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Scientific content analysis of Light Emitting Diode (LED) for high school physics STEM based learning

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Abstract
The embedded STEM approach is currently the most easily implemented in Indonesia compared to other types of approaches. This approach requires a context to be delivered in the learning process. The context selection must consider its relevance to everyday life and be closely linked to process competencies. This study conducts a scientific content analysis of Light Emitting Diode. It investigates its potential application in high school physics embedded-STEM learning. The research adopts a descriptive qualitative methodology using the Model of Educational Reconstruction as the research framework. Data were collected through a literature review of three scientific references on LEDs. The scientific content analysis of LEDs was performed using the hermeneutic analysis method. The literature analysis of these subthemes revealed that the significant Physics concepts relevant to LEDs include energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics. Consequently, LEDs hold significant potential as a context for embedded STEM learning in high school physics. The results of this study provide a foundation for the subsequent phase of constructing embedded STEM learning designs with the topic of LEDs, such as the development of textbooks, learning strategies, and their evaluation.
Keywords: contextual physics, LED, embedded STEM

INTRODUCTION

STEM education has become a global educational trend. For several decades, STEM education has been developed and implemented in countries such as the United States, the United Kingdom, Australia, Finland, Thailand, and Malaysia (Winarni et al., 2016). Numerous studies on STEM education have been conducted in Indonesia over nearly a decade (Syukri et al., 2013). However, most of these studies have been conducted at the elementary education level. Implementing full STEM learning is relatively easier at the elementary level compared to the middle and high school levels. This is due to the thematic integrated curriculum in elementary schools (Roberts, 2012). Additionally, each class level is taught by a single teacher, unlike in middle or high schools, where the curriculum is not thematic (subjects are still separate) and different teachers teach each subject. Therefore, implementing STEM learning in high schools faces more significant challenges than in elementary schools.

Restructuring the entire curriculum is a practical and challenging option. The embedded STEM approach is the most feasible option to integrate STEM without restructuring the curriculum (Chen, 2001; Roberts, 2012). This approach requires a context (functional, social, or cultural) to deliver the domain knowledge to students (Chen, 2001). This aligns with the view that STEM education intersects with context-based learning (Sutaphan & Yunyeong, 2019). Thus, developing STEM learning with a context-based approach necessitates studies related to the context to be used.

LEDs are a potential context for STEM learning in high school physics subjects because LEDs are commonly found in everyday objects students use, such as TVs, lamps, and mobile phones. Etkina and Planinšič stated that LEDs have been widely used in physics education as tools to demonstrate physical phenomena in daily life (Etkina & Planinšič, 2014). Additionally, LEDs relate to several physics concepts, such as electric fields and the motion of charged particles in electric fields, the photoelectric effect, and DC circuits. Boltsi et al. highlighted in their study how LEDs can enhance learning experiences by providing energy-efficient, versatile, and engaging visual aids. They emphasize the role of LED technology in creating interactive and dynamic learning environments, which are crucial for fostering student engagement and improving educational outcomes in STEM disciplines (Boltsi et al., 2024).

In Pane's (2023) research, LEDs can be utilized for designing and animating decorative garden lighting. LEDs enhance garden decorations' aesthetics and energy efficiency due to their numerous advantages over traditional light sources, including high energy efficiency, long lifespan, and flexibility in lighting design. Various steps can be taken to implement an LED lighting system, including component selection, power regulation, and controller programming for light animation. In another study, LEDs can be used in the learning process to experiment on linear motion topics using Arduino-based infrared (I.R.) sensors (Solakhudin, 2024). Arduino can be integrated with various sensors and actuators, including LEDs, to create more effective interactive learning tools and practical experiments. LEDs can be used as educational tools to understand fundamental concepts in electronics and programming (Prayoga et al., 2024).

Based on studies of similar research on contextual learning development, the Model of Educational Reconstruction (MER.) is a common framework used to reconstruct relatively new contexts in science or those not yet in the school curriculum (Karim et al., 2016; Anugrah et al., 2017; Kersting et al., 2018; Nursa'adah, 2018). MER consists of three components: 1) clarification and analysis of scientific content, 2) research on the learning process, and 3) design and evaluation of the learning process (Duit et al., 2012). Content structure analysis involves dissecting the scientific content to identify key concepts, principles, and ideas fundamental to the subject matter. This process includes evaluating the scientific accuracy and coherence of the content to ensure it aligns with current scientific understanding. Recent studies emphasize the importance of engaging with subject matter experts during this phase to maintain content integrity (e.g., Duit et al., 2023). Didactic reconstruction is the key to reinterpreting scientific content to make it pedagogically suitable for teaching (Konrad et al., 2024). The final component involves developing and evaluating instructional materials based on the insights gained from content analysis, didactic reconstruction, and empirical studies. These materials include lesson plans, textbooks, digital resources, and assessment tools (Fischer et al., 2023).

Previous studies have not examined the LED context specifically for high school physics learning. Therefore, this study aims to reconstruct the education of the LED context for high school physics learning. However, this reconstruction process is limited to the first stage, which is the clarification and analysis of the scientific content of the LED context. According to Anugrah in his research on the scientific analysis of the batik context, this stage is fundamental and needs to be thoroughly conducted as a basis for subsequent stages (Anugrah et al., 2021). Therefore, this study clarifies and analyzes the scientific content of LEDs and related high school physics concepts. The results can be used in further research on the development of STEM learning in high school physics, such as developing teaching materials, media, strategies, and evaluation of physics learning with LED contexts.

RESEARCH METHOD

This study used a descriptive qualitative method. The LED context's scientific content structure was analyzed through a literature review of textbooks and journal articles about LEDs. After clarifying the scientific content of LEDs, an analysis of high school physics concepts related to LED scientific content was conducted. The reference used in this research phase is Learning Outcomes from *Kurikulum Merdeka*. The research flow can be seen in Figure 1 below, and the instruments developed and used for data collection are detailed in Table 1 below.

Table 1. Research Instruments for Analyzing the Scientific Perspective of LED

Research Question	Instrument	Data Obtained
A scientific perspective on LED context	Book and journal article analysis format on LED context	Raw manuscript on LED context
High school physics concepts related to LED scientific content	Analysis format of high school physics concepts related to LED context	High school physics concepts related to LED

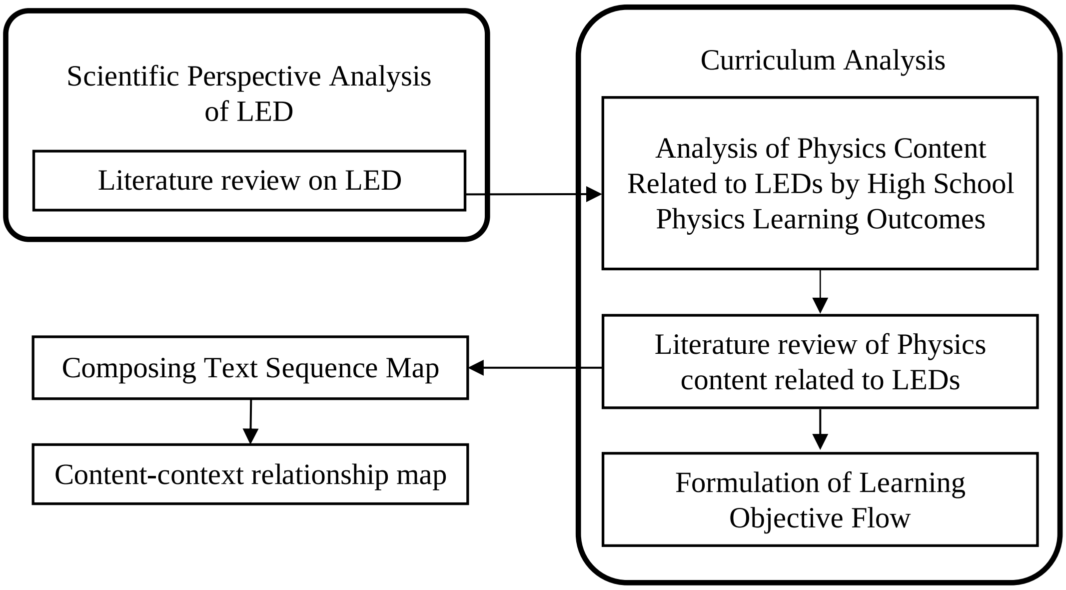

Figure 1. The research flow

The LED scientific content structure was analysed based on Katmann's hermeneutic analysis method for scientific clarification of the selected context (Kattmann et al., 1996). This analysis includes 1) high school physics concepts related to LEDs, 2) limitations in explaining LEDs for high school levels, 3) social and ethical implications related to these scientific concepts, and 4) applicable fields influenced by these concepts.

FINDINGS & DISCUSSION

Scientists' Perspective on the LED Context

Scientists' perspectives on the LED context were obtained through a literature study of three references related to LEDs. Scientific information related to the LED context was obtained from these references. The results are detailed in Table 2 below.

Table 2. Literature Analysis on the LED Context

No	Title	Author(s)	Content
1	Fundamentals of Solar Cells and Light-Emitting Diodes	Wang, Liu and Gao (2019)	Electroluminescence principle; LED work principle
2	Light-emitting diodes: Second Edition	Schubert (2006)	LED electrical properties; emission energy and spectrum
3	Light-emitting Diodes (LED)	Rahman (2012)	Introduction to LEDs; LED emitting process; how LEDs work; LED light colour

The literature study results were processed and systematically compiled into an introductory LED text. This text begins with an introduction to LEDs, followed by a discussion of the principles of light emission in LEDs, components, and working principles of LEDs. Subsections elaborate on the scientists' perspective on the LED context.

Introduction to LED

LED (light-emitting diode) is an electronic component composed of semiconductor diodes that can emit light (Singh, 2009). A diode is an active component with two poles that function analogously to a valve, allowing current to flow in one direction but blocking it in the opposite direction. The first LED was reported in 1928 by Oleg Vladimirovich Losev, where light emission was observed in inorganic semiconductor Si-carbide (Zheludev, 2008). The energy gap between the valence band and the emitter's conduction band determines the light colour LED produces. However, LED lighting also depends on the amount of electrical current applied (Wang et al., 2019).

An LED (Light Emitting Diode) is comprised of two legs made from a type of wire. The longer wire is the anode, while the shorter is the cathode. The anode is an electrode (metal or other conductive material) in an electrochemical cell that polarises when current flows. Conversely, the cathode is an electrode that becomes polarized when electric current flows out of it. LEDs offer several advantages, including:

- Higher energy efficiency compared to other types of lamps (energy savings of 80-90%)
- Longer lifespan, reaching up to 100,000 hours
- Low operating DC voltage requirement
- Cool light output (no UV radiation or thermal energy)
- Small and compact size
- Availability in various colours
- Cost-effectiveness.

However, LEDs also have some disadvantages, including:

- High ambient temperatures can cause electrical disturbances in LEDs
- The cost per lumen is higher compared to other lamps
- The light intensity produced is relatively low (Rahman, 2012).

Light emission in LEDs occurs through electroluminescence (EL), the emission of light caused by an electric current. This process refers to the electro-optical conversion process in which a semiconductor emits light in response to the injection of an electric current. In the EL mechanism, holes and electrons are separately injected into the valence and conduction bands of the semiconductor, where they recombine and release their energy as photons-light (Wang et al., 2019).

LED Components

The basic structure of an LED device consists of an emitting layer sandwiched between a transparent conductive oxide and a metal electrode. The basic structure of an LED device is depicted in Figure 2 below. Functional layers such as the hole injection layer (HIL), hole transport layer (HTL), electron injection layer (EIL), and electron transport layer (ETL) can be utilized to provide balanced hole and electron injection and transport, forming a multilayer LED. In some cases, the hole-blocking layer (HBL) and electron-blocking layer (EBL) are also incorporated into the multilayer LED because these blocking layers can prevent carrier leakage of opposite charge carriers, thereby enhancing efficiency. Despite the complexity of device fabrication, multilayer LEDs serve as a robust platform with a broader scope for device optimization.

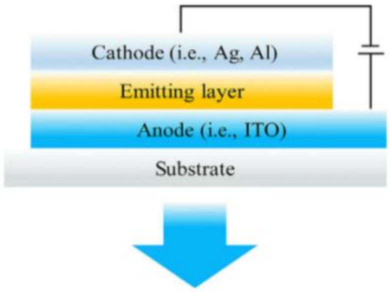

Figure 2. The basic structure of LED (Wang et al., 2019)

Most reported LEDs are bottom-emitting devices, where light is emitted from the side of the substrate. However, for practical applications, it would be preferable for light to be emitted from the last deposited layer, referred to as top-emitting LEDs. Top-emitting LEDs allow for easier integration with backplane electronics such as active matrix Si, but they require the use of transparent top electrodes instead of the classic opaque metal cathodes. New, thin, transparent electrodes are needed to replace ITO, which would damage the underlying layers during deposition.

Another commonly used device structure is the tandem structure, where p-n connectors connect multiple light-emitting units. This tandem structure can be seen in Figure 3. Tandem LEDs can significantly increase light efficiency by generating multiple photons per injected charge unit. Consequently, tandem LEDs are also known as multi-photon emission (MPE) LEDs. Considering that standard multilayer LEDs have a specific current I0 and voltage V0, tandem devices with N light-emitting units, similar to standard LEDs, will require approximately I0/N current and V0N voltage, respectively, to achieve the same brightness. Therefore, power consumption will be the same in tandem LEDs, and tandem device structures typically do not enhance power efficiency. Power consumption will be higher than standard multilayer LEDs if the unit connectors require additional voltage drop.

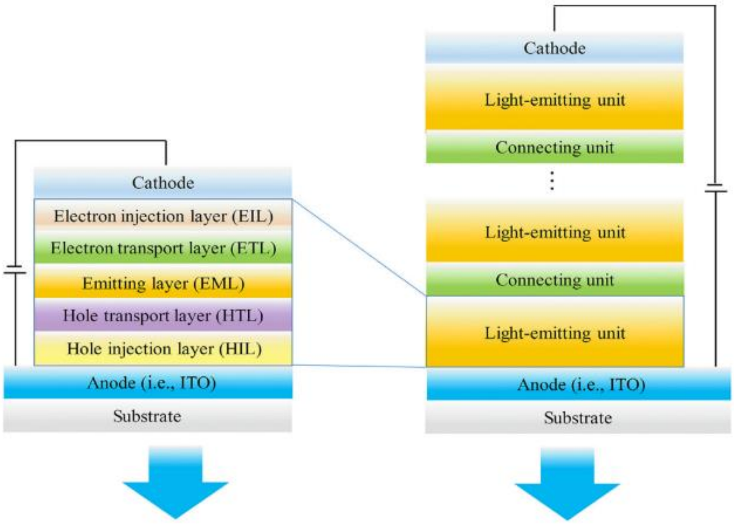

Figure 3. Structure of standard multilayer (left) and tandem (right) LED (Wang et al., 2019)

Fortunately, it is possible to achieve lower power consumption (and consequently higher power efficiency) of tandem structures by optimizing the unit connectors. More importantly, tandem structures can improve operational lifetime because current density is reduced, with device ageing typically being superlinear (cubic or even quadratic). Additionally, tandemstructured devices exhibit fewer short-circuit defects. Despite these advantages, tandem LEDs face challenges forming reliable hole injection (HI) contacts for the top light-emitting units. The use of transparent ITO electrodes as part of the connecting units is effective; however, ITO deposition causes sputtering damage to the underlying layers, and its high conductivity leads to cross-talk issues. Moreover, tandem LED structures are quite complex, increasing the fabrication difficulty, particularly for solution-processed LEDs.

Principles of LED

Light is a form of energy produced by photons. Photons are released as a result of electron movement. Within an atom, electrons move in orbitals surrounding the nucleus. Electrons in different orbitals have varying amounts of energy. In other words, electrons with higher energy move in orbitals farther from the nucleus. An electron releases energy when it transitions from a higher orbital to a lower one. This released energy is in the form of photons. As we know, free electrons moving across a diode can fall into the empty holes of the p-type layer. This affects the conduction band and moves it towards the lowest orbit. Consequently, electrons release energy in the form of photons (Rahman, 2012).

The energy of photons (eq. 1) emitted from a semiconductor with an energy gap, E_g, is given by the band gap energy, which is:

$$hv \approx E_g \tag{1}$$

Each electron injected into the active region will produce a photon in an ideal diode. Energy conservation thus requires that the energy with which the electron is injected equals the photon energy. Therefore, energy conservation (eq. 2) necessitates:

$$eV = hv \tag{2}$$

This means that the voltage applied to the LED, multiplied by the elementary charge, equals the photon energy. Several effects can alter the diode voltage from the ideal value (Schubert, 2006). LEDs come in many colours, including red, yellow, blue, green, white, and white (infrared), each with its characteristics and used according to specific needs. LEDs are made from n-type semiconductor material in the valence band and p-type in the conduction band, separated by a depletion region. In the conduction band, there are more holes, and in the valence band, there are many electrons. When the forward bias voltage is applied, a diffusion current causing holes appears. When the circuit's positive pole is connected to the n-type layer and the negative pole is connected to the p-type layer, free electrons gather at one diode pole, and holes gather at the other pole. The depletion region becomes larger. Holes move to the n-type, and electrons in the n-type move to the p-type, causing current flow. When recombination current occurs (diffusion and drift current appear), some electrons will recombine with holes, producing energy in photon light (LED color emission). At the same time, the rest will generate heat energy. The illustration can be seen in Figure 3.

The energy of a photon will be proportional to the energy difference between the conduction band and the valence band (band-gap energy). The wavelength (eq. 3) of the emitted photon is

$$\lambda = \frac{c}{f} = \frac{c}{E_g/h} = \frac{hc}{E_g} \tag{3}$$

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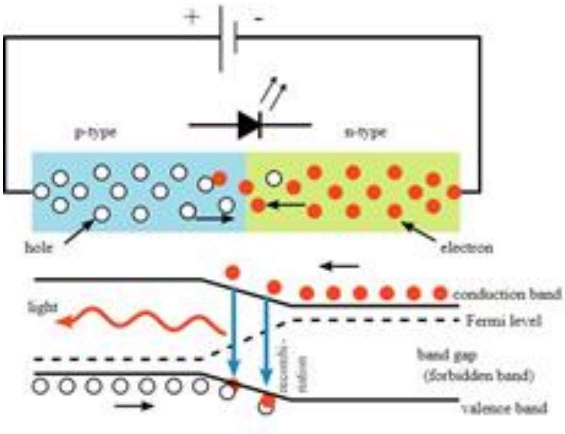

Figure 4. The occurrence of a depletion area due to the polarization of holes at one pole and electrons at the other pole (Rahman, 2012)

Unlike standard signal diodes designed for rectification and made from germanium or silicon, LEDs are made from exotic semiconductor compounds such as Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC), or Indium Gallium Nitride (GaInN), mixed in various ratios. The precise mixing of semiconductor materials results in different energy gaps between the conduction and valence bands. Consequently, different wavelengths of light are produced, determining the colour emitted by the LED. For example, LEDs on the market designed for visible regions commonly use gallium due to their compatibility with arsenic and phosphorus atoms. The composition consists of 60% non-gallium, occupied by arsenic, and 40% by phosphorus ions, resulting in a band gap energy (E_g) of 1.8 eV. This band gap energy produces red light.

The physical mechanism by which semiconductor LEDs emit light is the spontaneous recombination of electron-hole pairs and simultaneous photon emission. This process fundamentally differs from the stimulated emission process occurring in semiconductor lasers and superluminescent LEDs. Spontaneous recombination has specific characteristics that determine the optical properties of LEDs. This section will discuss the properties of spontaneous emission in LEDs.

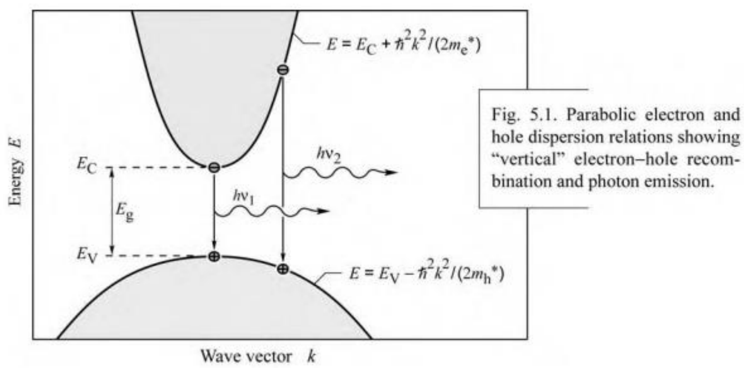

Figure 5. Parabolic electron-hole dispersion (Schubert, 2006)

The electron-hole recombination process is schematically illustrated in Figure 5. Electrons in the conduction band and holes in the valence band are assumed to have a parabolic dispersion relationship (eq. 4 and 5):

$$E = E_C + \frac{h^2k^2}{2m_e^*} \quad \text{(for electron)} \tag{4}$$

$$E = E_V - \frac{h^2k^2}{2m_h^*} \quad \text{(for hole)} \tag{5}$$

where $2m_e^*$ and $2m_h^*$ are the effective masses of electrons and holes, h is Planck's constant divided by 2π, k is the wave number of the carriers, and E_V and E_C are the edges of the valence and conduction bands, respectively.

The energy and momentum conservation requirements lead to further insights into the radiative recombination mechanism. According to the Boltzmann distribution, electrons and holes have an average kinetic energy of kT. Energy conservation dictates that the energy of the photon (eq. 6) is given by the difference between the electron energy, E_e, and the hole energy, E_h, which is

$$hv = E_e - E_h \approx E_g \tag{6}$$

The photon's energy is approximately equal to the band gap energy, E_g, if the thermal energy is small compared to the band gap energy $kT << E_g$. Therefore, the desired emission wavelength of the LED can be achieved by selecting a semiconductor material with an appropriate band gap energy. For instance, GaAs have a band gap energy of 1.42 eV at room temperature. Thus, a GaAs LED emits at an infrared wavelength of 870 nm.

It is helpful to compare the average momentum of the carrier with the photon momentum. A carrier with kinetic energy kT and an effective mass $m*$ has momentum (eq. 7)

$$p = m \times v = \sqrt{2m \times \frac{1}{2} m \times v^2} = \sqrt{2m \times kT} \tag{7}$$

The momentum of a photon with energy (E_g) can be derived from the de Broglie relation in eq. 8:

$$p = hk = \frac{hv}{c} = \frac{E_g}{c} \tag{8}$$

Calculations of carrier and photon momentum show that the carrier momentum is an order of magnitude greater than the photon momentum. Thus, the electron momentum cannot change significantly during the transition from the conduction band to the valence band. Consequently, the transition is "vertical", meaning the electron recombines only with a hole with the same momentum or k-value.

Using the requirement that the electron and hole momenta are the same, the photon energy (eq. 9) can be written as a combined dispersion relation:

$$hv = E_C + \frac{h^2k^2}{2m_e^*} - E_V - \frac{h^2k^2}{2m_h^*} = E_g + \frac{h^2k^2}{2m_r^*} \tag{9}$$

where $mr*$ is the reduced mass given in eq. 10:

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \tag{10}$$

Using the combined dispersion relation, the joint density of states can be calculated and obtained in eq. 11:

$$\rho(E) = \frac{1}{2\pi^2}\left(\frac{2m_r^*}{h^2}\right)^{3/2}\sqrt{E - E_g} \tag{11}$$

The Boltzmann distribution in eq gives the distribution of carriers in the allowed band. 12:

$$f_B(E) = e^{-E/kT} \tag{12}$$

The emission intensity as an energy function is proportional to the product of the above equations, shown in eq. 13:

$$(E) \propto \sqrt{E - E_g}\, e^{-E/kT} \tag{13}$$

The maximum emission intensity occurs at (eq. 14):

$$E = E_g + \frac{1}{2}kT \tag{14}$$

The full width at half maximum of the emission is (eq. 15)

$$\Delta E = 1.8kT \quad \text{or} \quad \Delta\lambda = \frac{1.8kT\,\lambda^2}{hc} \tag{15}$$

For example, the theoretical room temperature linewidth of a GaAs LED emitting at 870 nm is E = 46 meV or = 28 nm.

The spectral linewidth of LED emission is significant in several ways. Firstly, the emission linewidth of an LED in the visible range is relatively narrow compared to the entire visible spectrum range. LED emission is even narrower than the spectral width of a single colour as perceived by the human eye. For instance, the red colour range in wavelength spans from 625 to 730 nm, which is much broader than the typical LED emission spectrum. Therefore, LED emission is perceived by the human eye as monochromatic.

Secondly, optical fibres are dispersive, leading to different propagation speeds for light pulses of various wavelengths. Material dispersion in optical fibres limits the "bit rate × distance product" achievable with LEDs. The spontaneous carrier lifetime in LEDs in direct-gap semiconductors is 1-100 ns, depending on the doping concentration of the active region (or carrier concentration) and the material quality. Thus, modulation speeds up to 1 Gbit/s can be achieved with LEDs (Schubert, 2006).

High School Physics Concepts Related to LED

High school physics concepts that can explain the scientific content in the context of LEDs, as previously described in the subsection. The analysis of these high school physics concepts related to the context of LEDs is conducted with reference to the Content Standards for high school physics subjects. The results of this analysis are presented in Table 3.

Table 3. Scientific perspective of LEDs and its related high school physics concepts

No	Context	Content
1	LED Development	Energy Transformation
2	LED Definition	Electric Current
		Light as Electromagnetic Wave
3	LED Structure	Electric Charge and Behavior on Conductors and Insulators
		Electric Current

No	Context	Content
		Distinguishing DC and AC
4	LED Working Principle	Electrical Circuit Characteristics
		Electromagnetic Induction Phenomenon
		Distinguishing DC and AC
		Electromagnetic Radiation
		Light as Electromagnetic Wave
		Light as a Component of Radiation

The table above shows that the high school physics concepts capable of elucidating the scientific content of LEDs are: energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics.

CONCLUSION

To use the context of LEDs in high school STEM physics learning, a reconstruction process is first required to tailor the context to students according to their cognitive levels. The initial stage of this reconstruction involves a literature review to unearth the scientific content related to LEDs, including their definition, components, and operational principles. This stage is necessary to analyze high school physics concepts related to LEDs. This study shows that high school physics concepts related to LEDs include energy and its transformations, direct current electricity, electromagnetic radiation, electronic systems, and quantum physics. The findings of this study are crucial for advancing to the subsequent stage of reconstructing the LED context in high school Physics learning, which involves investigating the perspectives of both students and teachers, as well as developing learning instruments such as textbooks, strategies, and assessments.

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