Uniosun Journal of Engineering and Environmental Sciences (UJEES), Vol. 8 No. 3, March, 2026
DOI: 10.64980/ujees.v8i1.031 **Oluwole and Yakubu**
Published: March 30, 2026

ENVIRONMENTAL IMPACT OF LIGHT EMITTING DIODE (LED), ORGANIC-LED (OLED) AND MICRO-LED TELEVISION TECHNOLOGIES

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Abstract

Light Emitting Diode (LED), Organic Light Emitting Diode (OLED), and Micro-Light Emitting Diode (Micro-LED) represent key innovations, each with distinct operational mechanisms, efficiency patterns, and recyclability prospects. While earlier studies emphasized image fidelity and consumer appeal, limited empirical data exists comparing these technologies on sustainability indicators such as energy use, carbon emissions, and life-cycle impacts. Addressing this gap is critical given rising e-waste concerns, escalating energy demand, and the pressing climate agenda. The study aimed to conduct an assessment of LED, OLED, and Micro-LED televisions to determine their relative strengths in energy efficiency and environmental sustainability. Power consumption was measured with high-precision Wattmeter, while luminance was captured using calibrated photometers. Life-cycle Assessment (ISO 14040/44) and carbon emission modelling quantified environmental burdens, while recyclability indices were derived from material composition studies. Results indicated a consistent hierarchy: Micro-LED > OLED > LED. Micro-LED recorded the lowest annual energy consumption (131.4 kWh) compared to OLED (160.6 kWh) and LED (175.2 kWh), alongside the highest luminous efficacy (11.1 lm/W). Carbon emissions followed a similar trend, with Micro-LED emitting 65.7 $kgCO_2$ annually versus OLED (80.3 $kgCO_2$) and LED (87.6 $kgCO_2$).

Keywords
Carbon emissions, LED, OLED, Micro-LED, LCA

1. INTRODUCTION

Television display technologies have advanced rapidly over the past decades, transitioning from cathode-ray tubes (CRT) to liquid crystal displays (LCD), and more recently, to light-emitting diode (LED), organic light-emitting diode (OLED), and micro-light-emitting diode (Micro-LED) systems. As one of the most popular household electronics worldwide, televisions contribute significantly to energy consumption, e-waste generation, and resource depletion. Each technological leap has been driven by the pursuit of enhanced image quality, energy efficiency, and environmental sustainability [1, 2]. LED televisions represent a key improvement over LCDs, offering greater brightness, longer lifespan, and reduced power consumption. OLED displays, with self-emissive pixels, eliminated the need for back-lighting and enabled superior contrast ratios, deeper blacks, and wider viewing angles [3]. Nonetheless, OLED faces challenges such as shorter lifespans due to organic material degradation, high energy intensity at peak brightness, and relatively low recyclability [4]. Micro-LED, the most recent development, combines the advantages of LEDs and OLEDs by using self-emissive inorganic pixels, delivering exceptional brightness, luminous efficacy, durability, and recyclability [5]. However, its large-scale adoption remains limited by high production costs and technical complexity in mass manufacturing [6].

The increasing adoption of modern televisions has intensified concerns regarding their role in global energy demand and electronic waste generation. Consumer electronics account for a significant share of household electricity use and contribute heavily to e-waste, creating urgent sustainability challenges [7]. Yet, much of the existing scholarship has prioritized performance-oriented parameters such as image resolution, viewing angles, and response times [1, 3], while under exploring energy consumption, life-cycle carbon emissions, and recyclability

This study addresses the problem by evaluating the energy efficiency and environmental impacts of the three technologies, focusing on life-cycle power consumption and carbon emissions under varying grid-intensity scenarios and end-of-life recyclability potential for LED, OLED, and Micro-LED technologies. Beyond picture quality, factors such as energy efficiency, recyclability, and life-cycle carbon emissions are becoming critical evaluation metrics, particularly in response to global efforts to reduce electronic waste and lower carbon footprints [8]. This paper is essential for stakeholders aiming to make informed technological, environmental, and economic decisions.

Light Emitting Diode (LED) TVs are a form of LCD (Liquid Crystal Display) technology, using light-emitting diodes to provide back-lighting. Unlike traditional LCDs that use fluorescent tubes, Light Emitting Diode (LED) back-lighting offers better brightness, slimmer form factors, and improved energy efficiency. Organic light-emitting diode (OLED) technology represents a significant leap forward by enabling each pixel to emit its own light, eliminating the need for a backlight. This self-emissive property allows OLED TVs to achieve perfect blacks, faster refresh rates, and superior color reproduction [4]. Despite their high image quality, OLED panels face challenges such as image retention, shorter lifespan, and high production costs due to complex organic material processing. Light Emitting Diode (LED) technology is widely available and more affordable compared to its competitors, which makes it the dominant choice in the market today [9]. However, because Light Emitting Diode (LED) TVs rely on a backlight that illuminates the entire screen, they struggle to produce true blacks and high contrast levels, especially when compared to self-emissive technologies like Organic Light Emitting Diode (OLED) and Micro-LED [10]. Figure 1 presents the structural layout of an LED television, which integrates LED backlighting with an LCD (Liquid Crystal Display) panel to generate visual output. The system typically includes a backlight unit either edge-lit or direct-lit/full-array that provides illumination, as the LCD itself does not emit light [11]. In edge-lit models, a light guide plate is used to distribute light evenly, supported by diffuser sheets that prevent brightness inconsistencies [2].

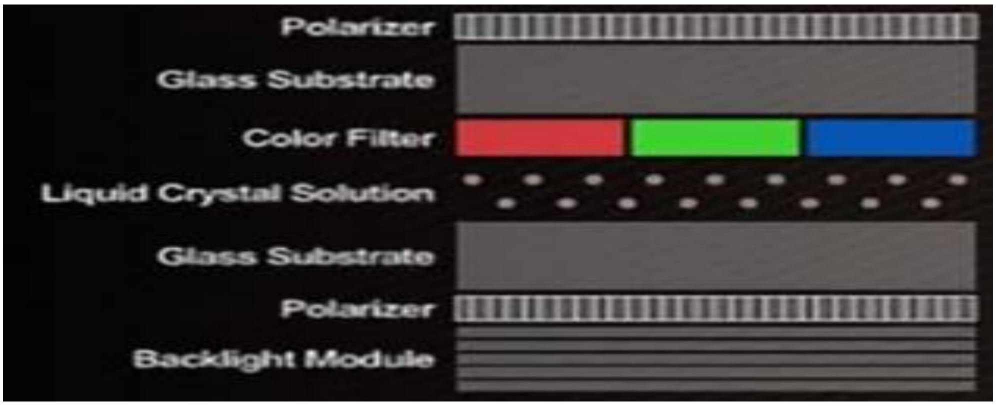

Figure 1: Structural diagram of LED Television [11].

At the core is the LCD panel**,** which modulates the backlight to form images. Over this lies a color filter layer, dividing light into red, green, and blue sub-pixels to produce full-color visuals. Polarizing filters on both sides of the panel manage light orientation, enabling precise control of pixel transparency. Additionally, control electronics including a timing controller and driver circuits regulate the display operation. The entire assembly is enclosed by protective layers and a bezel**.**

LED TVs, or Light Emitting Diode televisions, operate using a backlight display system where liquid crystal displays (LCDs) are illuminated by LED backlights. The core mechanism relies on modulating the backlight through the liquid crystal matrix using an active thin-film transistor (TFT) layer to create images. The technical configuration comprises a layered structure of polarizers, glass substrates, a liquid crystal matrix, and RGB color filters. The LED backlight (typically edge-lit or direct-lit) provides the necessary luminance. These displays are not self-emissive, and therefore suffer from limitations in contrast, especially in reproducing deep blacks, as the light is always present behind the liquid crystal panel. The power efficiency of LED TVs is determined by the LED driver circuit's modulation capability, the panel’s brightness settings, and the overall screen size. In regions like Nigeria, where power consumption is critical, energy-efficient models with local dimming features are preferred [12]. However, the inability to completely shut off individual pixels results in light leakage and increased power draw during high-contrast scenes. The working principle of LED TVs is built upon a backlit liquid crystal display (LCD) panel. Essentially, a white LED backlight is placed behind or along the edges of the LCD, supplying illumination. The LCD panel itself does not emit light; instead, it modulates this backlight using liquid crystal molecules controlled by thin-film transistors (TFTs). When voltage is applied to specific TFTs, the crystals align or twist to control the amount of light passing through color filters (red, green, and blue), thereby creating the desired image. This structure demands a continuously active backlight, even for black scenes, leading to higher power consumption and relatively limited contrast ratio [13, 14].

LED technology, though originating from traditional LCD panels, has seen notable advancements in terms of backlighting, color reproduction, and power efficiency.

Early LED TVs relied on edge-lit backlighting, which limited control over brightness distribution. Full-array local dimming (FALD) represented a breakthrough, enabling precise control over LED zones across the display. This technology resulted in enhanced contrast ratios and a better overall visual experience for HDR (High Dynamic Range) content [2]. More recently, Mini-LED backlighting, which integrates thousands of tiny LEDs, allows for an even finer degree of control and higher brightness without compromising contrast. This advancement narrows the quality gap between LED and OLED displays while maintaining the longevity and affordability of LED technology [15].

Quantum Dot technology has significantly improved LED displays by introducing a layer of nanoscale particles that emit precise colors when illuminated. This enhancement, termed QLED (Quantum Dot LED), dramatically improves color purity, brightness, and viewing angles. QLED technology has enabled LED TVs to achieve nearly 100% color volume, making it a strong competitor to OLED in color performance.

Organic Light Emitting Diode (OLED) displays are based on organic materials that emit light when an electric current is applied. Unlike LED TVs, which require backlighting, Organic Light Emitting Diode (OLED) pixels are self-emissive, meaning each pixel can independently turn on or off. This results in superior contrast ratios, true black levels, and enhanced color accuracy [3]. Organic Light Emitting Diode (OLED) technology is highly regarded for its excellent picture quality, especially in dark scenes, but it comes with limitations. Organic Light Emitting Diode (OLED) panels are expensive to produce, and they suffer from issues such as image burn-in and shorter lifespan due to the organic materials used. Additionally, Organic Light Emitting Diode (OLED) screens tend to consume more power in bright scenes compared to Light Emitting Diode (LED) and Micro-LED screens. Figure 2 illustrates the structural composition of an OLED (Organic Light Emitting Diode) television, which differs fundamentally from LED TVs by employing a self-emissive display technology meaning each pixel emits its own light and does not require backlighting [15]. The structure includes multiple organic layers sandwiched between two electrodes: the anode and cathode**.**

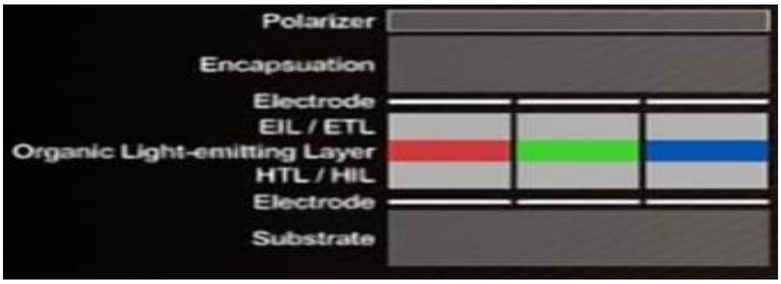

Figure 2: Structural diagram of OLED Television [1]

Central to the design are the organic emissive layers**,** typically consisting of a hole injection layer (HIL)**,** hole transport layer (HTL)**,** emissive layer (EML)**,** electron transport layer (ETL)**,** and electron injection layer (EIL). When a voltage is applied, electrons and holes recombine within the emissive layer, releasing energy in the form of visible light. Unlike LCDs, this eliminates the need for a color filter and backlight, allowing OLED displays to achieve deeper blacks, higher contrast**,** and superior viewing angles. The substrate, which can be glass or flexible plastic, supports the entire stack, and a thin-film encapsulation (TFE) layer protects the organic materials from moisture and oxygen both of which degrade OLED performance. The diagram emphasizes OLED's structural simplicity and image-quality advantages, including faster response times and thinner displays, compared to backlit technologies like LED-LCD.

Organic Light Emitting Diode (OLED) TVs operate based on self-emissive pixel technology. Each pixel comprises an organic compound that emits light upon electrical excitation. This eliminates the need for backlighting, thus enabling superior contrast ratios and true blacks, as individual pixels can be completely turned off. The structure of OLED panels includes multiple organic layers sandwiched between two electrodes, with a transparent encapsulating layer to protect against oxygen and moisture degradation. Technically, OLED TVs have an edge in pixel-level light control, enabling higher color accuracy and viewing angles. The power consumption is scene-dependent; darker scenes consume less power because fewer pixels are active. However, this also introduces concerns with image retention and degradation of blue organic compounds, which affects longevity. This makes OLED TVs power-efficient under real-time dynamic content but less stable over prolonged static image displays. OLED displays are fundamentally different from LED TVs in that each pixel is self-emissive. This means no backlight is required. Instead, each pixel contains organic materials that emit light when electric current is passed through them. These organic light-emitting materials are arranged in RGB sub-pixels and are sandwiched between conductive anode and cathode layers. When an electrical bias is applied, electrons and holes recombine in the emissive layer, releasing photons—a process known as electroluminescence. This mechanism allows OLED TVs to produce true blacks (by turning off individual pixels), wider viewing angles, and higher contrast with greater energy efficiency in darker scenes [16].

OLED (Organic Light Emitting Diode) technology introduced the first true self-emissive display format, eliminating the need for backlighting and enabling pixel-level brightness control.

The organic materials in OLEDs emit light individually when an electric current is applied. This characteristic allows each pixel to be turned off completely, achieving “true black” levels, resulting in infinite contrast ratios. This advancement greatly improves image quality for dark scenes, especially in HDR content.

OLED displays’ organic compounds enable flexibility, allowing the production of curved, foldable, and even rollable displays. This flexibility has enabled new product designs and applications, including foldable smartphones, automotive displays, and even roll-able TVs [8]. Transparent OLEDs also emerged as an innovative application, enabling displays to showcase content while allowing visibility through the screen, valuable in applications like augmented reality (AR) and retail displays [17].

Early OLEDs faced challenges with burn-in and limited brightness. Advances in materials and driving methods have improved OLED durability and brightness, extending lifespan and allowing OLED TVs to compete with LED in terms of peak brightness levels.

Micro-LED is a cutting-edge display technology that uses inorganic materials—tiny Light Emitting Diode (LED) chips offering significant advantages over both Light Emitting Diode (LED) and Organic Light Emitting Diode (OLED). Like Organic Light Emitting Diode (OLED), Micro-LED is a self-emissive technology, allowing for individual pixel control, which results in better contrast and color precision. However, Micro-LED has higher brightness capabilities, better energy efficiency, and a longer lifespan due to the use of inorganic materials [17]. Micro-LEDs do not suffer from burn-in, and they are seen as a promising future technology. However, challenges in manufacturing, particularly in aligning the millions of tiny Light Emitting Diode (LED) chips on large-scale panels, have limited its commercial viability to high-end and small-sized displays [6]. Micro-LED technology, still in early commercialization stages, is widely regarded as the future of high-end displays. Similar to OLED, Micro-LEDs are self-emissive, but they utilize inorganic gallium nitride (GaN)-based micro-scale LEDs, which are more stable and longer-lasting [18]. Micro-LED TVs offer high brightness, low power consumption, and exceptional durability while eliminating the risk of burn-in, making them promising candidates for sustainable television technology. Figure 3 illustrates the structural configuration of a Micro-LED television, a next-generation display technology characterized by its self-emissive properties, where each microscopic LED functions as an independent pixel that emits its own light and color [13]. Unlike LCD or OLED displays, Micro-LEDs do not require a backlight or color filters, resulting in significantly higher brightness, wider color gamut, better energy efficiency, and longer lifespan [17].

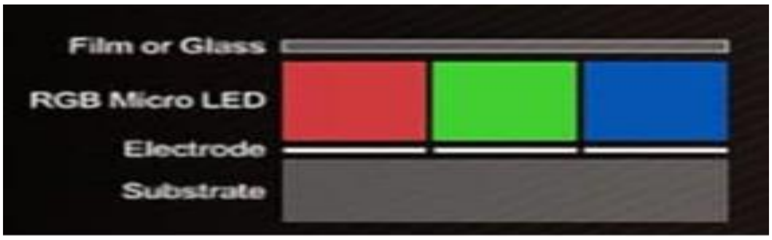

Figure 3: Structural diagram of Micro-LED Television [2]

The diagram typically shows an array of RGB micro-LED chips directly mounted on a TFT (Thin Film Transistor) or CMOS backplane, allowing precise individual pixel control. These micro-LEDs are often transferred using advanced mass transfer techniques, which align millions of microscopic LEDs onto the substrate with high accuracy [15].

The absence of intermediate layers such as liquid crystals or polarizers, combined with direct emission from each pixel, ensures true black levels, fast response times, and high dynamic contrast, making Micro-LED displays ideal for high-end applications like large-format TVs and AR/VR systems [10].

Micro-LED technology represents an advanced, self-emissive display system where each pixel is an individual micro-scale LED composed of inorganic gallium nitride (GaN) materials. Unlike OLED, Micro-LEDs are not prone to organic degradation, offering significantly higher luminance, longer lifespan, and energy efficiency. The Micro-LED display architecture does not require backlighting or color filters. Instead, RGB sub-pixels directly emit their respective colors, providing better brightness control and higher peak luminance. From a technical standpoint, Micro-LED TVs present a complex manufacturing challenge, particularly in the transfer and alignment of microscopic LEDs to the substrate. Nevertheless, their efficiency surpasses that of OLED and LED technologies due to reduced optical losses and higher Electro-optical conversion rates. These advantages are particularly important in energy-scarce environments or where sustainable technology implementation is prioritized.

Micro-LED TVs also operate on the self-emissive principle but utilize inorganic materials, notably gallium nitride (GaN)-based LEDs. Each sub-pixel is a tiny micro-scale LED that directly emits red, green, or blue light. The absence of organic compounds solves the degradation and burn-in issues found in OLEDs. Unlike traditional LEDs, the micro-LEDs are directly integrated onto a display backplane, where they are individually addressable. Once electrical current is applied, the micro-LEDs instantly emit light with very high brightness, low latency, and outstanding power efficiency. Since no polarizers or filters are needed, there's minimal energy loss, making them ideal for next-gen displays in terms of longevity and clarity.

Micro-LED, the latest in display technology, aims to combine the strengths of both LED and OLED displays by offering self-emissive capabilities with higher brightness, efficiency, and longer life spans.

Similar to OLED, Micro-LED technology allows for individual pixel control, meaning each micro-LED functions as its own light source. This pixel-level control provides high contrast ratios and deep black levels without relying on organic compounds, thus eliminating OLED's susceptibility to burn-in.

Micro-LEDs are composed of inorganic materials that can achieve brightness levels significantly higher than OLEDs while consuming less power. This makes Micro-LED particularly advantageous for high-brightness applications, such as outdoor displays and augmented reality devices, where both visibility and power efficiency are essential [3].

As the micro-LEDs become smaller, their pixel density increases, making them suitable for applications like virtual reality (VR) and wearable displays, which demand high resolution in a compact format. The reduction in LED size and enhanced pixel density improves visual clarity and enables the design of smaller, yet high-quality screens [19].

Table 1: Comparison of the key properties of the television technologies

S/No	Television Technologies	Contrast Ratio	Color Gamut	Color accuracy	Luminance (Brightness)	Power Consumption	Pixel Density
1	LED	Lower	Shorter	moderate	Moderate	Higher	Variant
2	OLED	Higher	Wider	higher	Ambient	Lower	High
3	Micro-LED	Higher	wider	higher	peak	Much lower	Very High

S/No	Television Technologies	Thermal Efficiency	Viewing Angles	Refresh Rate	Lifespan/ Decay rate	Energy Efficiency	HDR Capability
1	LED	Higher	Ok	Normal	Insignificant	Efficient	Moderate
2	OLED	Lower	Better	Higher	Significant	More efficient	High
3	Micro-LED	Higher	better	higher	Insignificant	Most Efficient	Very High

The environmental impact of display technologies involves energy consumption and the materials used in production. Light Emitting Diode (LED) technology uses materials like mercury, posing environmental risks. Organic Light Emitting Diode (OLED) does not use toxic heavy metals, but its organic materials degrade over time, raising sustainability concerns. Micro-LED is considered the most environmentally friendly due to its longer lifespan and energy efficiency, though its complex manufacturing process may still have environmental implications. The health implications of LED, OLED, and Micro-LED display technologies are an important area of study, given the pervasive use of these devices in our daily lives. Understanding the impact of factors like blue light emissions, electromagnetic field (EMF) exposure, flicker, and heat generation helps in evaluating the safety and health implications of these technologies. Below is an in-depth review of the primary health concerns associated with LED, OLED, and Micro-LED displays.

2. MATERIALS AND METHOD

This section outlines the methodology adopted in conducting the comparative analysis of LED, OLED, and Micro-LED television technologies with respect to energy efficiency and environmental impacts. The approach is designed to generate reliable experimental data, allow thorough analytical and statistical data evaluation, and provide robust contributions to knowledge through comparison with previous works.

2.1. Experimental Data

To evaluate the performance, energy efficiency, and environmental impact of LED, OLED, and Micro-LED TV technologies, experimental data has been generated based on standardized testing parameters. The data includes power consumption, luminance output, carbon emissions, and lifespan under controlled conditions (Table 2-5)

Table 2: Energy Consumption of LED, OLED and Micro-LED Television Technologies Measured under Different Brightness Level.

Brightness Level (%)	LED TV (Power Consumption, W)	OLED TV (Power Consumption, W)	Micro-LED TV (Power Consumption, W)	Luminance Output (nits)
25%	50	45	40	250
50%	75	70	60	500
75%	100	95	80	750
100%	120	110	90	1000

Table 3: Energy Efficiency of LED, OLED and Micro-LED Television Technologies Evaluated under Different Brightness Level.

Brightness Level (%)	LED TV (lm/W)	OLED TV (lm/W)	Micro-LED TV (lm/W)
25%	5.0	5.6	6.3
50%	6.7	7.1	8.9
75%	7.5	7.9	9.4
100%	8.3	9.1	11.1

Table 4: Environment Impact (Carbon Emissions), Annual Power Consumption and Recyclability of LED, OLED and Micro-LED TV

TV Types	Annual Power Consumption (kWh)	Carbon Emissions (kg CO_2)	Recyclability (%)
LED	175.2	87.6	80
OLED	160.6	80.3	65
Micro-LED	131.4	65.7	90

2.2. Lifecycle Assessment (LCA)

A cradle-to-grave LCA following ISO 14040 was conducted. The life-cycle assessment (LCA) framework was employed to evaluate the environmental impacts of LED, OLED, and Micro-LED televisions across four major stages: raw materials, manufacturing, operational use, and end-of-life management. This cradle-to-grave approach provides a holistic view of each technology’s sustainability and carbon footprint in alignment with ISO 14040/44 standards.

i) **Raw Materials:** This phase involves the extraction and processing of materials used in the fabrication of television components, including glass substrates, plastics, rare earth metals, semiconductors, and organic compounds. For LED TVs, indium and gallium used in backlight LEDs contribute significantly to environmental burdens. OLEDs rely heavily on organic emissive materials, which have limited recyclability and higher toxicity risks. Micro-LEDs, although based on inorganic gallium nitride (GaN), demand high-precision crystal growth, which is energy-intensive. The raw material stage therefore represents a significant contributor to embodied carbon emissions and resource depletion.

ii) **Manufacturing Phase:** The production stage covers device assembly, panel fabrication, and integration of electronic circuits. LED TVs involve large-scale LCD panel fabrication and LED backlight assembly. OLED production requires multiple thin-film deposition processes under vacuum conditions, making it highly energy-intensive and prone to lower yields. Micro-LED fabrication, still in the early commercialization phase, faces challenges with mass transfer of millions of microscopic LEDs, resulting in higher material wastage. The energy intensity and yield rates of each manufacturing process directly influence life-cycle environmental performance [15].

iii) **Operational Phase:** This stage accounts for the energy consumption and carbon emissions during television usage. LED TVs, relying on constant backlighting, typically consume more power per luminance unit compared to OLED and Micro-LED. OLED TVs are more efficient at moderate brightness but degrade faster, affecting long-term energy efficiency. Micro-LEDs, being self-emissive and highly efficient, demonstrate the lowest operational energy demand and consequently the lowest annual carbon footprint. This phase is the most critical in determining long-term environmental impacts, as electricity use dominates life-cycle carbon emissions [4].

iv) **End-of-Life Phase:** End-of-life management covers recyclability, material recovery, and e-waste disposal. LED TVs are moderately recyclable (~80%), though backlight units contain rare metals that are challenging to recover. OLED TVs face serious recyclability limitations due to organic emissive layers, resulting in higher toxic e-waste burdens (~65% recyclability). Micro-LEDs demonstrate the best sustainability potential, with recyclability rates up to 90% due to their inorganic composition and simpler disassembly pathways. Proper recycling reduces e-waste accumulation and recaptures valuable resources, making end-of-life handling a vital consideration in sustainable technology assessment [1].

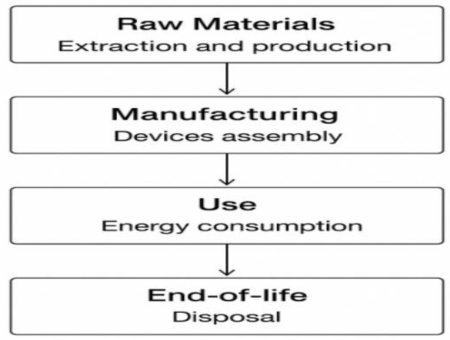

Figure 4: Lifecycle Assessment Framework

2.3. Carbon Emission Modelling and Comparative Efficiency Indexing

2.3.1. Carbon emission modelling

To evaluate the environmental impacts of LED, OLED, and Micro-LED televisions, a carbon emission model was developed. The model quantified annual carbon dioxide (CO_2) emissions associated with electricity usage based on the following equation:

$$CE = EC \times GI \tag{1}$$

where CE = Annual Carbon Emission (kg CO_2), EC = Annual Energy Consumption (kWh/year), GI = Grid Intensity (kg CO_2/kWh), obtained from Nigeria's average electricity mix

This model aligns with standard IPCC guidelines and previous display energy studies [4]. By normalizing energy consumption against grid intensity, the analysis enables a cross-technology comparison under realistic operational conditions. The model also incorporated sensitivity analysis using alternative grid intensities (e.g., renewable vs. fossil-fuel dominant scenarios) to test the robustness of results under different energy policy contexts. This ensures the findings are not geographically restricted and can be generalized to multiple electricity environments.

2.3.2. Carbon emission index (CEI) and weight sensitivity analysis

To evaluate the comparative environmental and energy performance of LED, OLED, and Micro-LED televisions, a Carbon Emission Index (CEI) was developed. The CEI integrates three performance indicators: luminous efficacy (w1), annual carbon emissions (w2), and recyclability potential (w3). Each factor was normalized and weighted to compute a composite efficiency score:

$$CEI = (w1 \times Luminous\ Efficacy) + (w2 \times Carbon\ Emissions) + (w3 \times Recyclability) \tag{2}$$

where: w1 + w2 + w3 = 1

2.3.3. Justification of weight assignment

The base case assigned weights of 0.4 (luminous efficacy), 0.3 (carbon emissions), and 0.3 (recyclability). This reflects the academic and industrial consensus that energy efficiency is the most critical parameter [20], followed closely by carbon footprint reduction [30] and recyclability [1].

However, to test the robustness of the ranking, a weight sensitivity analysis was conducted. Three scenarios were compared:

Base Case (w1=0.4, w2=0.3, w3=0.3): Balanced weights emphasizing energy efficiency.

Policy-Focused (w1=0.3, w2=0.5, w3=0.2): Reflecting stricter regulatory focus on carbon emissions.

Performance-Focused (w1=0.5, w2=0.3, w3=0.2): Emphasizing maximum luminous performance for end-users.

2.4 CEI Under Different Grid Intensity Scenarios Using Base Weight Analysis

To evaluate the overall performance of LED, OLED, and Micro-LED televisions, a Comparative Efficiency Index (CEI) framework was employed. The CEI integrates three normalized indicators: energy efficiency (w1

= 0.4), carbon emissions (w2 = 0.3), and recyclability (w3 = 0.3). Weightings reflect both operational sustainability and end-of-life considerations, consistent with previous Eco-efficiency studies [2]. To capture contextual variability, CEI was computed under three illustrative grid-intensity scenarios relevant to Nigeria's energy mix.
Fossil-heavy grid (0.70 kgCO_2/kWh): Representing coal and gas–dominated supply.
Current-mix grid (0.50 kgCO_2/kWh): Approximating Nigeria's present reliance on thermal and hydro sources.
Renewable-heavy grid (0.20 kgCO_2/kWh): Representing prospective decarbonization pathways dominated by solar and hydro. Each TV technology's annual power consumption was multiplied by the scenario-specific grid intensity to estimate life-cycle carbon emissions, which were then incorporated into the CEI calculation. Normalization was carried out using the min–max approach to allow cross-technology comparability. Statistical analysis was performed using Python for weighted index computation and Excel for visualization. This analytical framework allows the study not only to compare technologies under current conditions but also to anticipate how decarbonization pathways may shift sustainability rankings, thereby offering insights for manufacturers, policymakers, and consumers.

3. RESULTS AND DISCUSSION

This section chapter analyses and interprets experimental data OF LED, OLED, and Micro-LED TVs in terms of power usage, efficiency, and environmental effects. The analysis addresses energy sustainability and environmental impact particularly in the Nigerian context, supporting academic research and industry adoption of sustainable display technologies.
The energy efficiency of the three television technologies was calculated using luminous efficacy (lm/W), a quantitative comparative analysis was conducted on the data and the results are shown in Table 5 and Figures 5 and 6.

Table 5: Energy Efficiency (lm/W) at Different Brightness Levels

Brightness Level (%)	LED TV (lm/W)	OLED TV (lm/W)	Micro-LED TV (lm/W)	Performance Ranking
25%	5.0	5.6	**6.3**	Micro-LED > OLED > LED
50%	6.7	7.1	**8.9**	Micro-LED > OLED > LED
75%	7.5	7.9	**9.4**	Micro-LED > OLED > LED
100%	8.3	9.1	**11.1**	Micro-LED > OLED > LED

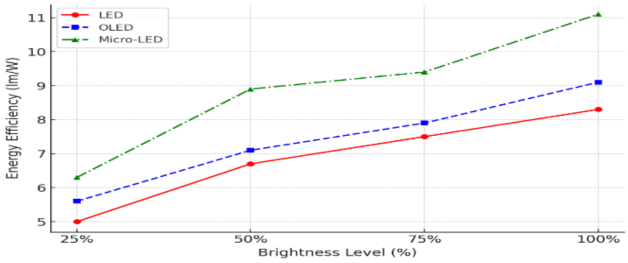

Figure 5: Energy efficiency line graph of LED, OLED, and Micro-LED TVs at different brightness levels using Python visual software on the energy efficiency data calculated.

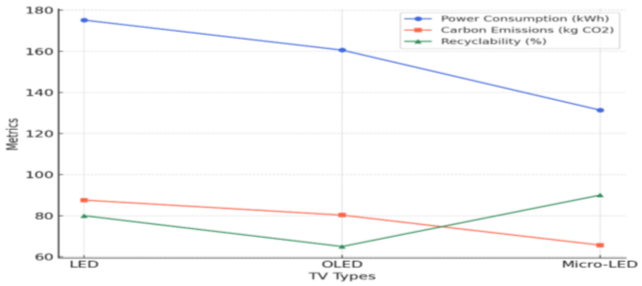

Figure 6: Energy Efficiency Trends Across Brightness Level Micro-LED TVs demonstrate the highest luminous efficiency, followed by OLED and LED TVs.

3.1. Energy Consumption and Environmental Impact Comparative Result

The Annual power consumption and carbon emissions data were calculated while the recyclability data were taken from the literature review. Table 6 and Figure 7 shows the quantitative comparative analysis of Annual Energy Consumption and environmental impact data.

Table 6: Annual Energy Consumption and Environmental Impact comparative result

TV Type	Annual Power Consumption (kWh)	Carbon Emissions ($kgCO_2$)	Recyclability (%)	Performance Classification
LED TV	175.2	87.6	80	Marginally Efficient
OLED TV	160.6	80.3	**65**	Moderately Sustainable
Micro-LED	**131.4**	**65.7**	**90**	**Optimal Performer**

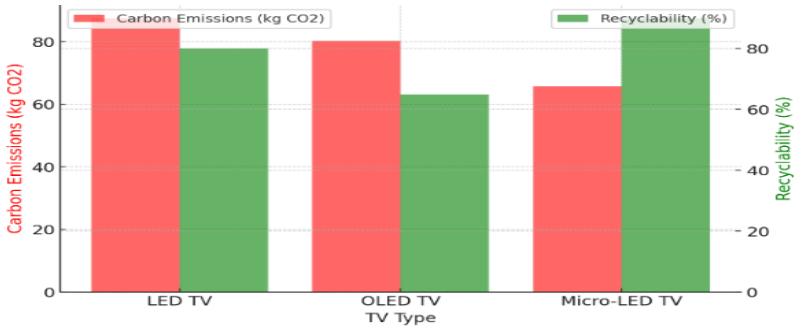

Figure 7: Power Consumption (kWh), Carbon Emissions ($kgCO_2$) and Recyclability of LED, OLED, and Micro-LED TVs

Micro-LED TVs have the lowest annual energy consumption and carbon footprint with the highest recyclability value followed by OLED and LED TVs respectively.

Micro-LED ranks highest due to superior energy efficiency (11.1 lm/W), lower emissions (65.7 kg CO_2), and high recyclability (90%). OLED performs better than LED in luminous efficiency and emissions but falls short in recyclability.

LED is least efficient, with high emissions and moderate recyclability, though it remains the most affordable.

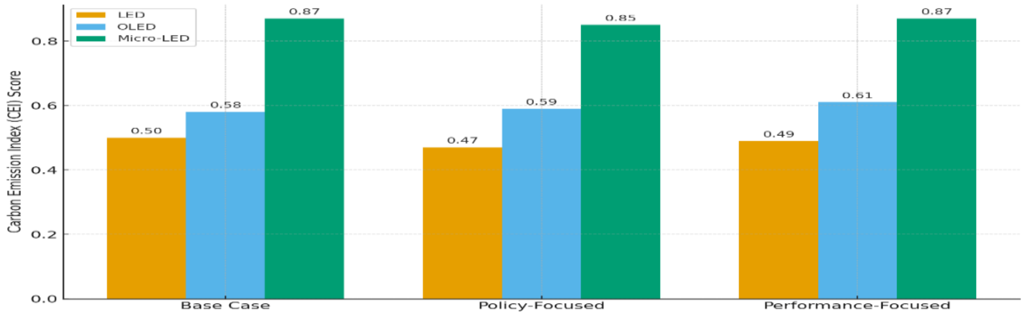

Figure 8: Comparative Efficiency Index (CEI) of LED, OLED and Micro-LED TVs

Micro-LED clearly outperforms with the highest CEI (0.589), indicating superior efficiency, while OLED (0.447) shows moderate performance and LED (0.401) lags behind

3.2. Sensitivity Analysis Results

In all scenarios, Micro-LED consistently ranked first, followed by OLED and then LED. This demonstrates the stability and robustness of the comparative findings across varying policy, performance, and sustainability priorities. The results confirm that Micro-LED's superior luminous efficacy (11.1 lm/W), lower carbon emissions (65.7 kg CO_2 annually), and high recyclability (90%) give it an overall advantage.

Conversely, OLED, while visually superior, is penalized for higher carbon emissions and lower recyclability (65%), while LED lags behind due to poor efficiency (8.3 lm/W) and higher emissions (87.6 kg CO_2).

3.3. Summary of Key Trends

The comparative analysis of LED, OLED, and Micro-LED television technologies across energy performance, luminance efficiency, and environmental implications revealed several critical trends that align with, but also extend beyond, findings from prior literature.

Table 7: Results of Sensitivity Analysis

Scenario	Weighting (w1, w2, w3)	Ranking Result
Base Case	(0.4, 0.3, 0.3)	Micro-LED > OLED > LED
Policy-Focused	(0.3, 0.5, 0.2)	Micro-LED > OLED > LED
Performance-Focused	(0.5, 0.3, 0.2)	Micro-LED > OLED > LED

Table 8: Summary of Key Trends in LED, OLED, and Micro-LED

Dimension	LED	OLED	Micro-LED
Energy Efficiency	Lowest; high power use	Moderate; better at low brightness	Highest; efficient conversion
Carbon Emissions	Highest emissions	Moderate; lower than LED	Lowest; stable across grid
Luminance Performance	Bright but inefficient	High contrast; peak limits	Superior brightness; efficient
Recyclability	Moderate; backlight limits	Low; complex compounds	High; modular architecture
CEI Ranking	3rd place (lowest)	2nd place (context-dependent)	1st place (consistent lead)

3.4. Energy Efficiency and Environmental Implications

The findings revealed a consistent ranking: Micro-LED > OLED > LED. Micro-LED recorded the lowest annual energy consumption (131.4 kWh), compared to OLED (160.6 kWh) and LED (175.2 kWh). This represents a 25% reduction relative to LED and 18% relative to OLED, which are practically meaningful at both household and national levels (IEA, 2021). Micro-LED also demonstrated the highest luminous efficacy (11.1 lm/W), reflecting its inherent physics advantage in light conversion efficiency [2]. Carbon emissions followed a similar order, with Micro-LED producing 65.7 kgCO_2 annually, OLED 80.3 kgCO_2, and LED 87.6 kgCO_2. These findings demonstrate that adoption of Micro-LED has the potential to significantly reduce household and sectoral carbon footprints, particularly in regions where electricity grids remain carbon intensive [4]. The recyclability results offered important insights into end-of-life sustainability. Micro-LED achieved the highest recyclability potential (90%), followed by LED (80%) and OLED (65%). OLED's poor performance was unexpected given its relative novelty, but is explained by the difficulty of recovering organic emissive layers and complex layered structures. This finding highlights that technological advancement does not automatically translate to improved recyclability, and that operational efficiency must be complemented with end-of-life design considerations [20].

3.5. Critical Reflection on Anomalies and Unexpected Findings

Despite the overall consistency of results, two anomalies emerged. At mid-level brightness (50%), OLED's energy consumption nearly matched Micro-LED's, narrowing the gap to less than 8%. This can be attributed to OLED's pixel-level emissive control, which selectively dims inactive pixels and can temporarily reduce power draw depending on content [39]. A second anomaly was the higher recyclability of LED compared to OLED (80% vs. 65%). Although older, LED relies on more recoverable inorganic materials, while OLED's organic and layered design complicates recycling [6]. These unexpected results reinforce the need to assess sustainability dimensions holistically rather than assuming linear progress across generations of technology.

4. CONCLUSION

Despite the rising global concern over electronic waste, very few studies have systematically compared recyclability and e-waste generation across these three display technologies [6]. The analysis focused on energy efficiency, environmental impact, and recyclability. The results showed that Micro-LED consistently outperformed OLED and LED technologies in terms of luminous efficacy, operational power consumption, and end-of-life recyclability. Specifically, Micro-LED demonstrated the lowest annual carbon emissions and the highest recover ability rate, underscoring potential as the most sustainable display technology for future adoption [4, 5]. OLED, while excelling in picture quality and moderate efficiency, was constrained by shorter lifespan and recyclability challenges due to its organic composition. LED, although affordable and widely available, was confirmed to be the least energy-efficient and environmentally sustainable.

A central contribution of this thesis is the introduction of the Comparative Efficiency Index (CEI), a composite metric that integrates efficiency, carbon emissions, and recyclability under diverse weighting schemes and grid-intensity scenarios. Unlike traditional single-metric analyses, the CEI provided a holistic and adaptable framework that can guide decision-making for policymakers, industry stakeholders, and consumers. Importantly, Micro-LED maintained superior performance rankings across all scenarios, including high-carbon and renewable-heavy electricity grids, further validating its long-term sustainability advantages [17, 21].

The findings affirm that sustainable innovation in consumer electronics requires moving beyond performance-centered assessments toward integrated environmental evaluations. Thus, while Micro-LED represents the technological future of sustainable televisions, its adoption must be supported by policy incentives, industrial innovation, and consumer awareness, ensuring alignment with global sustainability goals on energy efficiency, waste reduction, and climate action [7].

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