability of mini-grid projects by enabling providers to sell more electricity, thereby spreading the fixed costs of infrastructure over a larger customer base. In Tanzania, initiatives like the Rural Electrification Densification Programme (REDP) have further highlighted the importance of promoting productive uses of electricity (12). By providing technical training, business support, and financing for small-scale productive appliances, the REDP program has contributed to the growth of local businesses and improved socio-economic outcomes in newly electrified villages.

In the broader context of rural development, access to reliable and affordable electricity has far-reaching implications for sectors such as education and healthcare. Schools equipped with electricity are better able to provide quality education through access to modern teaching tools, internet connectivity, and science equipment. In households, electricity enables children to study after dark, contributing to improved educational outcomes. Similarly, healthcare facilities in off-grid areas benefit from the ability to power essential medical equipment, such as refrigeration units for vaccines and diagnostic tools, improving the overall quality of healthcare services available to rural populations (13).

Ultimately, the key to successful off-grid electrification in SSA lies in the integration of energy access with broader socio-economic development goals. By promoting productive uses of energy and fostering local business growth, off-grid energy providers can create a virtuous cycle of development that improves livelihoods, enhances food security, and boosts educational and healthcare outcomes. This requires not only innovative business models but also supportive policy frameworks that encourage private investment, reduce financing risks, and ensure that off-grid energy solutions are accessible to all. To achieve these goals, governments and development agencies must work closely with the private sector to create an enabling environment that fosters both the supply and demand for off-grid energy services.

2. Settings and methods

The extensive literature review undertaken in this background analysis reveals several key findings to be addressed. This research focuses on building a scheme to identify the completeness of the policy framework that enables these innovative business models while addressing the socio-economic development of the regions involved. The selected country for this research, where the research activities have been undertaken, is Kenya, known for having a relatively comprehensive off-grid policy framework. Kenya has set ambitious goals for achieving full electrification as part of its national development objectives. Programs like The Last Mile Connectivity Project and the Kenya National Electrification Strategy (KNES) aimed to extend electricity access across the whole country. However, despite the success of the country's electricity access rollout in recent years these targets remain unmet prompting a revised timeline for achieving universal access by 2026. The analysis aims to identify potential policy gaps within Kenya's off-grid policy framework. Drawing from the results of this analysis, any identified gaps will be addressed through modeling to demonstrate the benefits of filling these gaps. This approach not only highlights the necessity of robust policy frameworks but also showcases the tangible socio-economic benefits that can be achieved through effective policy implementation and innovative business models in the off-grid energy sector.

2.1. The policy matrix

The matrix includes a wide range of indicators to cover all aspects of off-grid policy development, including those aimed at facilitating business model innovations (BMI), following the structure set by (Trotter et. al.) in "Policy mixes for business model innovation: The case of off-grid energy for sustainable development in sub-Saharan Africa" (9): the structure assesses both the overarching policy strategies and the specific policy instruments implemented to achieve these strategies. The policy matrix is divided into two main components: society-wide policies and sector-specific policies, each with their own strategies and instruments.

Policy Strategy and Instrument Mix

i) **Policy Strategy**: The policy strategy component encompasses the combination of policy objectives and the principal plans for achieving them. These strategies often address multiple objectives at varying levels of abstraction, such as long-term targets for climate policy, renewable energy adoption, and the deployment of specific technologies. Effective policy strategies can reinforce each other by signaling a growing market and providing clear direction while allowing flexibility for innovation and opportunity.

ii) **Instrument Mix**: The instrument mix consists of the concrete tools used to achieve the overarching objectives outlined in the policy strategies. These instruments can be categorized into:

- **Technology-push instruments**: These include R&D grants and subsidies designed to reduce the cost of innovation and encourage the development of new technologies.
- **Demand-pull instruments**: Tools such as feed-in tariffs and tax incentives that enhance market expectations and create demand for emerging technologies.
- **Systemic instruments**: These ensure that the necessary infrastructure is in place to support both technology-push and demand-pull instruments, facilitating a cohesive and supportive environment for innovation.

Balancing these instruments is crucial to effectively supporting structural changes within the energy sector. For instance, while individual instruments like the EU Emissions Trading System (EU ETS) mayhaveweaknesses, their combination with long-term targets has been instrumental in driving structural changes in the electricity industry (14).

Types of Policies in the Matrix

i) **Sector-Specific Policies**:

- **Policy Strategies**: These are designed to create a long-term foundation for companies to establish themselves within the off-grid energy market. They provide a roadmap for achieving specific sectoral objectives and help in signaling the direction of market development.
- **Policy Instrument Mix**: This includes the supportive conditions and spe cific tools needed to facilitate the operations of companies within the sector. Examples include subsidies for renewable energy projects, regulatory frame works that enable mini-grid development, and financial incentives for private investments.

ii) Society-Wide Policies:

- **Policy Strategies**: These integrate broader societal objectives into the sector specific strategies. They ensure that the development of the off-grid energy sector aligns with national and international goals, such as climate change mitigation, sustainable development, and social equity.
- **Policy Instrument Mix**: This involves the implementation of societal con straints and requirements, such as environmental regulations, social impact assessments, and policies aimed at ensuring equitable access to energy.

The policy matrix is also designed to assess the framework by including internationally recognized indicators from the RISE-ESMAP (Regulatory Indicators for Sustainable Energy-Energy Sector Management Assistance Program) framework (15). These indicators ensure that the matrix aligns with global policy standards. Additionally, input from interviews with local experts from academia, the private sector, and public policy makers has been incorporated to create a more robust and thorough evaluation tool. This inclusion ensures that the matrix not only evaluates the presence of policies but also their effectiveness in promoting an integrated approach to rural electrification and economic development.

2.2. Energy modeling strategy

As identified in the literature review, attracting private and household investment through Business Model Innovation (BMI) and productive use of energy is crucial for the successful implementation of off-grid electrification strategies. A key policy gap that needs to be addressed is the integration of off-grid energy solutions with broader socio economic development goals. This chapter aims to demonstrate the practical benefits of bridging this gap through energy modeling. The strategy chosen involves characterizing a real mini-grid cluster and applying a growth demand scenario for the productive use (PU) of energy. The analysis will focus on assessing the benefits of demand growth.

i. Selecting the Mini-Grid Cluster

The first step is to select and characterize a real mini-grid cluster. This involves gathering data on existing mini grids, including their locations, capacities, technologies used (such as photovoltaic (PV) systems, battery storage, and diesel generators), and the types of customers served (residential, commercial, and institutional). The characterization will include analyzing load curves, peak demands, and daily energy consumption patterns.

ii. Growth Demand Scenario for Productive Use of Energy

A growth demand scenario will be applied to the characterized mini-grid cluster. This scenario will consider an increase in energy demand driven by the productive use of energy, such as agricultural processing, cold storage, internet services, and other commercial activities. The scenario will project the potential growth in demand over a specific period, reflecting the economic development and increased energy needs of the community.

iii. Analyzing the Benefits of Demand Growth

The initial analysis will focus on the benefits of demand growth. Increased energy demand from productive uses can enhance the economic viability of mini-grids by generating higher revenue and improving load factors. This, in turn, can attract more investment and support the sustainable operation of the mini-grids. Microgrids-py software (16) will be used to simulate and optimize this scenario, focusing on minimizing the Net Present Cost (NPC).

iv. Optimization Objectives

The primary optimization objectives for both scenarios will be the Levelized Cost of Energy (LCOE) and the Net Present Cost (NPC) of the plants.

3. Results

3.1. Policy evaluation results

POLICY MATRIX			Kenya	Tanzania	Uganda
Sector-Specific	Policy strategy	Long-term plan to increase off-grid energy deployments	1	0,5	1
		Long-term plan to create a private sector-led off-grid energy market	1	0,5	1
	Systemic instruments	Regulatory instruments (e.g. framework for off-grid energy companies)	1	1	1
		Information instruments (e.g. effective flow of infotmation)	0,5	0	1
	Technology-push instruments	Economic instruments (e.g. grants)	1	1	1
		Information instruments (e.g. building capacities)	0,7	1	1
	Demand-pull instruments	Economic instruments (e.g. household connection subsidies)	1	0,5	1
		Information instruments (e.g. rural community engagement)	0	0	1
Society-wide	Policy strategy	Strategy to ensure affordability of public services applied to off-grid energy	0	0	1
		Strategy to promote comprehensive growth through off-grid energy	0,5	0	0,5
		Local industry growth objectives applied to off-grid energy sector	0	0	1
	Systemic instruments	Regulatory instruments (e.g. local standards, local content requirements)	1	0	1
	Demand-pull instruments	Regulatory instruments (e.g. legally binding electricity tariff limits)	1	0	1
		Economic instruments (e.g. property taxes, import taxes)	0,5	1	1
SCORE			9,2	5,5	13,5

Legend
- Present
- Unclear/Tension between policies/Outdated
- Absent

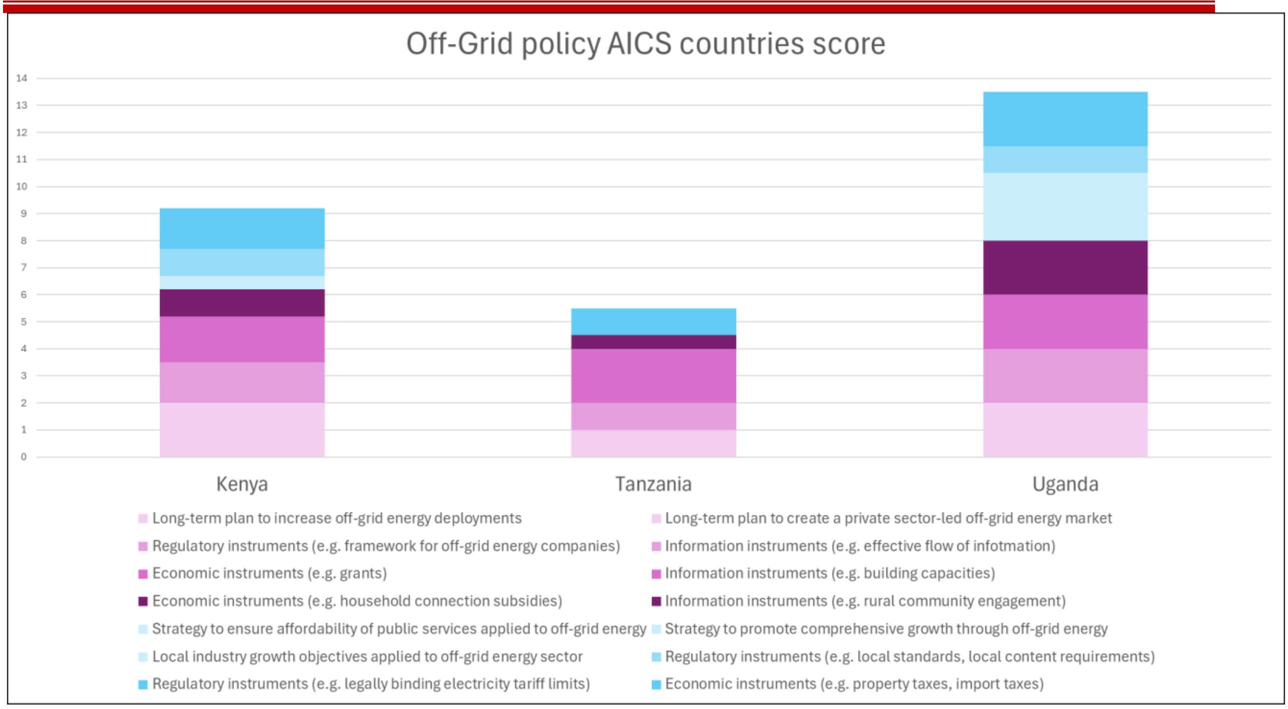

Figure 3.1: Comparison East African countries score applied to the policy matrix

This comparison helps us identifying two major policy gaps in the Kenyan framework:

i) Lack of information instruments

Kenya lacks a program to engage with communities who are about to receive mini grid electricity or who have just recently received mini grid electricity, to increase awareness, uptake, and demand for electricity services. There is no legal requirement for community engagement, to actively include the private sector developing new sector regulations or to hold infrequent but regular off-grid sector events. Between companies and consumers, between companies and policy makers, and between different companies themselves, these interactions are pivotal to ensure clarity in the market. Uganda for instance targets all three of these interactions: the government legally requires community engagement, actively includes the private sector developing new sector regulations and holds infrequent but regular off-grid sector events (9). Moreover, there is no national or large-scale program to engage with communities who are about to receive mini grid electricity or who have just recently received mini grid electricity, to increase awareness, uptake, and demand for electricity services. Not by chance, as discussed by (Taneja, 2018) (17), a major issue related to the economic feasibility of mini grids is the declining average consumption levels as a result of the very low consumption levels of people who have gained electricity access in recent years.

ii) Missing society-wide strategy to promote integrated development and PU

Kenya, despite its substantial progress in rural electrification, lacks comprehensive strategies that link off-grid energy solutions with broader integrated development goals. Integrated development is one of the best ways to achieve global electrification while respecting the so-called "Energy Trilemma" of respecting simultaneously environmental, economic and social sustainability, as shown in the Figure 2.3. In this framework, according to the World Energy Council's report "World energy trilemma index 2024", Kenya's score places the country in the bottom 25% globally (18). While several initiatives under Kenya Vision 2030 aim to promote rural development, these efforts are not sufficiently connected to off-grid energy programs, resulting in missed opportunities for holistic socio-economic growth.

Kenya Vision 2030 (19) is a long-term development blueprint aimed at transforming Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens by 2030. The vision includes various rural development strategies designed to enhance financial inclusion, support agricultural productivity, foster business startups, and develop marine fisheries. However, these strategies do not explicitly integrate off-grid energy solutions, which could significantly amplify their impact. One of the key initiatives, the Rural Kenya Financial Inclusion Facility, aims to enhance access to financial services for rural populations. This initiative focuses on expanding banking services, providing microloans, and offering financial literacy programs to rural residents. While these efforts are crucial for economic empowerment, integrating off-grid energy solutions could further support financial inclusion by enabling rural households and businesses to utilize affordable and reliable energy for productive activities. Similarly, the Agricultural and Rural Financial Inclusion Kenya strategy targets the financial inclusion of agricultural and rural communities by providing tailored financial products such as loans, insurance, and savings accounts. These financial services are designed to support agricultural productivity and resilience. However, without a direct link to off-grid energy solutions, these communities may struggle with energy-related challenges that hinder their full economic potential. Integrating off-grid energy into this strategy could enhance agricultural efficiency through the use of energy-powered irrigation systems, cold storage, and processing equipment. Kenya Vision 2030 also includes initiatives to incubate rural business startups, providing them with the necessary resources, mentorship, and funding to thrive. These incubators play a vital role in nurturing entrepreneurship and innovation in rural areas. However, the success of these startups often depends on access to reliable and affordable energy. By incorporating off-grid energy solutions into the incubation process, these startups could significantly reduce operational costs, improve productivity, and scale their businesses more effectively. The Kenya Marine Fisheries and Socio-Economic Development (KEMFSED) project aims to enhance the socio-economic benefits of marine fisheries in Kenya by improving fisheries management, infrastructure, and market access. This initiative focuses on sustainable fisheries practices and boosting the livelihoods of coastal communities. Integrating off grid energy solutions could support these objectives by providing energy for fish processing, refrigeration, and transportation, thereby reducing post-harvest losses and increasing market competitiveness. Lastly, talking about industrial and commercial development, Kenya has prioritized Special Economic Zones (a similar model to the one China uses and had used in the past) as a key enabler to the manufacturing sector which aims at delivering industrialization and social transformation for investment attraction: easier trading mechanisms and tax exemptions make these area particularly attractive for enhancing commercial uses of energy, but logically the identified areas are densely populated and close to the main grid. A model like this, applied to off-grid areas, would be beneficial to increase the potential of commercial activities. Lack of these incentives or ways to add financial pressure to innovate (for example regulatory constraints on the amount of households to electrify, even if not profitable) is linked to the lack of productive uses of energy in these off-grid sites. According to (Trotter et al. 2022), where this society-wide objective of affordability of public services has not featured in relevant policy strategies, mini-grid companies in their sample are charging roughly double the per-kWh price compared to what mini-grid companies charge where such constraints exist.

iii) Key findings through stakeholder engagement

Interviews with sector experts provided valuable insights that reinforced the findings from the literature review and policy analysis, and helped reshaping the policy matrix to be as pragmatic and as inclusive as possible. Several respondents pointed out that, while Kenya has made notable progress in rural electrification, there are significant gaps in its policy framework, particularly in promoting integrated development and productive use of energy. One recurring issue identified through these interviews was the lack of adequate communication and stakeholder involvement in planning and decision-making processes for large-scale projects like the Kenya Off-Grid Solar Access Project (KOSAP). Despite the project's significance, many interviewees highlighted that local populations and developers were not sufficiently engaged during the planning stages. This lack of involvement has contributed to various challenges in project implementation and reduced the overall effectiveness of the electrification efforts, leading to continuous delays in the tendering process. Notably, many private stakeholders confirmed the substantial benefits of integrating development strategies, such as combining energy access with productive uses like agro-processing or cold storage. They emphasized that applying these integrated development strategies has not only enhanced the profitability and bankability of projects, but also made them more attractive to international financing institutions due to their strong social involvement approach. This alignment with socio-economic development goals improves investor confidence, as projects that actively engage local communities and promote productive uses of energy are seen as both financially viable and socially impactful. While gaps were identified, stakeholders also pointed out positive initiatives led by Kenya in terms of off-grid electrification. For instance, the fact that counties—Kenya's federal regions—are empowered to present their own electrification plans was viewed as a positive development. The National Electrification Strategy (KNES), developed in 2018, serves as a guiding document, but counties can tailor their approaches to align with their specific climatic, geological, and socio-economic conditions (21). While this approach introduces complexity in planning, as county-level plans must be harmonized with the national electrification strategy, it also ensures that local needs and challenges are addressed more effectively. Many interviewees highlighted that this decentralized planning can result in more targeted and context-specific electrification strategies, especially in rural areas with unique energy requirements.

3.2.Energy modeling results

Site selection

The Energy Access Explorer, an online platform that provides data-driven insights into energy access, played a crucial role in this process. This tool aggregates and analyzes data from various sources on demographics, infrastructure, and natural resources highlighting areas with limited energy access and identifying opportunities for energy infrastructure investment. This GIS tool allows through its datasets to apply different layers of demand, supply and demographic indicators. Figure 3.1 shows the selected layers used in the site selection process. An interactive map, shown in Figure 3.2, was constructed using the data present in the Energy Access Explorer databases gathered with additional missing data on proposed mini grid (in particular the KOSAP proposed mini grid sites managed by KPLC), detailing the locations of mini grids, including information on the technology used and the customer base. This map provided a comprehensive overview of the energy landscape, facilitating a strategic approach to site selection. The most suitable area for detailed analysis was then identified using the Energy Access Explorer tool. Selection criteria included the proximity of mini grid sites to each other, crucial for potential interconnection, the presence of crop agriculture, schools, and hospitals, and distance from the main grid. Schools and hospitals require reliable power for operation, while agricultural activities benefit from electricity for irrigation, processing, and preservation of produce, thereby supporting the local economy. Focusing on areas with these characteristics aims to maximize the socio-economic bene fits of the mini grid systems, ensuring sustainability from an operational standpoint and contributing significantly to community development. This approach helps in creating a robust demand base through public infrastructure and the productive use of energy, essential for the financial viability of the mini grids, and supports broader goals of improving living standards and economic opportunities in rural areas.

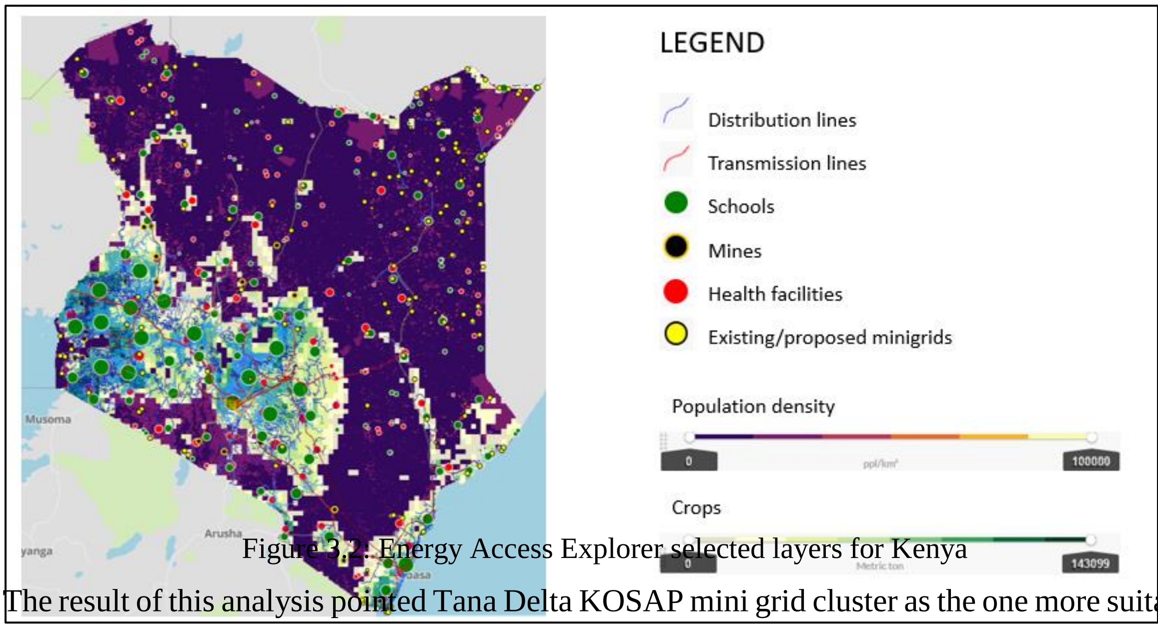

Figure 3.2: Energy Access Explorer selected layers for Kenya

The result of this analysis pointed Tana Delta KOSAP mini grid cluster as the one more suitable for our analysis shown in Figure 3.4 below.

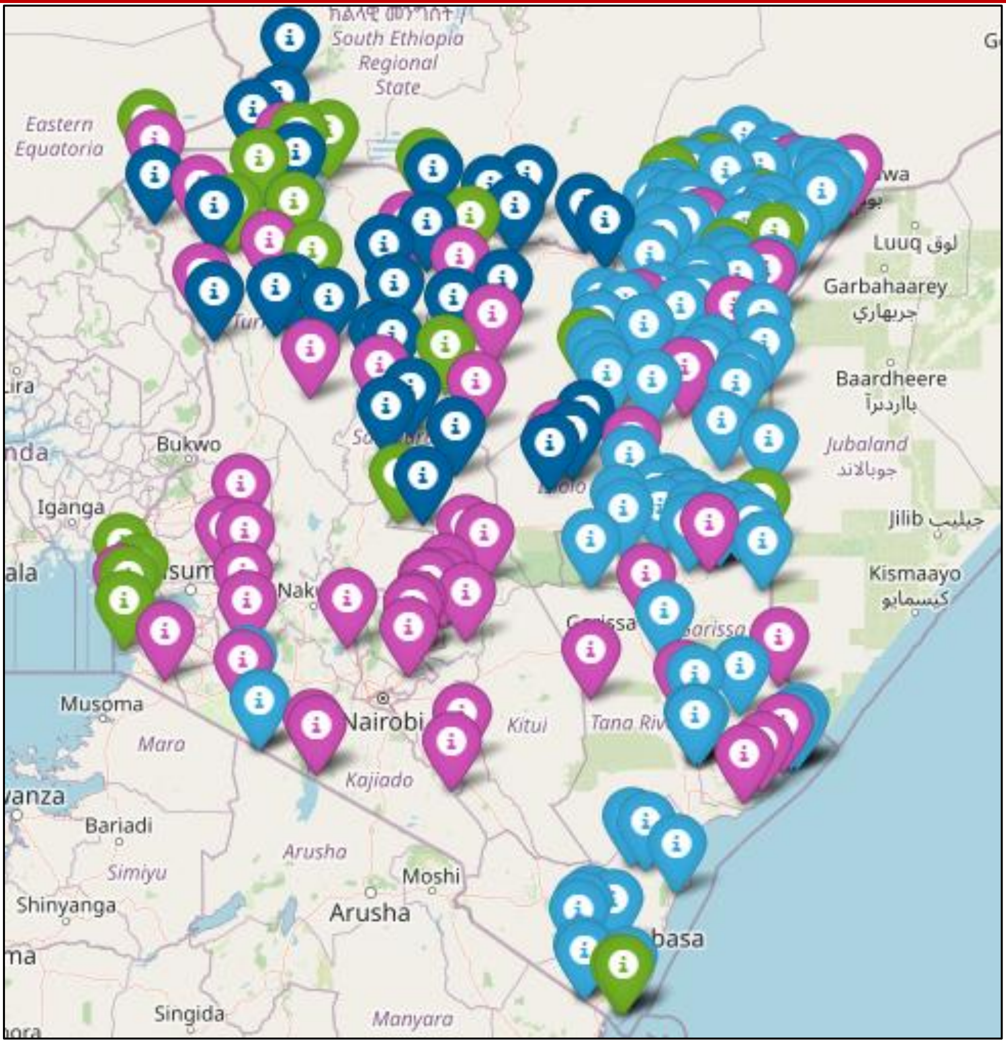

Figure 3.3: Proposed (KOSAP) and existing mini grid sites in Kenya

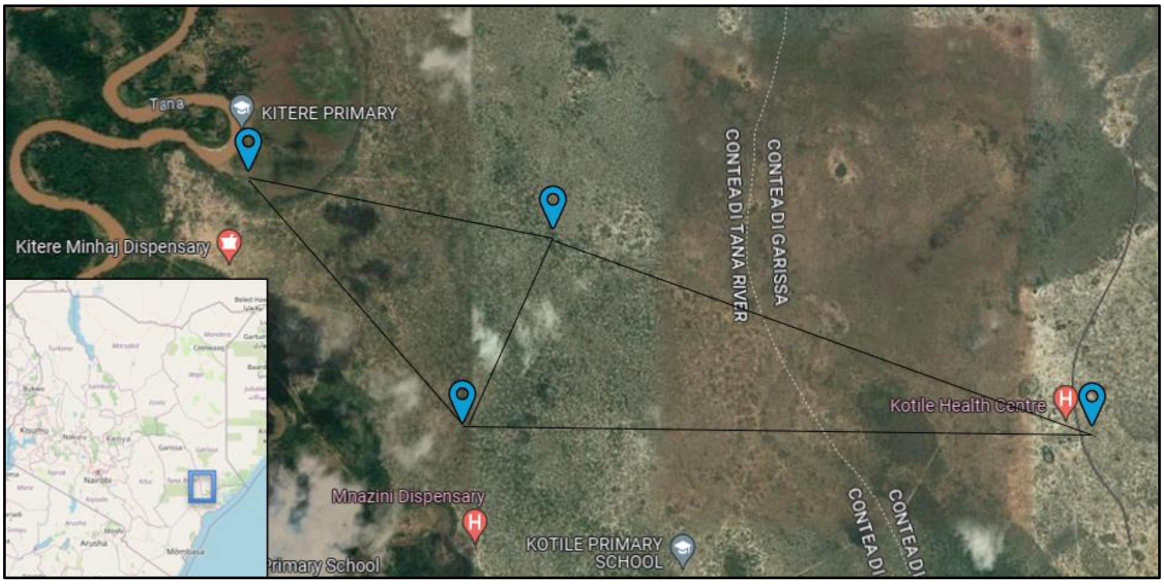

Figure 3.4: Site selection result: Tana Delta KOSAP mini grid cluster and relative distances

The fact that the selected site is part of the KOSAP project is advantageous, as the Environmental and Social Impact Assessment (ESIA) reports for KOSAP provide detailed information on the planned capacity of each technology to be installed, as well as the geographical and socio-economic characteristics of each site (Figure 3.5). This information is crucial for developers to identify the types of potential customers and their specific needs, which are essential for the Public-Private Partnership (PPP) framework.

Table 3.1: Tana River cluster main characteristics

Site	**Latitude**	**Longitude**	**Commissioning Date**	**Mini-grid technology**
Mnazini	-1,980944	40,145972	mag-25	PV-Hybrid
Kitere	-1,956722	40,151878	mag-25	PV-Hybrid
Kotile	-1,977612	40,21064	mag-25	PV-Hybrid
Munguvueni	-2,018028	40,151722	mag-25	PV-Hybrid

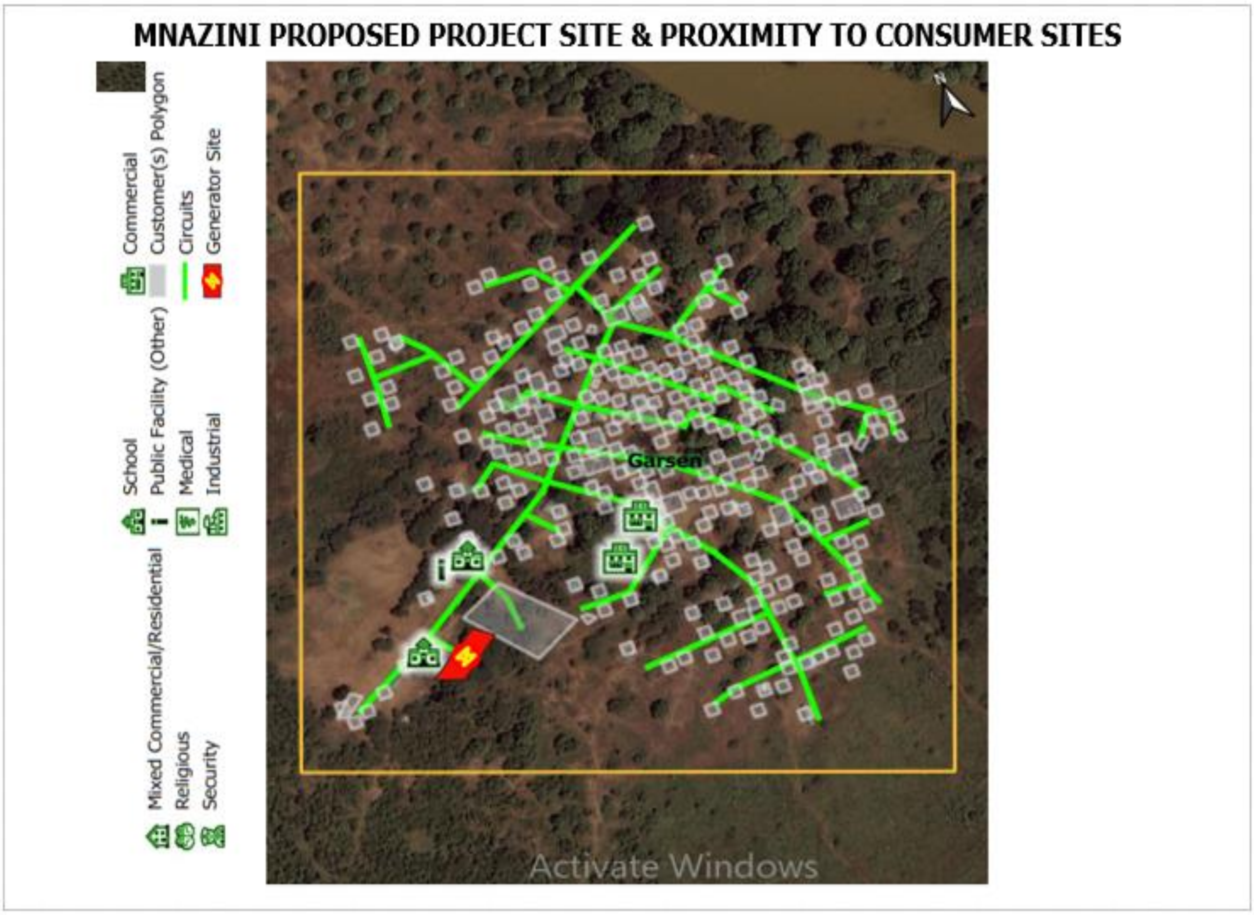

Figure 3.5: Mnazini proposed project site and proximity to consumer sites

3.3.Site characterization: Load curve

The ESIA reports offer only daily and peak demand data, which are insufficient for constructing the detailed hourly load curves necessary for modeling analysis. To address this, assumptions were made using the load curve archetypes defined in (Lorenzoni et al. 2020) "Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach" research, shown in the Figure 3.6 below.

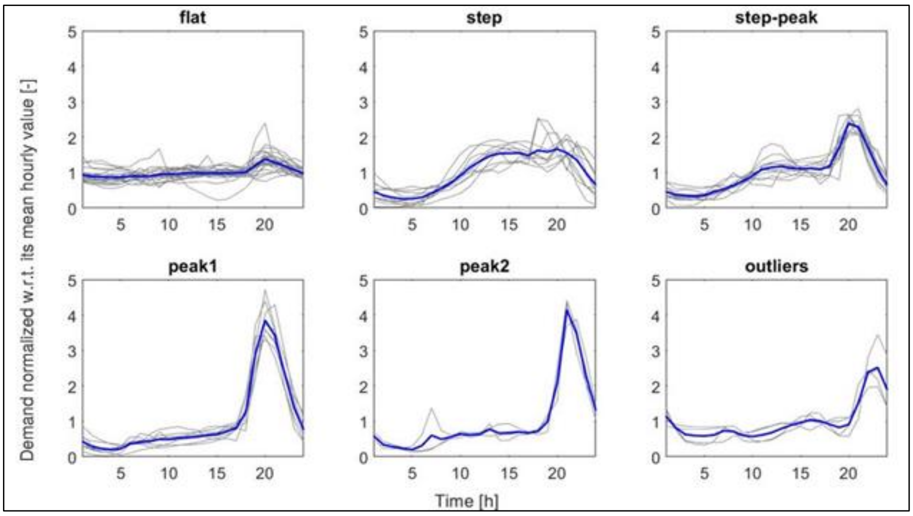

Figure 3.6 - Load demand archetypes

The share of costumers Tier per load curve archetype is shown in the Figure 3.7 below:

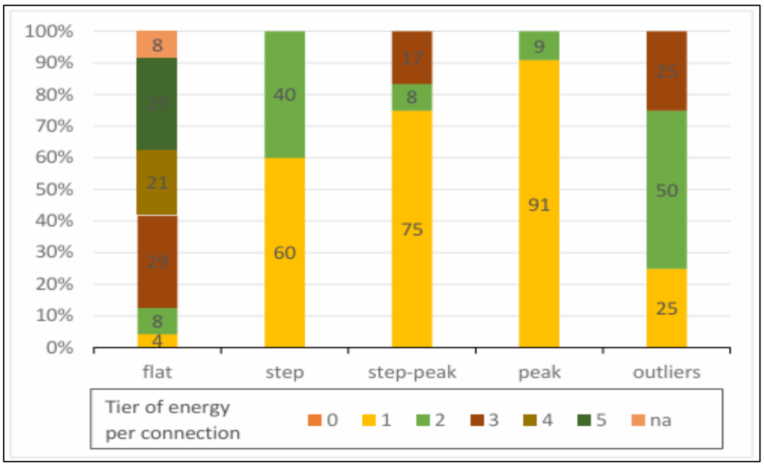

Figure 3.7 - Tier consumers share across load curve archetypes

Looking at the ESIA reports the breakdown of residential and non-residential users, which indicates a predominant majority of residential users (mostly Tier 1) versus a minority of small businesses (typically Tier 2), together with a high expected peak demand in contrast to a relatively low daily demand, suggest that the Peak archetype should be selected as our assumed archetype for the mini grid sites under our scope.

This load curve archetype, assumed to be reasonably representative of other mini-grid sites in the region, was scaled to match the selected sites, adjusting for the specific breakdown of customer types (residential, non-residential) and for the peak power forecasted in each site, as shown in the Figure 3.8 below.

The curves have slightly different shapes due to the different percentage of non-residential costumers: according to (Lorenzoni et al. 2020) load demand archetypes, we can assign 90% of non-residential costumers' contribution in the first 15 hours of the day.

The integration of these archetypes and existing data sources into a coherent load profile model helps to bridge the gap between available data and the detailed demand profiles needed for advanced energy system modeling. This approach ensures that the analysis is grounded in realistic assumptions about energy use, which is crucial for accurate system sizing and operational planning in off-grid and mini-grid contexts.

The solar renewable time series have been obtained by the well-known renewable.ninja service for the proposed case studies. Given the proximity of the sites, only one common time series was utilized.

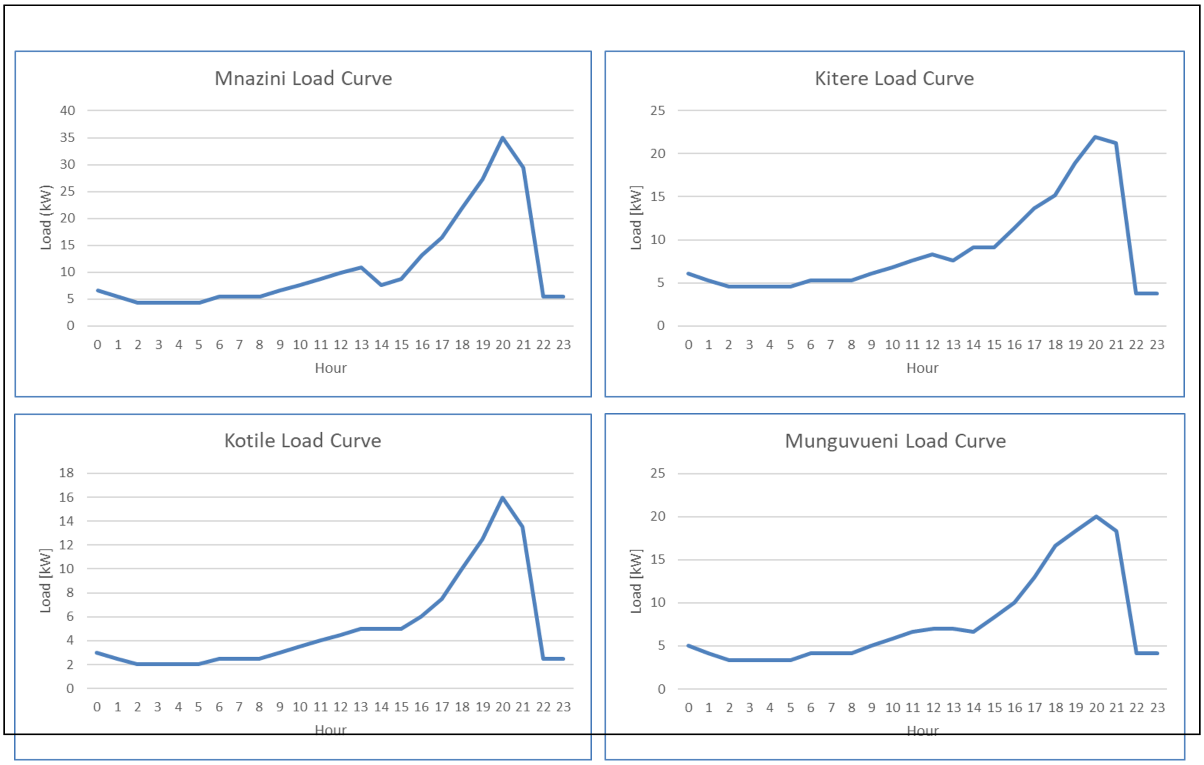

Figure 3.8: Adjusted load curves mini grid sites Tana River

3.4.Site characterization: technology performance and economic parameters

The technical parameters have been selected using the available data on the ESIA reports (20) together with the baseline scenario data listed in the Microgrids.py documentation (16), which refer to an average East African baseline case scenario.

The diesel generator operates with an efficiency of 0.25 liters per hour per kilowatt (L/h/kW). For the photovoltaic (PV) system, the inverter efficiency is set at 98%, with a tilt angle of 15° and an expected operational lifetime of 25 years. The battery energy storage system (BESS) utilizes lithium-ion technology, with a roundtrip energy conversion efficiency of 90%. The Depth of Discharge (DOD) is 80%, allowing for charge and discharge cycles within 4 hours, and the minimum cycles lifetime is specified at 3000 cycles.

Regarding the renewable energy mix, the Environmental and Social Impact Assessment (ESIA) reports indicate a goal of having a minimum of 60% of the total energy generated come from renewable sources.

In terms of economic parameters, the capital expenditure (CAPEX) for the PV system is $2000 per kilowatt, with an annual fixed operational expenditure (OPEX) of $16.6 per kilowatt. The CAPEX for the diesel generator is set at $100 per kilowatt, with an annual fixed OPEX of $24 per kilowatt and a fuel cost of $0.0493 per kilowatt-hour (kWh). Additionally, the variable OPEX for the diesel generator is estimated at $0.025 per kWh.For the battery storage system, the CAPEX is set at $250 per kilowatt. The cost of the electricity transmission line required to interconnect the mini-grid sites is estimated at $11,000 per kilometer (17).

3.5.PU growth scenario selection

A successful implementation of the discussed Integrated Development (ID) policies is expected to lead to an increase in the productive use of energy. To analyse its impact on the business models of our selected mini-grid cluster, we need to assume a certain growth in energy demand over time. The basis for our assumed demand growth is based on results drawn from real case scenarios of PU enhancements in rural settlements (11) (12).

Based on this information, the strategy could be as follows: plan for a 30% increase in energy demand every four years, with existing commercial users experiencing an annual demand growth of 48%. Additionally, the emergence of new commercial activities, which address specific village needs, could independently boost electricity consumption by 10%. These new commercial ventures might be limited to two or three, with one emerging every three years. This approach effectively synthesizes the insights from previously cited projects that have successfully implemented these policies in various off-grid locations. Moreover, this increase in electricity consumption will gradually shift the shape of the curve from a peak to a step-peak shape, which is characteristic of villages with an increased number of commercial activities (which typically operate during daytime hours, mainly between 9am and 5pm).

After implementing these changes, the projected demand shift is illustrated in Figure 3.9. A minor peak in demand, followed by a slight drop, is observed during the late afternoon hours. This pattern is consistent across various mini grid load curves and may be explained by the timing when commercial activities are winding down, but residential consumption remains low as people have not yet returned home.

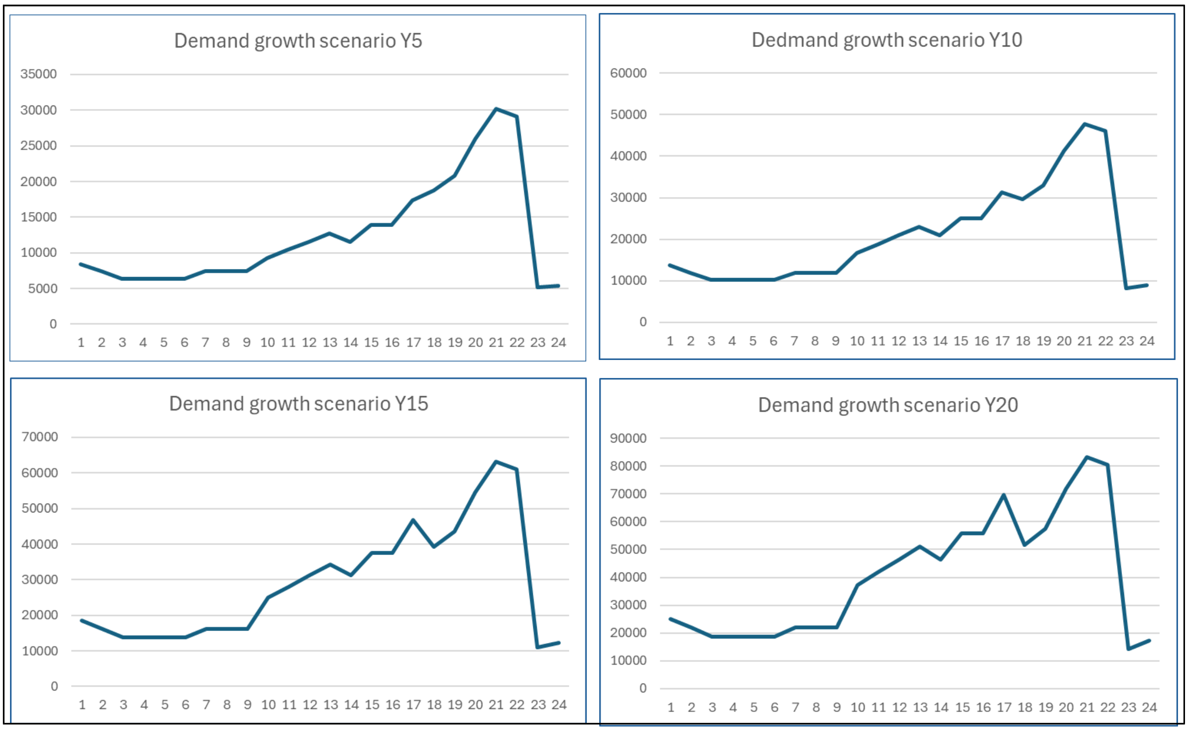

Figure 3.9: Demand growth scenario applied to Marsabit village

3.6. MicrogridsPy optimization for isolated scenario: PU vs BAU

The potential benefits of the demand growth, driven by the successful implementation of Integrated Development (ID) policies, were analyzed using MicrogridsPy software. This tool allows for the simulation and optimization of isolated mini-grid scenarios under varying demand conditions. Two distinct scenarios were explored: a baseline scenario representing the Business-As-Usual (BAU) approach, and a growth scenario reflecting an increase in productive use (PU) of energy.

Baseline Scenario (BAU):

In the BAU scenario, no demand growth was assumed. The simulation modeled an isolated mini-grid system in which all investments in energy infrastructure—such as generation capacity, storage, and backup systems—were made upfront in the first year. This scenario serves as a reference point for understanding how a static energy demand without significant growth in productive use impacts the financial and operational performance of the system.

The optimization outcomes for the four selected villages are presented in the figures below. Figures 3.10 and 3.11 illustrate the capacity sizes of each installed technology in the four villages. As shown, the optimal solution primarily relies on photovoltaic (PV) systems and battery energy storage systems (BESS), with a minor contribution from diesel-powered generators across all four cases.

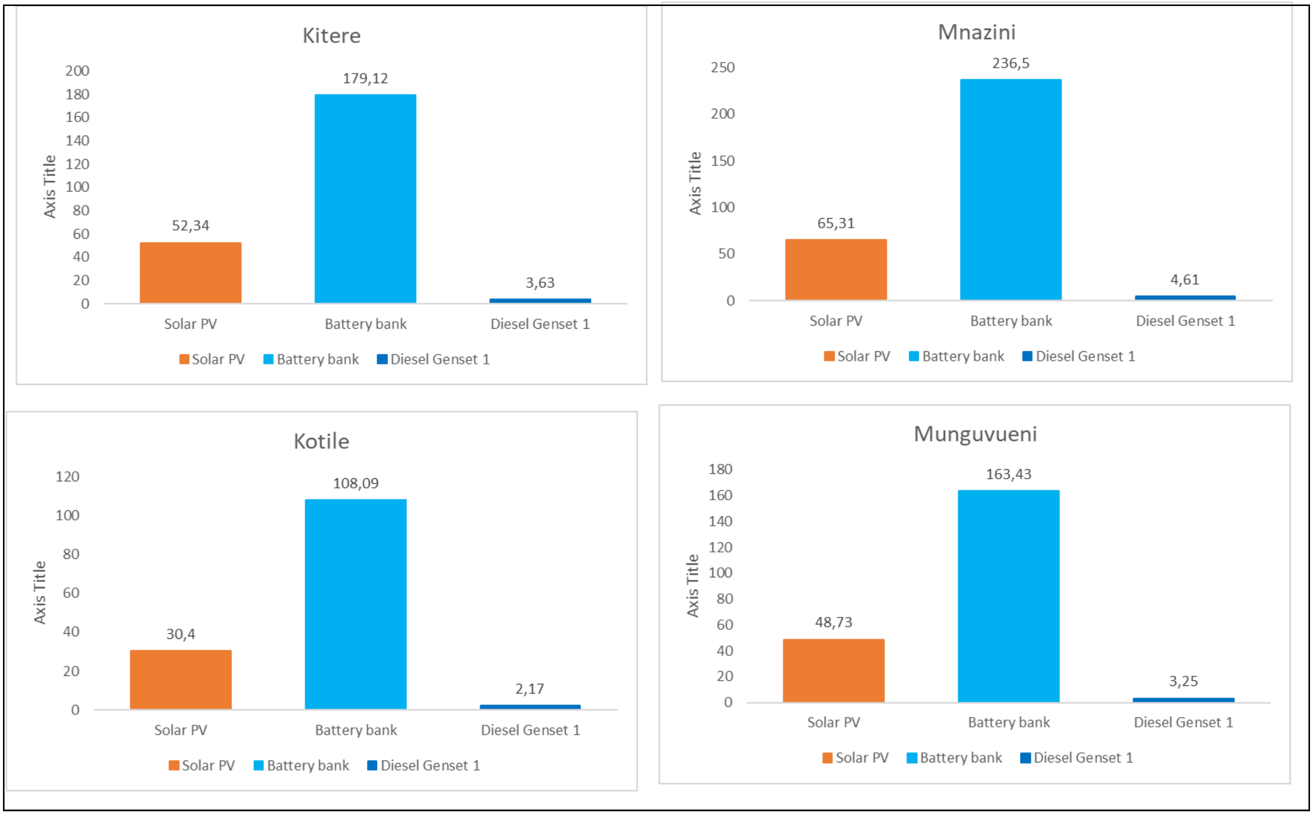

Figure 3.10: Technology capacity distribution by village (BAU scenario)

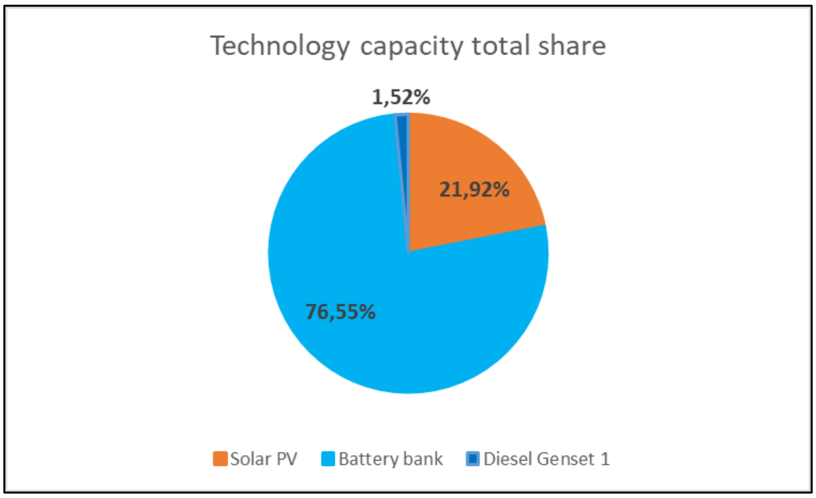

Figure 3.11: Technology capacity total share (BAU scenario)

Figure 3.12 displays the dispatch plot for the first three operational days. In this plot, curtailment occurs only on the first day, as excess PV production exceeds the system's ability to absorb it. However, in the following days, the batteries fully absorb the PV generation, ensuring smooth operation without unmet demand or further curtailment.

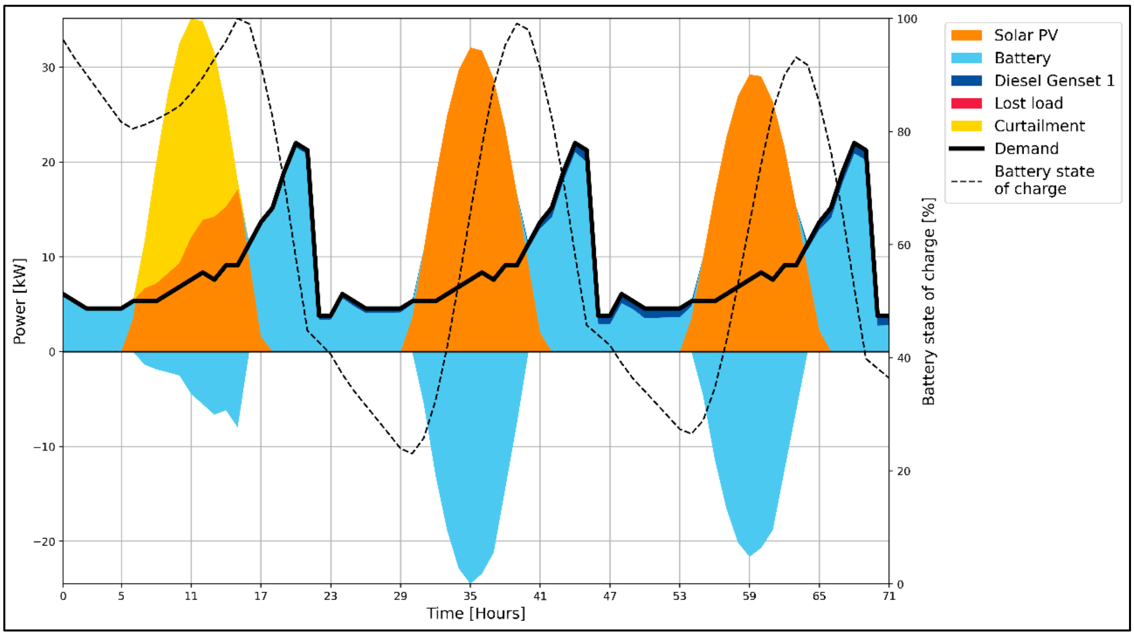

Figure 3.12: Dispatch plot (daily demand BAU scenario)

In this scenario, the system operates with minimal changes in load demand over time, which results in a relatively stable, albeit less efficient, energy use pattern. The absence of demand growth means the system doesn't benefit from economies of scale or the more efficient resource utilization that comes with increasing load factors.

Finally, the table below presents the main economic parameters for the villages, further highlighting the differences in costs and performance under the BAU scenario. As seen, the lack of demand growth limits the system's potential to reduce costs and improve efficiency:

Table 3.2 - Mini grids economic indicators (BAU scenario)

Site	**Net present cost [kUSD]**	**Yearly demand [kWh]**	**LCOE [USD/kWh]**	**Total revenue [kUSD]**	**Payback period [y]**
Kitere	94,136	76700	0,2845	436,425	4,3
Kotile	60,104	44347	0,2783	246,838	4,9
Mnazini	129,979	94900	0,2813	533,907	4,9
Munguvueni	94,136	67950	0,2845	386,640	4,9

Demand Growth Scenario (PU)

In the PU growth scenario, the anticipated increase in demand, was applied. This scenario involved four investment steps, one every five years, to match the projected increase in energy demand. Each investment phase accounted for the expansion of generation and storage capacity to accommodate the rise in productive use of energy. Given the similar characteristics of the 4 sites, let's take one as an example: The optimization outcomes for the Kitere village are presented in the figures below.

The Figure 3.13 below shows the different investment steps for each technology stacked in column

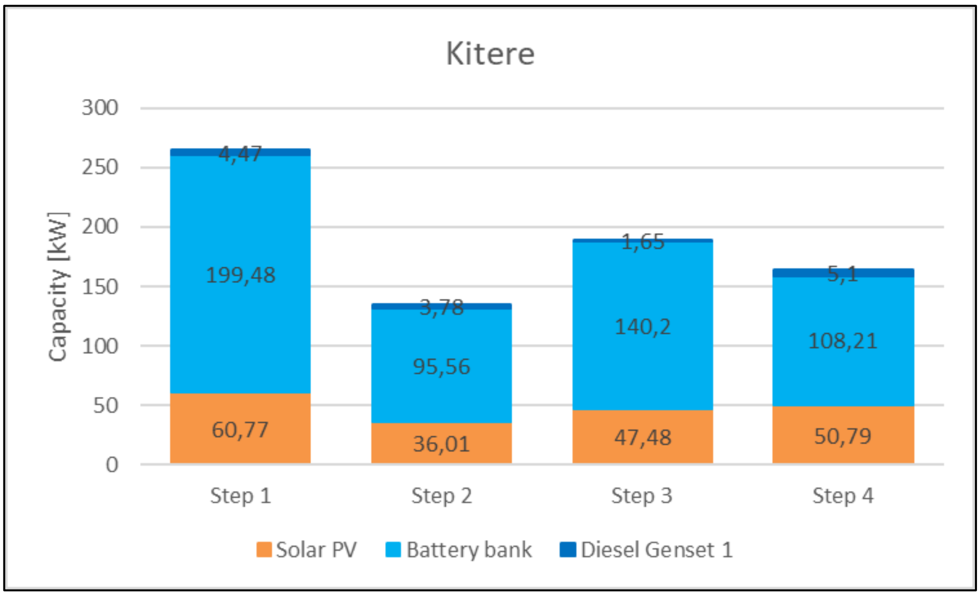

Figure 3.13 - Technology capacity distribution by investment step

By adopting a phased investment approach, the model was able to progressively scale up the system's infrastructure in response to growing energy needs, thus spreading out capital expenditures over time and improving financial sustainability.

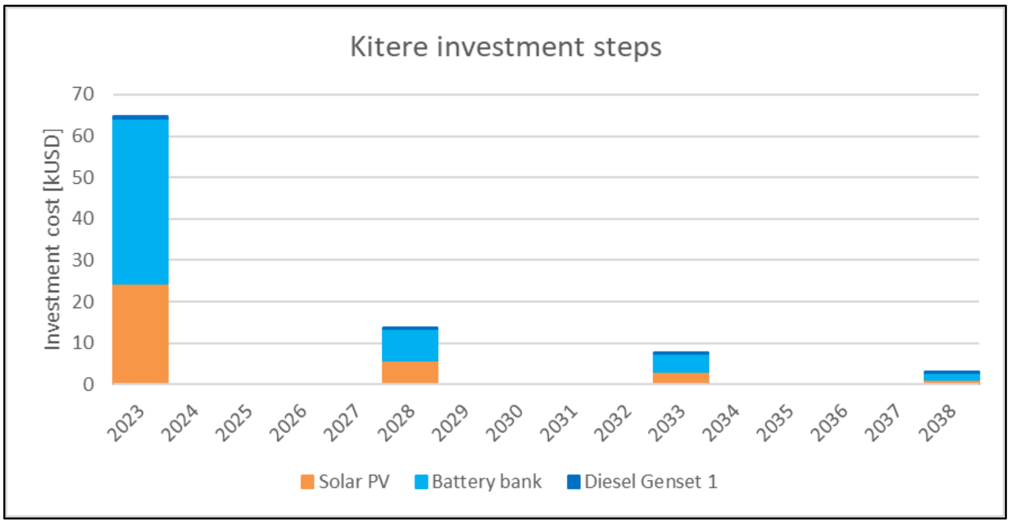

Figure 3.14 - Kitere mini grid investment steps

Despite a substantial increase in the capacity installed at each step, the investment steps are smaller each time: this happens because this is the actualized value and to each investment a 10% interest rate is applied.

Here below the Figure representing the dispatch plot and its changes every 5 years:

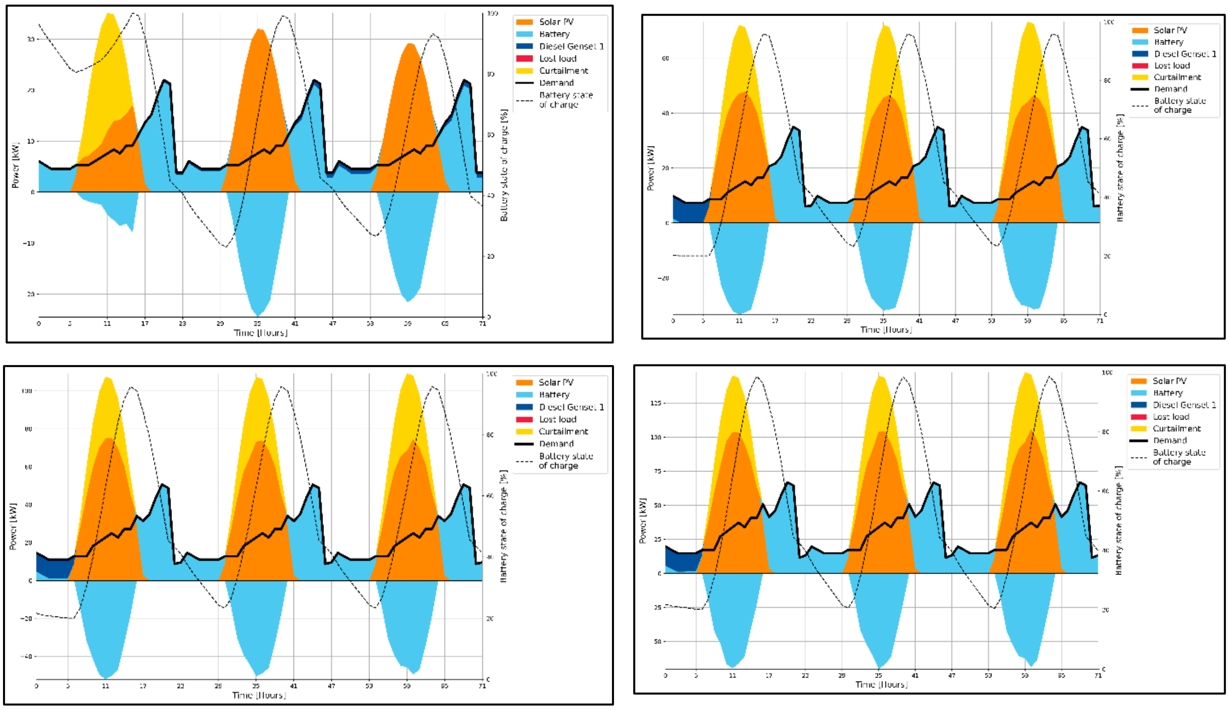

Figure 3.15 - Dispatch plot: daily demand and supply change every investment step

Table 3.3 – Kitere economic indicators (PU scenario)

Step	**Net step present cost [kUSD]**	**Total step demand [MWh]**	**LCOE [USD/kWh]**	**Step revenue [kUSD]**	**Payback period [y]**
2023-2028	107,983	466,094	0,2144	99,930	3,2
2028-2033	13,622	762,847		163,554	
2033-2038	7,623	1116,010		239,272	
2038-2043	2,757	1554,333		333,249	

For the studied Kitere site, in the PU growth scenario, with a 40% increase in NPC, the benefits included a 25% reduction in LCOE, a 91% increase in revenue, and a payback period that was achieved 25% faster.

4. Discussion

Comparing the output of the optimization simulation between the BAU and the PU scenarios, it is highlighted how the increase in demand output driven by productive use leads to a significant decrease in both the Levelized Cost of Energy (LCOE) and the Net Present Cost (NPC) of the mini-grids, relative to the amount of electricity produced and cost of the project. This cost reduction is primarily due to higher utilization rates of the installed energy systems. In the Business-As-Usual (BAU) scenario, where demand remains static, the system's capacity is underutilized, resulting in higher LCOE and NPC. Conversely, in the demand growth scenario, the increased load factors, facilitated by productive use of energy, lead to more efficient system operation and cost reductions. Additionally, this improved system efficiency and higher utilization of resources contribute to a shorter payback period (ROI) period. The combination of these factors highlights the significant financial benefits that can be achieved by fostering productive use and encouraging demand growth in off-grid energy projects.

5. Conclusions

The extensive analysis conducted throughout this thesis reveals several key shortcomings in Kenya's off-grid electrification policies, particularly when it comes to promoting Integrated Development (ID) and the productive use of energy (PU). While Kenya has made significant strides in rural electrification, its policy framework lacks a society-wide strategy that ties off-grid energy to broader economic and social development goals. This gap is especially critical when considering the potential of Business Model Innovations (BMIs) and productive use to drive private investments and foster long-term sustainability in rural electrification efforts. Kenya's rural development programs, such as those outlined in Kenya Vision 2030, focus on economic growth and sector-specific goals but do not integrate off-grid energy solu tions into these broader development plans. As a result, opportunities to maximize the benefits of electrification—through productive use in sectors like agriculture, education, and healthcare—are missed. Additionally, there are few mechanisms for involving local communities and stakeholders in decision-making processes, leaving the local population disengaged from projects that directly impact their lives. This lack of participatory processes and information-sharing instruments further hinders the effectiveness of Kenya's off-grid energy programs. The optimization analysis provided in this thesis demonstrates that addressing these policy gaps has tangible benefits. The results clearly show that fostering productive use of energy, alongside ID strategies, significantly improves the financial viability of mini-grid projects. The introduction of demand growth through productive use not only lowers the Levelized Cost of Energy (LCOE), but also reduces the payback period (ROI) period for developers. This makes mini grids more economically viable for developers, while simultaneously offering more affordable electricity to local communities. In conclusion, Kenya must prioritize the development of a more integrated, society-wide strategy that promotes the productive use of energy within its off-grid electrification efforts. Such a strategy would help bridge the gap between energy access and broader economic development, ensuring that rural electrification projects contribute to lasting social and economic benefits. By addressing these policy gaps and leveraging the demon stated benefits of BMIs and productive use, Kenya can accelerate its path to universal electrification and foster sustainable growth in its off-grid regions.

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Evaluation of the Efficiency of Tamarind Seeds Powder in Water Treatment

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ABSTRACT

Drinking water has to meet certain standards for it to be safe for public health. The World Health Organisation (WHO) has provided guidelines for the quality of drinking water. However, with increased pollution of water sources, these standards have not always been met. This has therefore necessitated the need to treat water before consumption. The main objective of this study was to evaluate the efficiency of tamarind seeds in water treatment with a key focus on pH, turbidity and coliforms. The raw water used for this study was obtained from shallow wells in Chebaiywo area of Eldoret, Kenya. Treatment of raw water was conducted using stock solution prepared from two sets of tamarind seed powder: bulk powder with effective particle size of 0.18mm (solubility 30%) and finer powder with effective particle size less than 0.15mm (solubility 63%). The results obtained from the study gave 75% to 96.4% efficiency in turbidity reduction and 88.5% to 91.3% efficiency in coliform reduction using bulk powder (D_{10} = 0.18mm). The efficiency of treatment using finer powder (D_{10}<0.15mm) gave an efficiency of 87.5 to 100% for turbidity reduction and 91% and 94.4% for coliform reduction. Treatment using finer powder therefore, gave better treatment efficiencies for both turbidity and coliform removal. The treatment however had minimal effect on the pH of water. It was concluded that tamarind seed extract is efficient in water treatment. However, the residual coliform count did not satisfy the acceptable guidelines for 0 coliform count. There is therefore need for further research in order to improve tamarind seed powder coliform removal performance.

Keywords: Tamarind seeds, coagulation, antioxidation, turbidity, coliforms, Water treatment, Eldoret, Kenya

1. INTRODUCTION

Access to safe drinking water is one of the objectives of the Sustainable Development Goals (SDGs). In particular, SDG 6 aims to achieve universal and equitable access to safe and affordable drinking water by 2030 (WHO, 2019). The World Health Organization has laid down the criterion for quality and acceptability of water for drinking to ensure good health. Drinking water must be acceptable in colour, odour and taste. It must also be free from micro-organisms, chemical substances and radiological hazards that are a threat to a human health.

Globally, more than 30% of people living in the least developed countries do not have access to improved drinking water (WHO, 2019). Statistics reveal that from 1990 to 2005, more than 1.1 billion people worldwide had gained access to improved drinking source, with 83% of people worldwide having access to improved drinking water source (Pooi and Ng, 2018). However, an estimate of 663 million people still lack access to improved drinking water and are consuming untreated water from rivers, wells, springs, and surface water (WHO, 2017). The use of unimproved water source will cause users to be susceptible to waterborne diseases.

By 2014, 31.6% of Kenyans were using unimproved drinking-water sources with 7.3% using unprotected dug wells (Mulwa and Fangninou, 2021). Nearly half (41.5%) of the rural population were using unimproved drinking-water sources (Yu et al., 2019) with bacterial contamination of drinking water being a major public health problem in rural areas. These statistics reveal that indeed access to safe drinking water is still a point of concern especially in rural areas in Kenya which must be addressed.

Overtime, several methods have been used to treat water (Sobsey, 2002) with combinations of these methods often proving to yield promising results. For instance, coagulation could be combined with disinfection (Souter et al., 2003); or media filtration followed by chemical disinfection, media filtration followed by membrane filtration, or composite filtration combined with chemical disinfection (Classen et al., 2006).

An elaborate and economically viable water treatment measure should be explored to ensure easy accessibility of quality and acceptable drinking water. Plant products have been explored for water treatment since they are eco-friendly and of low cost like Moringa seeds, soya beans (Jadhav et al., 2021; Egbuikwem and Sangodoyin, 2013).

In this study, tamarind seeds powder was used to treat water. Tamarind seeds have been explored as a natural coagulant in water treatment with a percentage turbidity removal of over 90% (Sa'id et al., 2016). The polyelectrolyte ion and polysaccharide present inside the tamarind seeds has been recognized and confirmed as one of the many factors that contribute to the efficiency of the natural tamarind seeds as the coagulant (Zainol and Fadli, 2020). The performances are almost as efficient as the commercial coagulants (Effendi et al., 2017). Tamarind seeds have also been extensively explored in reduction of total suspended solids, Sulphates and heavy metals (Sa'id et al., 2016; Effendi et al., 2017) yielding satisfactory results.

2. MATERIALS AND METHODS

2.1. Preparation of tamarind seed extraction and characterization

2.1.1. Preparation of tamarind seed powder

Tamarind fruits were acquired from Kitui, Kenya and sun-dried. Once the pods dried, they were gently pressed with fingers to split them open and the fruit soaked in water overnight after which the pulp was removed and seeds retained. The seeds were then oven-dried for 5 hours at 100°C.

Fig 1: Oven-dried Tamarind seeds

Sorting was then done to remove the defective seeds. The un-defective seeds were then ground at a hammer mill and stored in a clean container.

2.1.2. De-oiling of tamarind seed powder

De-oiling was done to optimize the protein and polysaccharide content in the tamarind seed for good treatment results. The tamarind seed powder was mixed with hexane solvent in a conical flask to achieve hexane/powder ratio of 3:1 (v/w). The mixture was then stirred and covered using aluminum foil to prevent vaporization of hexane which is highly volatile. The conical flask and its contents were then stored in a dark place in the lab for three days to allow time for extraction to take place. Filtering was then done to separate the hexane-oil mixture with the solid residue (tamarind seeds meal) using sieve size 160 micrometers. The tamarind seeds meal was then dried.

Recovery of hexane

Distillation using the Liebig's condenser set up was used to separate the Tamarind oil and hexane. Hexane has a lower boiling point of about 69°C than Tamarind oil whose boiling point is as high as 120-180°C and therefore when the mixture is subjected to heating, hexane evaporates faster and condenses and is thus recovered (Zawawi et al., 2020).

2.1.3. Tamarind Seed Powder Characterization

Particle size distribution

Particle size distribution was done to determine how the particle sizes in the tamarind seed extract are distributed and to know the effective size (D10) which in turn affects the solubility. The sieving was done according to the British Standard (BS 1377 – 2: 1990) using a stack of sieve aperture sizes 2 mm to 0.075 mm. the sieving procedure was done as follows:.

A mass of tamarind seed powder was weighed on an electronic balance (accuracy of 0.1g). The sieves were cleaned using a fine wire brush and then stacked together where, the sieve with the largest aperture size was placed at the top and that with the smallest aperture at the bottom and a pan underneath. The weighed mass of tamarind seed powder was then poured slowly into the stack of sieves which was followed by shaking the sieves manually. The mass retained on each sieve was then weighed and recorded after which the percentage passing each sieve was computed using equation 2 and consequently the effective size determined.

$$\%\, mass\ retained = \frac{mass\ retained}{Total\ mass} \times 100 \qquad (1)$$

$$\%\, passing\ = 100 - \sum_{i=1}^{i} \%\, retained \qquad (2)$$

Solubility

Solubility test was conducted to determine the effective concentration of the stock solution used in the treatment. Solubility test gives insight into the portion of tamarind seed extract that will be active in water treatment and is a factor of the effective particle size.

Solubility test was done for the Tamarind Seeds Powder by dissolving 1g of Tamarind seed powder in 100ml of cold water and determining the mass dissolved in water using equation 3.

$$Dissolved\ mass\ = Initial\ mass - (Mass\ of\ wet\ filter\ paper\ with\ residue - Mass\ of\ dry\ filter\ paper\ and\ residue) \qquad (3)$$

The solubility was done for the combined powder, the powder retained on each sieve and powder passing sieve 0.15mm. The solubility was then computed using equation 4. Figure 2 below shows the colour change upon dissolving the tamarind seed powder in water.

$$Solubility = \frac{Dissolved\ mass}{Initial\ mass} \times 100 \qquad (4)$$

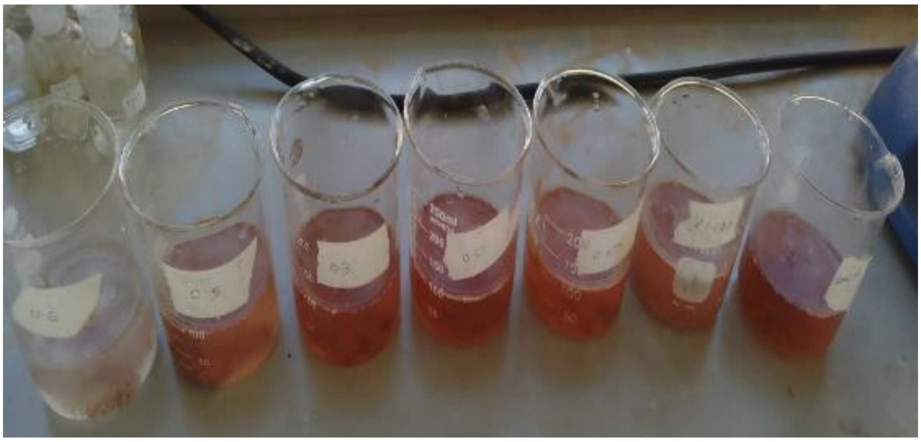

Fig 2: Colour change from dissolution of tamarind seed extract

Preparation of tamarind seed extract solution (coagulant)

The coagulant was prepared by dissolving 10g of tamarind seed meal powder in one litre of distilled water to form 1% of the solution. The stock solution was prepared for both bulk powder and the powder with particle sizes less than 0.15mm.

2.2. Collection of water sample

The water samples used for the study were collected from shallow wells randomly selected in Chebaiywo area of Eldoret. The wells in the area were given numbers and four wells randomly selected from the population. The water samples were filtered during collection to remove large suspended solids.

2.3. Determination of quality of raw water

Three parameters (pH, turbidity and faecal coliform count) of the raw water from each well were determined before treatment was commenced.

2.3.1. pH determination

The pH was determined using a pH meter. This involved cleaning the pH meter with distilled water and then dipping it into the water sample after which the pH value was read off.

2.3.2. Turbidity test

The turbidity meter used was Paqualab Photometer. The Palintest method was used to determine turbidity of the water sample and value read off in Formazin Turbidity units (FTU). The tube was filled with 10ml of the sample and placed on the photometer and phot 47 selected on the photometer and the Turbidity reading obtained.

2.3.3. Test for Faecal coliforms

This was carried out using membrane filtration technique with m-FC agar plates at 44.5 °C for 24 hours (Grabow, 1996). The volume of groundwater sample analysed was 100 ml as required since the standard method of reporting the results of microbial analysis is the number of colony forming Units per 100 ml (CFU/100ml) volume analysed.

2.4. Jar test

A standard jar test procedure was conducted to determine the optimum dosage and the contact time required to optimize the treatment efficiency for samples drawn from each well.

The samples were mixed homogeneously and one litre of sample measured into each of the six beakers. The coagulant was added into the beakers in different dosages starting with 10 ml in beaker 1 and making a 10 ml increment in each other beaker. The mixture was stirred rapidly at 120 rpm for 5 minutes, followed by slow mixing at 40 rpm for 20 minutes. The mixture was then allowed to settle for 30 minutes. After the 30 minutes settling time, the supernatant was carefully drawn and tested for residual turbidity, pH and faecal coliforms. The testing was done at intervals of 30 minutes to determine the optimum contact time. The final turbidity and pH for each beaker measured using a photometer and pH meter was recorded. The final Faecal coliforms count was also obtained for the supernatant for each dose of coagulant and after the different contact times.

2.5.Analysis of results

The removal efficiency of turbidity and Faecal coliforms was computed using equations 5 and 6 shown below.

$$\text{Turbidity removal efficiency} = \frac{\text{Initial turbidity} - \text{Final turbidity}}{\text{Initial turbidity}} \times 100 \quad (5)$$

$$\text{Faecal Coliform (FC) reduction efficiency} = \frac{\text{Initial FC count} - \text{Final FC count}}{\text{Initial FC count}} \times 100 \quad (6)$$

3. RESULTS

3.1. Effective size of Tamarind Seed Powder

Figure 3 below shows the results for particle size distribution for the bulk tamarind powder.

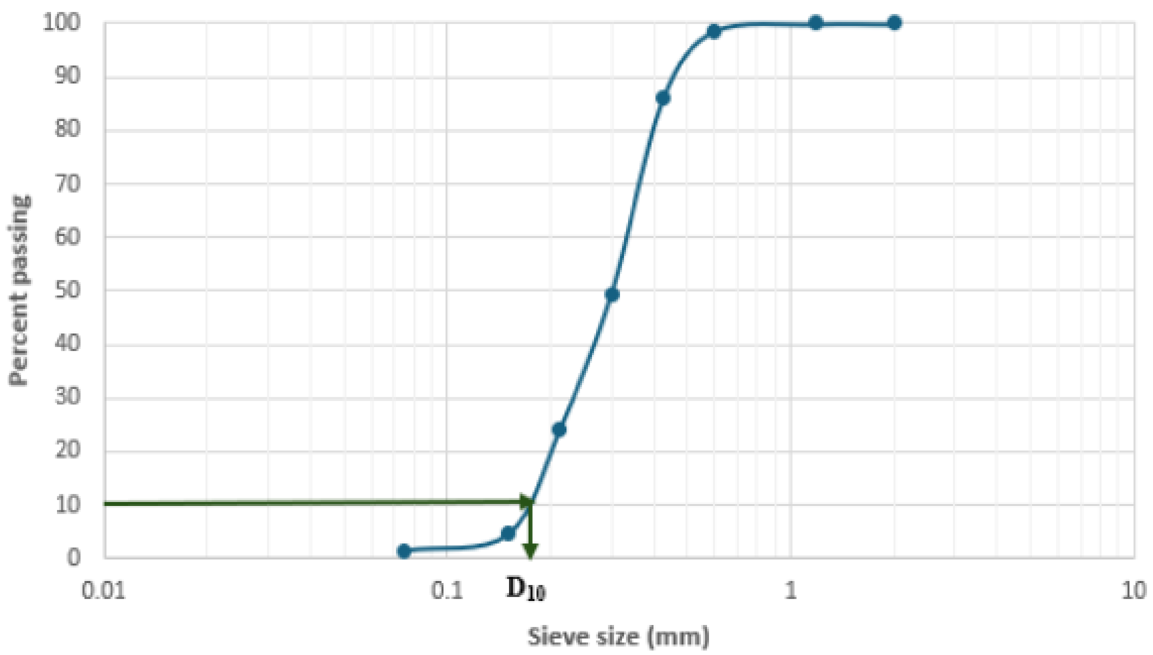

Fig 3: Particle size distribution curve for tamarind seed powder

From the particle distribution curve above, the effective size (D10) of the bulk powder was determined as 0.18 mm.

3.2. Solubility of Tamarind Powder

Table 1 below shows the solubility of the tamarind seed extract.

Table 1: Solubility of tamarind seed powder

Sieve size (mm)	Mass of residue (g)	Mass dissolved (g)	Solubility (%)
0.6	0.7916	0.2084	20.84
0.425	0.7116	0.2884	28.84
0.3	0.7106	0.2894	28.94
0.212	0.7098	0.2902	29.02
0.15	0.705	0.295	29.5
0.075	0.3754	0.6246	62.46
< 0.075 (Pan)	0.3390	0.6610	66.1
Bulk powder	0.6990	0.3010	30.1
< 0.15mm	0.3700	0.6300	63.0

3.3.Treatment Efficiency of Tamarind Seed Powder

The removal efficiency of tamarind seed powder was computed in terms turbidity and Faecal coliforms reduction. Table 2 below gives the raw water quality for the samples collected from four wells.

Table 2: Raw water quality

Well no.	Turbidity (FTU)	Coliform Count (CFU/100ml)	pH
1	28	46	6.79
2	20	18	6.61
3	12	36	6.48
4	8	78	6.53

Figures 4 and 5 below gives the treatment efficiency of tamarind seed bulk powder (D10=0.18) in terms of turbidity removal and coliform reduction respectively, of well 1 water. Table 3 below shows the reduction efficiencies of water samples from all the four wells sampled.

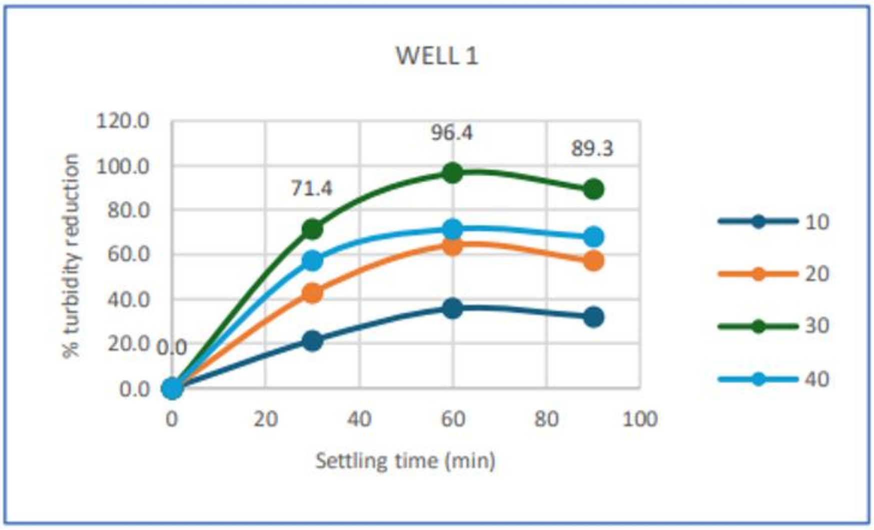

Fig 4: Turbidity reduction curve for well 1 (Tamarind seed powder D_{10} = 0.18mm)

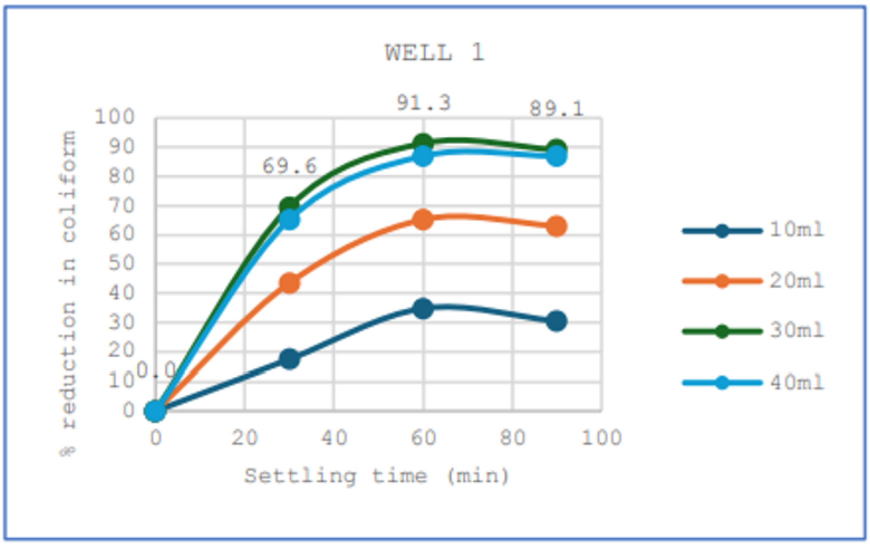

Fig 5: Coliform reduction curve for well 1 (Tamarind seed powder D10 = 0.18mm)

Table 3: Water Treatment efficiencies of water samples using bulk tamarind seed powder (D10=0.18mm)

Well No.	**Residual turbidity**	**% Turbidity reduction**	**Residual coliform**	**% Coliform reduction**	**Residual pH**	**SD of pH**
1	1	96.4	4	91.3	6.81	0.0540
2	1	95	2	88.9	6.62	0.0431
3	1	91.7	4	88.9	6.38	0.0312
4	2	75	9	88.5	6.62	0.0344

Water samples from Well 1 were also treated using the stock solution from fine tamarind seed powder of particle sizes less than 0.15 mm (Fig 6 and 7).

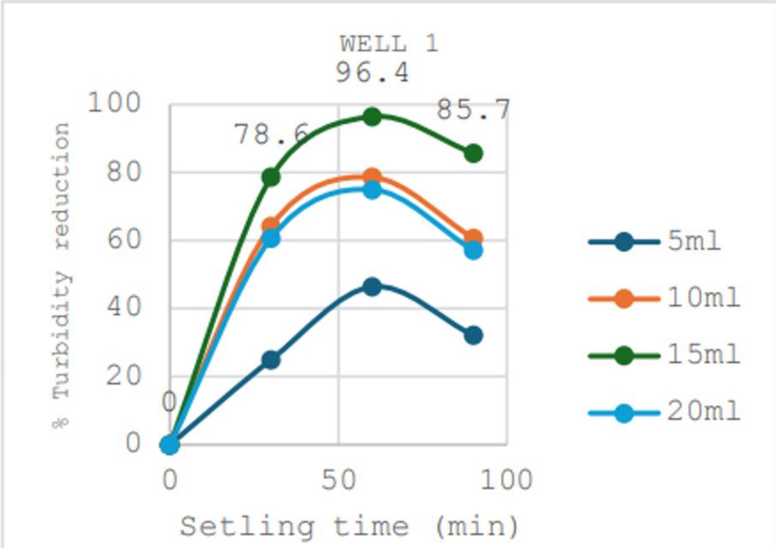

Fig 6: Turbidity reduction curve for well 1 (Tamarind seed powder D_{10} < 0.15mm)

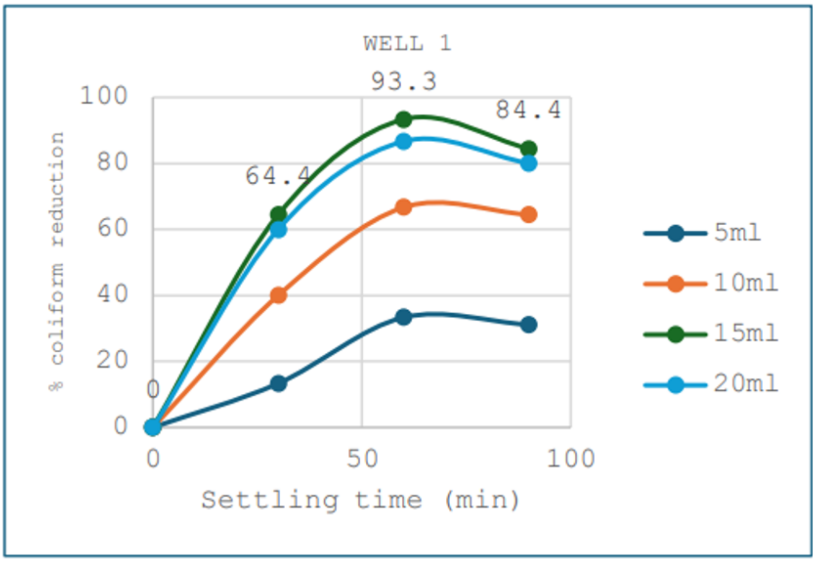

Fig 7: Coliform reduction curve for well 1 (Tamarind seed powder D10 = 0.18mm)

Table 4 below shows the treatment efficiencies of water samples from all the selected four wells using fine tamarind seed fine powder (D10<0.15).

Table 4: Treatment efficiencies of water samples using fine tamarind seed fine powder (D_{10}<0.15).

Well No.	**Residual turbidity**	**% Turbidity reduction**	**Residual coliform**	**% Coliform reduction**	**Residual pH**	**SD of pH**
1	1	96.4	3	93.3	6.81	0.054
2	1	95	1	94.4	6.62	0.0431
3	0	100	2	94.4	6.38	0.0312
4	1	87.5	7	91	6.62	0.0344

4. DISCUSSION

4.1. Tamarind Seed Powder Particle Size and Solubility

The effective size of the tamarind seed bulk powder was 0.18mm (Fig. 3) and this indicates the particle size that is effective in the treatment process and it affects the solubility in that, the larger the effective size, the lesser the solubility (Johnson, 2012). Solubility increases with decrease in the effective size of particles (Marcotte et al., 2020).

The solubility increased from 20.84% for mass retained on sieve 0.6 mm to 66.1% (Table 1) for mass retained on the pan. This therefore illustrates that solubility is dependent on the particle size of the solute. The smaller particles have a greater surface area to volume ratio which allows for more solvent molecules to interact with the surface of solute (Seager et al., 2018). The increased interaction is responsible for the higher dissolution rate and thus greater solubility in the solvent. On the other hand, larger particles have a smaller surface area to volume ratio and therefore less interaction of the solute and solvent accounting for the lower solubility rate (Sun et al., 2012).

The polarity of the molecules also affects the solubility rate in a given solvent (Jagtap et al., 2018). Tamarind seed powder contains proteins and carbohydrates that are polar due to the presence of functional groups like hydroxyl (-OH) and amine (-NH2) that form hydrogen bonds with water (Tolstikov and Fiehn, 2002). Tannins which are present in the tamarind seeds are polyphenolic compounds which exhibit polar characteristics (Santos-Buelga et al., 2012). Water is also a polar molecule and thus tamarind seed powder is able to dissolve in water due to their same polarity (Tolstikov and Fiehn, 2002; Santos-Buelga et al.,2012; Breynaert et al., 2020).

4.2.Turbidity Reduction Efficiency of Tamarind Seed Powder

It is observed from figure 4 and 6 that upon addition of the Tamarind seed extract, the turbidity decreased rapidly as the extract effectively neutralised the charges of the particles causing them to clump together and settle out of the water. With time, the rate of turbidity reduction slowed down. The turbidity reduction efficiency increased with the settling time from 0 minutes to 60 minutes beyond which it began to reduce slowly. The decrease in turbidity efficiency beyond 60 minutes could be attributed to re-suspension of particles. This happened when the flocs that were formed were not robust enough and they broke apart releasing particles including bacteria trapped in the flocs back into the water and thus increasing turbidity (Yukselen and Gregory, 2004). It can also be attributed to biological growth where bacteria contained in the settled water could increase/grow since the active ingredients of the extract have been used up in coagulation and what is left behind could be a substrate of the bacteria (Egbuikwem and Sangodoyin, 2013). The optimum settling time was therefore 60 minutes.

On the other hand, it was observed that increasing the dose of tamarind seed extract from 10ml consequently resulted in the increase of turbidity reduction (figure 4). This is because as the dose was being increased, there was an increase in the concentration of the active ingredients hence better efficiency. However, beyond 30ml dose, the efficiency of turbidity reduction slightly decreased. This could be due to charge reversal where with addition of more tamarind seed extract beyond 30ml, particles in the water acquired positive charge and repelled each other preventing aggregation and leading to an increase in turbidity (Kumar et al., 2017; Soni and Singh, 2019). It could also be due to excess tamarind seed extract that led to formation of smaller and lighter flocs that did not settle well or even broke apart further increasing the turbidity (LeeChoong et al., 2018). The optimum dose was therefore 30ml.

Treatment using tamarind seed extract (D10<0.15mm) as observed in Figure 6 resulted in turbidity reduction with increase in the dose from 5ml to 15ml due to a high amount of active ingredients. Beyond 15ml dose, the efficiency of turbidity reduction slightly decreased due to charge reversal and formation of lighter flocs. The optimum dose for the treatment was determined as 15ml.

It is observed from figure 6 that the best turbidity reduction efficiency remained the same at 96.4% for water samples from well 1, when tamarind seed extract size D10<0.15mm was used for treatment. However, the turbidity removal efficiency improved for well 3 samples from 91.7% (table 3) to 100% (table 4). The turbidity removal efficiency also slightly improved from 75% (table 3) to 87.5% (table 4) for water sampled from well 4. This could be attributed to high solubility of tamarind seed powder of small effective size (D10<0.15mm) that resulted in a high amount of active ingredients in the extract (Seager et al.,2018).

4.3. Coliform Reduction Efficiency of Tamarind Seed Powder

It is observed from figure 5 that the coliform reduction increased with increase in the tamarind extract dose from 10ml to 30ml and then slightly decreased for a dose of 40 ml. The coliform reduction efficiency increased with settling time from 0 minutes to 60 minutes beyond which it slightly decreased. The mechanisms of coliforms reduction are coagulation and antioxidation

(Egbuikwem and Sangodoyin, 2013; Soni and Singh, 2019). During coagulation, coliforms were trapped in the flocs alongside other particles and settled down with the flocs thus reducing their count in the water (Egbuikwem and Sangodoyin, 2013; Zenebe, 2022). This therefore explains why the coliform reduction pattern was similar to that of turbidity reduction (figure 4). On the other hand, Tamarind seeds contain phenolic compounds that have antioxidant properties (Soni and Singh, 2019). They degrade organic compounds including living organisms. They also damage the membrane and cell walls thus reducing their resistance to osmotic pressure (Sudjaroen et al., 2005). This therefore also accounted for coliform reduction in the samples.

Treatment using tamarind seed extract (D10<0.15mm) as observed in Figure 7 resulted in coliform reduction with increase in the dose from 5ml to 15ml due to a high amount of active ingredients. Beyond 15ml dose, the efficiency of coliform reduction slightly decreased due to charge reversal and formation of lighter flocs.

Coliform reduction efficiency improved to 93.3% from 91.3% reduction efficiency when treatment with fine tamarind powder (D10<0.15mm) was used to treat water samples from well 1(figures 5 and 7). It is also observed from Table 4 that treatment using tamarind seed extract of size D10<0.15mm improved the coliform removal efficiencies for the water samples from all the four wells. This could also be attributed to the small effective size of the tamarind seed powder that accounted for its high solubility in water (Seager et al.,2018) and therefore a high amount of active ingredients in the extract.

4.4. Effect of Tamarind Seed Powder on Water pH

With regard to effect on pH (Tables 2, 3 and 4), it was observed that the average standard deviation (SD) of pH from the mean is 0.04. The small standard deviation shows that the values of pH obtained are clustered around the mean. The pH of treated water (Table 3 and 4) varied from the pH of raw water (Table 2) with a deviation of ± 0.2. This depicts that tamarind seed extract has minimal effect on the pH of water. The observation is because the pH of 1% tamarind seed extract solution is 6.8 which is almost similar to the pH of raw water.

5. CONCLUSIONS

This study revealed that the efficiency of turbidity reduction using the bulk tamarind seed powder (D10 =0.18mm) ranged from 87.5 % to 96.4%. It also gave coliform reduction efficiency ranging from 88.5% to 91.3% with the treatment having minimal effect on the water pH. Treatment of water using the tamarind seed extract solution made from fine powder with particle size less than 0.15mm (D10 <0.15mm) gave high turbidity reduction efficiency ranging from 87.5% to 100% and, coliforms reduction efficiency of 91% to 94.4%. This shows that using a finer powder of tamarind seed yielded better treatment results and is recommended as the optimum particle size (D10 <0.15mm). The optimum dose of tamarind seed extract made from powder of 0.18mm effective size (D10=0.18mm) was found to be 30 ml (90 mg/l) for both coliform and turbidity reduction; and the settling time 60 minutes. The optimum dose for tamarind seed extract made from fine powder with particle sizes less than 0.15mm was found to be 15ml (94.5 mg/l) while the settling time still remained at 60 minutes.

Tamarind seed extract was thus efficient in turbidity reduction as it reduced the turbidity to acceptable guideline value for drinking water. It was also efficient in coliforms reduction. However, the guideline value of 0 coliforms count in drinking water was not achieved. This calls for more research using tamarind seed powder to explore ways of improving its performance to achieve 100% coliform reduction.

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The use of Recycled Plastic Material for Interlocking Blocks Road Pavement Construction in Kenya

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Abstract

This research addresses significant environmental concerns and global efforts to combat climate change by exploring sustainable alternatives to traditional construction materials. The study aimed to replace cement in paving blocks with molten recycled plastic, thereby reducing environmental pollution and conserving natural resources. Additionally, it sought to develop a high-performance alternative to conventional paving blocks. The research involved experimental analysis of pavers made from recycled plastic. Waste plastic was fused with river sand at high temperatures using an extrusion machine and molded into shape while in a semi-solid state. Various engineering tests were conducted, including assessments of water absorption, density, compressive strength, tensile strength, skid resistance, and abrasion resistance, to evaluate their suitability for road construction. The results demonstrated that the recycled plastic pavers exceeded the required standards for water absorption (0.505% vs. 6%), tensile strength (5.34 N/mm² vs. 3.6 N/mm²), and abrasion resistance (2.14% vs. 24.62% for natural materials). They were lighter than traditional concrete pavers, with a bulk density of 1740 kg/m³ compared to 2400 kg/m³ for concrete. While the compressive strength met the standards for medium and light-duty traffic, it fell short for heavy-duty traffic (35.5 N/mm² vs. 49 N/mm²). The pavers also exceeded skid resistance requirements for roads with over 2000 VPD but were less effective in high-traction areas. The findings suggest that recycled plastic can be sustainably used in road construction, though further research is needed to enhance production efficiency and address identified performance limitations.

Keywords: Cement, Pollution, Density, Compressive strength, Tensile strength, Performance, Abrasion, Standards.

1. Introduction

The growing issue of plastic waste presents significant environmental challenges, including increased pollution and pressure on waste management systems. In Kenya, where 92% of solid waste is improperly managed approximately 37000 tons of plastic ends up in the ocean each year (Paruta et al, 2020). This study investigates an innovative solution to address these problems by replacing cement with recycled plastic as a binder in paving blocks. By combining waste plastic with river sand at high temperatures, the research evaluates the viability of these plastic-based pavers for road construction, focusing on their strength, physical and mechanical properties and economic viability. Previous research has highlighted the potential of using plastic to replace cement, though challenges remain. While plastic- sand pavers in Kenya are priced slightly higher that traditional concrete pavers, they offer superior abrasion resistance and reduced water absorption. The tensile strength of these pavers meet the requirement for non-motorized transport pavements such as pedestrian walkways and cycling lanes (Abigail, 2022). Additionally, (Rajat et al., 2023) reported a comprehensive strength of up to 41N/mm2, while (INGABIRE Dominique , 2018) noted compressive strengths of 26N/mm2 and water absorption as low as 0.52%. Despite similar production and testing methods, previous studies have yielded inconsistent results (Mazen, 2022). This research introduces a unique set of test parameters- including compressive and tensile strength, abrasion resistance, skid resistance, water absorption, and bulk density. By comparing these results with international and local standards, the study advocates for the use of plastic-sand pavers across various traffic categories. Testing was guided by British and local standards of testing.

From The study recycled plastic can be effectively replace cement in paving blocks, offering improved road quality and reduced construction costs, with benefits for modes of transport. The Overarching goal is to minimize environmental impact, conserve natural resources, create new jobs and provide a high-performance alternative to traditional concrete paving blocks.

2. Methods

To make plastic-sand pavers, clean, Shredded plastic waste and river sand were sourced from local suppliers. The materials were thoroughly mixed using a shovel at a ratio of 3 parts plastic and 7 parts sand by weight. The mixture was then loaded into the hopper of an extrusion machine. Through the application heat and friction, the materials were fused into a semisolid state and injected into paving block molds. A compression machine was used to compact the material before setting. After setting under pressure, the paving blocks were demolded and cooled in a water bath. After approximately 30mins of cooling, the six samples were weighed (in Kilograms) and their dimensions- length (L), width(W) and height(H)- measured and noted using a vernier caliper. Bulk density was then calculated through equation (1) and compared to the bulk density of traditional concrete pavers.

$$\text{Bulk Density} = \frac{Weight(Kg)}{(LxWxH)m3} \quad (1)$$

The surfaces of six other plastic-sand paver samples were cleaned to remove dust, debris and dirt, and oven-dried at 100°C for 24hrs. The process was repeated until a constant weight was achieved. The final dry weight for each sample was recorded and the average mass notes as M1. Following the drying process, the samples were then fully submerged in water at room temperature for 24hrs. After immersion, the samples were surface-dried with a clean cloth and the process repeated to achieve a constant weight for each sample and their average weight noted as M2. The water absorption was calculated using equation (2). The test procedure was in alignment with (BS EN 1338, 2003)and the results were compared to the standard requirements.

$$\text{Water Absorption \%} = \frac{\text{M2}-\text{M1}}{\text{M1}}\text{x100} \quad (2)$$

The surfaces of six another plastic-sand paver samples were cleaned to remove dust, debris and dirt. The lengths and widths dimensions of the bearing surfaces were measured to the nearest 2mm and used to calculate the average bearing area, A (mm2). The bearing surfaces of compression test machine were cleaned, and each specimen placed into the machine so that the load applied to the opposite sides of the samples. Each sample was aligned centrally on the machine base plate. They were then subjected to a gradual, continuous load at a constant rate of 140Kg/cm2/min until failure occurred. The maximum loads sustained by each sample was recorded as W (KN). The compressive strength of each test sample was determined through equation (3). A correction factor of 1.06 was also applied to cater for the chamfer on the test samples. The average compressive strength of the plastic-sand pavers was calculated and compared to the average compressive strength of six control samples of traditional concrete pavers obtained from the local market and tested using the same compressive strength test procedure. The test procedure was in alignment with KS 827, 2003 method of testing for compressive strength and the results of the test were compared to the standard requirements.

$$\text{Compressive strength} = \frac{\text{Wx1000}}{\text{A}} \text{x } 1.06 \qquad (3)$$

Six more plastic-sand paver samples were cleaned to remove dust, debris and dirt after 24hrs of soaking in water at room temperature. Each sample was surface dried, aligned centrally on a compressive machine base plate and subjected to a gradual, continuous load at a constant rate of 140Kg/cm2/min through packing pieces as prescribed in BS EN 1338 until failure occurred. The maximum loads sustained by each sample was recorded as P (Newtons). The tensile strength of each test sample was determined through equation (4). The test procedure and method of calculation are aligned to BS EN 1338 method of testing tensile strength. The results of this test were compared to the standard requirements.

$$\text{Tensile strength}=0.637xkx\frac{P}{s} \qquad (4)$$

Where: k is a Thickness correction factor

P is the failure load in N

S is the test plane area (Lx H)

Twelve new plastic- sand samples were cleaned of debris and inspected for surface defects. A British pendulum tester was then set up and leveled using a spirit level and the leveling screws on the device’s frame. The head of the tester was then raised by releasing the locking knob and adjusting the height control knob until the pendulum arm and the foot could swing clear of the test sample. The pendulum arm was then raised to a horizontal position on the right side of the tester and secured with the release catch mechanism. The pointer was rotated anticlockwise to its stop position parallel to the pendulum arm. Zero setting was checked by releasing the pendulum arm to allow it to swing freely, and the arm was caught on its return swing. Next the leading edge of the slider was gently lowered onto the surface of the sample. The contact path length between the points of contact of each of the slider was set between 125mm-127mm. The test samples and slider were then sprayed with water, and the pendulum arm was released to swing through the arc. The arm was caught on its return swing before the slider touched the surface again and the reading indicated by the pointer was recorded. The procedure was repeated six times for both wet and dry samples to get the average reading for each sample and calculate the average skid resistance. A Temperature correcting factor of 1.0 applied to the readings, in accordance with (EN 13036-4, 2011) guidelines and the results of the test were compared to the standard requirements.

Abrasion resistance was evaluated using the Los Angeles abrasion test, a standard method for assessing the durability and wear of materials under simulated conditions of wear and tear. In this study, the abrasion resistance of natural aggregates was compared with shredded HDPE plastic of similar particle size. A five- kilogram sample of shredded HDPE plastic was divided into two portions: 2.5kg passing through 14mm and 10mm sieves, and 2.5kg passing through 10mm and 5mm sieves. The total sample was placed in a rotating drum with 11 steel balls. The drum was rotated at 33 revolutions per minute for 15 minutes. Afterward, the material was passed through a 2.36 mm sieve, and the retained weight was measured. This procedure was repeated with a sample of natural aggregates typically used in traditional paving blocks, and the results compared.

3. Results

Bulk Density and water absorption

The average water absorption of the plastic-sand pavers was measured at 0.505%, significantly lower than the standard requirement of 6% as specified by (BS EN 1338, 2003), a standard that defines the requirement for paving units, including their water absorption characteristics, to ensure durability and performance in various condition. The low water absorption of the plastic-sand pavers indicates better resistance to water ingress, which contributes to greater durability, especially in areas prone to waterlogging. These findings align with results from previous studies. Karma Tempa et al.,2022; S. Agyeman et al., 2019), reported water absorption rates of 0.63% and 0.56% respectively, closely matching the results of the current study. All studies show that plastic-sand pavers surpass the standard water absorption resistance requirements.

The average bulk density of the plastic-sand pavers was found to be 1740kg/m3, significantly lighter than traditional concrete pavers with a density is about 2400kg/m3. The density of the plastic-sand pavers is 0.725 times that of traditional concrete pavers. The lower density means a reduction in transportation and handling costs, making the plastic-sand pavers a more cost-effective option. (Karma Tempa et al, 2022) reported the bulk density of HDPE plastic-sand pavers to be 1601kg/m3 while (John, 2019) observed a bulk density of 1678.67kg/m3. The variances between these findings and the current findings are 3.5% and 7.99% respectively, indicating a small difference that could have resulted from the differences in the methods used in making test samples. However, the variance between the plastic-sand pavers and traditional concrete pavers is significant at 37.93%, to the advantage of the plastic-sand pavers.

Compressive Strength

The study found that the average compressive strength of 40 mm thick plastic-sand pavers was 42 N/mm², outperforming standard market-sampled 50 mm thick pavers, which had an average compressive strength of 40 N/mm². Compressive strength is a critical parameter for paving blocks, as it directly influences their ability to withstand the predominant forces applied during use. Similar studies conducted by (Rajat et al., 2023), (Karma Tempa et al, 2022), and (Susila et al, 2019) reported compressive strengths of 39.67 N/mm², 32.6 N/mm², and 32.7 N/mm², respectively. The higher compressive strength found in this study may be attributed to the manufacturing process, where the pavers were subjected to high-pressure compaction, unlike in the previous studies.

According to (KS 827, 2003), the required compressive strength for paving blocks is at least 49 N/mm² for heavy-duty applications, 35 N/mm² for medium-duty, and 25 N/mm² for light-duty applications. While previous studies suggested that plastic-sand pavers are adequate for light-duty applications such as pedestrian walkways, office driveways, and low-traffic rural roads, the current study indicates that the compressive strength of these pavers also makes them suitable for medium-duty applications. These include city streets, small to medium market roads, and low-volume arterial roads (IS 15658, 2006).

Tensile Strength

Few studies have investigated the tensile strength of plastic-sand pavers. Abigail (2022) found that the tensile strength of her plastic-sand pavers was 2 N/mm², while the BS EN 1338:2003 standard recommends a tensile strength of 3.6 N/mm². The current study found that an average tensile strength of up to 5.34 N/mm² could be achieved. The variation in results may be due to differences in the size and shape of the test samples, as larger or more irregular samples can affect the way tensile forces are distributed. The higher tensile strength observed in this study suggests that the pavers exceed the standard requirement and are therefore suitable for pavement construction. Tensile strength is an essential parameter because paving blocks are often subjected to tensile stresses due to uneven bedding layers, lateral forces, or temperature fluctuations. A higher tensile strength ensures greater resistance to cracking, better durability under lateral forces, and enhanced impact resistance. These properties contribute to the overall structural integrity and longevity of pavement installations. Further research into the factors affecting tensile strength in plastic-sand pavers could provide valuable insights for optimizing their performance in various applications.

Slip/Skid Resistance

Slip resistance is a critical factor in road safety, as it allows vehicles to navigate sharp corners, descend steep slopes, and stop safely in emergency situations. For pedestrian walkways, adequate slip resistance reduces the risk of slips and falls, making it an essential consideration for both vehicular and pedestrian surfaces. Slip/skid resistance is a key requirement in paving block construction, with standards such as (BS 6717, 2001)providing specific guidelines for acceptable levels of resistance. According to (BS 6717, 2001), a minimum skid resistance of 35 is recommended for pedestrian walkways, while 45 is required for vehicular traffic. Higher skid resistance values are necessary for special applications, such as approaches to traffic lights or steep gradients. (Lillian Gungat et al, 2020) achieved a wet slip resistance of 60 in her study on partial sand replacement with recycled plastic, demonstrating the potential of plastic-sand pavers in skid/slip resistance. The current study found that plastic-sand pavers had an average slip resistance of 47, making them suitable for both pedestrian and vehicular use under standard conditions. However, according to the Transport and Road Research Laboratory (TRRL) guidelines (1969), more demanding areas—such as roundabouts, sharp bends, and steep gradients—require skid resistance values as high as 65. This indicates that while plastic-sand pavers meet the general requirements, further research is needed to improve their performance in challenging conditions. Future studies could explore surface treatments or alterations to enhance slip resistance, particularly for high-risk areas.

Abrasion Resistance

Road pavements are constantly exposed to friction from both vehicular and pedestrian traffic. To ensure long-term durability, road surfaces must be resilient to wear. The safety of road users depends heavily on the friction generated by their interaction with the pavement surface. Without adequate friction, the road would lose its skid/slip resistance, compromising safety. Therefore, maintaining the surface's frictional properties throughout the pavement's life is essential. Abrasion resistance, which measures a material's ability to resist wearing or smoothening, is a key indicator of durability. In this study, the Los Angeles abrasion test was used to evaluate the performance of recycled plastic materials compared to traditional aggregates used in manufacturing pavers. The results showed that the recycled plastic material lost only 2.14% of its weight, whereas natural aggregates lost 24.16%. This indicates that the plastic material performed 11.29 times better than traditional aggregates in terms of abrasion resistance. These findings are consistent with other studies. (Rajat et al., 2023) found that the abrasion resistance of plastic-sand pavers was 11%, while (Abigail, 2022) and (Karma Tempa et al, 2022) reported losses of 0.01% and 0.38%, respectively. The variation in results could be attributed to differences in testing methods. However, the overall trend confirms that plastic-sand pavers generally exhibit superior abrasion resistance compared to traditional concrete pavers and this could lead to longer pavement life and reduced maintenance.

Economic Sustainability

Economic sustainability is a critical pillar for the success of any construction material. It must compete effectively with alternative solutions. In Kenya, Abigail (2022) found that finished plastic-sand pavers were retailing at 800KSh, about 6.7% higher than traditional concrete pavers, which sold for 750KSh. However, this study shows that the variance in the cost of raw materials is even more significant. In Bhutan, Karma Tempa et al. (2022) reported a cost benefit of 29.39% to 32.25% for plastic-sand pavers compared to traditional pavers. In contrast, the current study found that the raw material cost for 50mm thick concrete pavers in Kenya is 463KSh, whereas plastic-sand pavers cost 645KSh, representing a 40% higher cost in raw materials for plastic-sand pavers. The primary cost driver in the production of plastic-sand pavers is the cost of shredded plastic waste. However, mass production could eventually mitigate this challenge. Additionally, plastic-sand pavers require significantly less production time. Unlike concrete pavers, which need 28 days to cure, plastic-sand pavers set in under 30 minutes and are immediately ready for application. This rapid turnaround time could translate to savings in overhead costs, making the production of plastic-sand pavers potentially more efficient over time despite the higher initial material costs.

4. Discussion

The study reveals that plastic-sand pavers outperform traditional concrete pavers in several critical parameters, such as water absorption, bulk density, and tensile strength. These findings are consistent with previous research by (Karma Tempa et al, 2022) and (S. Agyeman et al, 2019), both of which demonstrate that plastic-sand pavers exhibit superior water absorption resistance. Similarly, previous reports show that plastic-sand pavers have a lower bulk density, making them a cost-effective and lightweight alternative. The compressive strength, though slightly lower than required for heavy-duty applications, is consistent with findings in other studies (Rajat et al., 2023). On tensile strength, the study noted strengths of up to 5.34 N/mm^2, exceeding some of previous findings like (Abigail, 2022) 2 N/mm^2. The abrasion resistance of plastic-sand pavers is also significantly better than traditional pavers, with the study findings matching those by (Rajat et al., 2023). This study advances the field of engineering by complimenting the findings of other previous studies and exploring the possibility of the expansion of application of the plastic-sand pavers to modes of transport other than non-motorised transport based on their superior physical and mechanical properties and highlighting some of their weaknesses for future studies. Superior performance in bulk density, water absorption, tensile strength and abrasion resistance demonstrates potential benefits for road safety and pavement longevity. Future research could focus on optimizing the mix ratio to reduce raw material cost and increase compressive strength, mass production methods could lower production costs, and specific treatments could increase skid resistance for more demanding road conditions.

5. Conclusions

Overall, the results presented strongly support the case for using plastic-sand pavers as a viable alternative to traditional concrete pavers. They not only meet, but often exceed, the relevant standards in terms of water absorption, compressive strength, tensile strength, slip resistance, and abrasion resistance. While there are areas for further improvement—particularly in slip resistance for high-risk conditions—plastic-sand pavers show significant promise for a wide range of applications, from pedestrian walkways to medium-duty roadways. This combination of performance and cost-efficiency makes them a sustainable and practical choice in modern construction projects.

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