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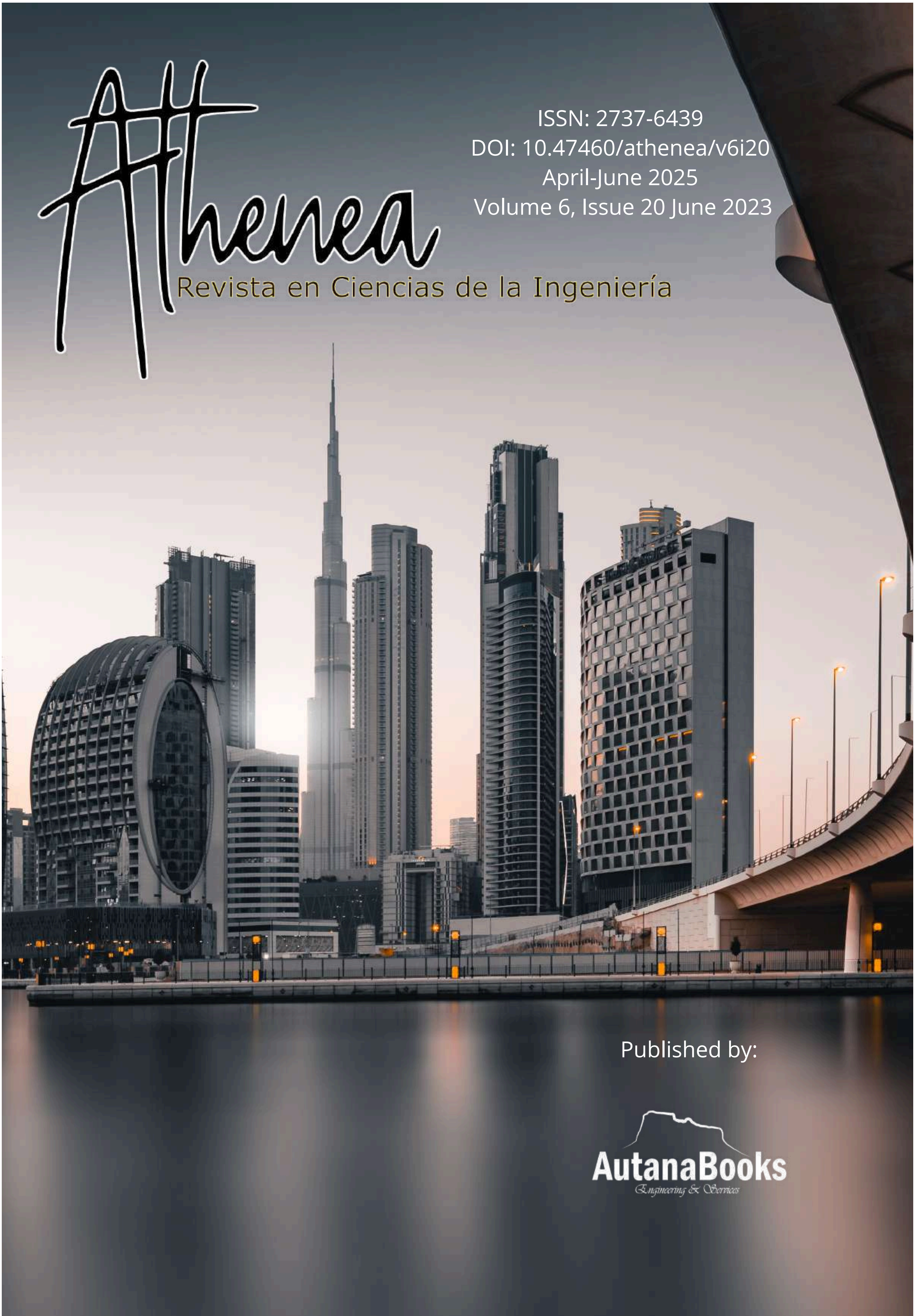

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En nuestra portada se refleja la modernidad y la concentración de saberes que caracterizan a la urbanidad de las grandes ciudades, espacios donde convergen la tecnología, la planificación y el desarrollo humano. La ingeniería, como disciplina aplicada, constituye uno de los pilares fundamentales que permite que las ciudades funcionen de manera continua y eficiente, garantizando infraestructura, servicios básicos, conectividad y condiciones adecuadas para la vida cotidiana.

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A review of flow and volume sensors applications in hemodialysis

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Abstract. This article describes distinct types of flow and volume sensors, and their respective applications used during hemodialysis. Through a review of the literature, new opportunities in the field of non-invasive methods are explored to optimize and develop innovative technologies in the field of biomedical implants and accelerate the completion of kidney disease treatment. The findings reveal that the combination of these devices and noninvasive techniques contributes significantly to the treatment of kidney diseases. In addition, it helps in the development of biological models and the performance of operational/mechanical analyses to predict more effective and rapid implementation methods for patient recovery.

Keywords: biofluids, flow and volume sensors, hemodialysis.

Una revisión de las aplicaciones de sensores de flujo y volumen en hemodiálisis

Resumen. - Este artículo describe diferentes tipos de sensores de flujo y volumen, y sus respectivas aplicaciones durante la hemodiálisis. A través de una revisión bibliográfica se exploran nuevas oportunidades en el campo de los métodos no invasivos para optimizar y desarrollar tecnologías innovadoras en el campo de los implantes biomédicos y acelerar la finalización del tratamiento de enfermedades renales. Los hallazgos revelan que la combinación de estos dispositivos y técnicas no invasivas contribuye significativamente al tratamiento de enfermedades renales. Además, facilita el desarrollo de modelos biológicos y la realización de análisis operativos/mecánicos para predecir métodos de implementación más efectivos y rápidos para la recuperación del paciente.

Palabras clave: biofluidos, sensores de flujo y volumen, hemodiálisis.

I. INTRODUCTION

Hemodialysis (HD) is a life-saving treatment for chronic kidney failure, replacing key kidney functions by filtering blood through a dialyzer to remove waste, excess fluids, and toxins. Specifically, it serves patients with chronic kidney disease (CKD) and end-stage renal disease (ESRD), where maintaining a balance between fluid removal and replacement is essential. To achieve this, accurate control of blood and dialysate flow rates, as well as ultrafiltration volume [1], is ensured through integrated flow and volume sensors, which play a key role in treatment efficacy and patient safety. As dialysis therapies become more complex, the demand for reliable sensor technologies continues to grow. In addition, ESRD, one of the leading causes of reduced lifespan with a high mortality rate, requires long-term dialysis, and by 2030, an estimated 5.4 million patients will need this therapy. Effective dialysis depends on proper vascular access to ensure sufficient blood flow [2]. Thus, epidermal blood flow sensors have been introduced for real-time monitoring.

Furthermore, access points such as arteriovenous fistulas (AVF), arteriovenous grafts (AVG) and catheters [3] can fail due to stenosis or thrombosis, making wearable thermal anemometric flow sensors crucial for early detection. In addition, flow sensors measure the movement of liquids or gases through output signals [4] or pressure changes [5], enhancing the precision of treatment and patient outcomes. Similarly, volume sensors are integral to modern HD systems, providing real-time fluid balance monitoring. In general, this review highlights the role of bio-fluids in medical device design, emphasizing the importance of flow and volume sensors to align with biological properties for effective patient care. According to Yánez et al. [6], blood comprises 8% of an adult's body mass, while total water content ranges from 58% to 80%, distributed between organs such as brain (73%), heart (73%), skin (65%), lungs (84%), kidneys (79%), liver (71%) and pancreas (73%). Ultimately, as advancements in biomedical engineering continue, flow and volume sensors will play an increasingly vital role in enhancing treatment precision, improving patient outcomes, and shaping the future of dialysis technology.

II. FIELDS OF INTEREST TO THE SUBJECT

Flow and volume sensors are crucial in biomedical devices, ensuring precise fluid control in medication delivery and diagnostics. As medical technology continues to evolve, flow sensors have become essential for accurately monitoring and managing fluid movement in various applications. Their development, progressing from Microelectromechanical Systems (MEMS) to microfluidic devices on a single chip [7], has allowed for increasing efficiency and adaptability. Doppler ultrasound sensors enabled transcutaneous blood flow measurements [8], while wearable sensors expanded to track vital signs like heart rate and oxygen levels [9]. Meanwhile, Laser Doppler flowmetry provided a non-invasive way to assess circulatory function, including retinal blood flow in rabbits [10]. Alongside these advancements, volume sensors have been essential in medical applications, particularly in regulating physiological functions. Relative blood volume monitoring has been used to track hematocrit changes [11] and improve blood pressure regulation during hemodialysis [12]. As technology advanced, bioimpedance analysis emerged to estimate total body water [13], while ultrasound dilution sensors measured cardiac output in pediatrics [14]. Additionally, portable nuclear magnetic resonance improved disease diagnosis and tumor detection [15]. Eventually, biomarker sensors introduced biological markers like glucose detection [16], leading to portable glucose monitors for diabetes care. The miniaturization and non-invasive design of these sensors have ensured high sensitivity, precision, and low power consumption, enabling broad medical applications. This research highlights their growing role in modern healthcare, demonstrating how engineering advancements continue to shape the medical field.

A. A Brief Review: Flow Sensors

Flow sensors in hemodialysis (HD) are critical for monitoring the rate at which fluids, primarily blood and dialysate, circulate through the system. Among the various types, electromagnetic flow sensors offer high accuracy by detecting voltage changes induced by magnetic fields as blood flow through the sensor, although they tend to be costly and technically complex. Ultrasonic flow sensors, in contrast, are widely used due to their non-invasive nature; they measure fluid velocity using high-frequency sound waves. Optical flow sensors determine flow rate by analyzing changes in light transmission through the fluid, often leveraging suspended particles within the blood to enhance measurement precision. Together, these technologies provide essential data for optimizing hemodialysis treatment and ensuring patient safety.

B. Flow Sensor Types

Microelectromechanical Systems (MEMS) flow sensors have been developed for intravenous (IV) systems to measure small flow rates, such as those involved in drug delivery. One such sensor employs artificial hair cells (AHCs) on a silicon die, incorporating two differently sized AHCs designed to minimize flow disturbance [7]. The sensor is coated with a parylene film to ensure waterproofing and compatibility with various drugs. Doppler ultrasound flow sensors utilize diffraction grating transducers (DGTs) made of flexible biofilm to generate low-energy optical signals, making them well-suited for long-term implantation. These sensors enhance sensitivity by creating overlapping ultrasonic beams [8] that detect dispersed ultrasound signals from blood flow. Wearable flow sensors represent a noninvasive solution for real-time medical monitoring [9], integrating flexible, wireless, multipoint devices that measure pulse waves, skin color, and tissue temperature. The system includes sensors, cables, a data transmitter, and a tablet or smartphone for data display, with installation supported by medical film dressings and a polydimethylsiloxane sheet.

Laser Doppler flowmetry offers a noninvasive and wearable approach, using six wireless sensors to detect Doppler shifts from red blood cell movement, allowing simultaneous monitoring of blood perfusion at multiple sites [10]. Similarly, epidermal blood flow sensors provide noninvasive, wearable monitoring of skin blood flow, effectively adapting to sensor placement variability and tissue differences. These sensors capture weak temperature signals associated with high-volume blood flow [2], offering continuous surveillance valuable in managing end-stage renal disease (ESRD) patients. Lastly, anemometric flow sensors also present a wearable, noninvasive solution, designed to detect changes in blood flow through vascular access points such as arteriovenous fistulas (AVF) and arteriovenous grafts (AVG) [3]. These sensors deliver immediate physiological feedback with high sensitivity and have demonstrated accurate performance in vivo studies. Collectively, these technologies underscore the progress in flow sensing for hemodialysis and broader clinical applications, balancing precision, ease of use, and patient comfort.

C. A Brief Review: Volume Sensors

Volume sensor analysis in dialysis plays a crucial role in monitoring and managing fluid volumes within the dialysis system to ensure effective treatment and optimal patient care. By accurately measuring and tracking fluid movement across various components, such as dialysate delivery, blood flow, and ultrafiltration, these sensors help maintain proper fluid balance and prevent complications like fluid overload or dehydration. Techniques such as *relative blood volume monitoring (RBVM) and bioimpedance analysis (BIA)* are commonly used to assess patient hydration status and guide real-time adjustments to ultrafiltration rates during dialysis sessions. Two main types of volume sensors are employed: *cumulative volume sensors*, which continuously monitor the total volume of blood or dialysate processed, providing essential data on fluid removal or replacement; and *real-time volume sensors*, which offer instantaneous volume measurements to enable dynamic control and maintain equilibrium. Many of these devices also incorporate optical technologies to measure hematocrit levels, serving as indicators of hemoconcentration and aiding in the precise evaluation of blood volume changes. Together, these volume sensing approaches enhance dialysis safety, personalization, and clinical outcomes.

D. Volume Sensor Types

Volume sensors represent a fundamental category within monitoring and automation systems, allowing for the precise measurement of the quantity of liquid or gas contained in each space. Their applications span multiple sectors, from the medical and food industries to automotive engineering and smart manufacturing processes. The choice of the appropriate sensor type depends on factors such as the type of fluid, the required accuracy, the operating environment, and response speed. Below are the main types of volume sensors, their operating principles, and their advantages in different technological contexts.

Relative Blood Volume Monitoring (RBVM) is a key technique in dialysis that tracks changes in hematocrit [11], the ratio of red blood cells to plasma, as fluid is removed from the patient [12]. This allows for real-time adjustments of ultrafiltration targets, helping to prevent complications such as intradialytic hypotension by avoiding excessive fluid removal. *Bioimpedance Analysis (BIA)* complements RBVM by estimating body water compartments, including extracellular water (ECW), intracellular water (ICW), and total body water (TBW) [13], through the measurement of the body's electrical properties. BIA aids in determining a patient's dry weight and guides fluid removal strategies during dialysis. Various BIA methods exist, including single-frequency, multi-frequency, and bioimpedance spectroscopy (BIS), and can be applied using whole-body or segmental approaches. *Ultrasound dilution sensors* provide additional fluid status insights by measuring blood flow and cardiac output, detecting changes in ultrasound wave velocity [14] after injecting a known volume of fluid, such as saline, into the arterial line. *Portable nuclear magnetic resonance (NMR) sensors* utilize low magnetic fields [15] to quickly assess fluid status at the bedside, offering rapid differentiation between hypervolemic and euvolemic states, significantly faster than conventional MRI techniques. Lastly, *biomarker sensors* enable the detection and quantification of specific biological markers [16] using technologies such as paper-based platforms, vibrating resonators, and optical detection systems. These sensors support early disease detection, monitoring fluid overload, treatment tracking, and personalized therapy, contributing to improved outcomes in dialysis care. Collectively, these volume sensing technologies enhance the precision, safety, and personalization of fluid management in hemodialysis.

E. Integration of Flow and Volume Sensors in the Hemodialysis Process

Flow and volume sensors integrated into dialysis machines play a crucial role in delivering safe, efficient, and individualized treatment by providing real-time data to monitor and regulate both blood and dialysate flow. These sensors enable automatic system responses to abnormalities such as low blood flow or excessive fluid removal, thereby preventing complications like dehydration or intradialytic hypotension and enhancing overall patient safety. In clinical hemodialysis, flow and volume sensors serve several key functions. *Monitoring blood flow* is essential to maintain optimal perfusion through the vascular access and extracorporeal circuit [17], and flow sensors help detect access dysfunction early, ensuring treatment efficacy. *Dialysate flow regulation* is another critical application, as dialysate flow rate directly impacts solute clearance; accurate monitoring via flow sensors improves dialysis efficiency and clinical outcomes [18]. *Ultrafiltration management* relies on volume sensors to precisely control the amount of fluid removed during treatment, aiding in the achievement of patient-specific dry weight targets and avoiding the risks of fluid overload or hypotension. Additionally, while non-flow sensors per se, *leak and air detection* systems use differential flow measurements between blood inflow and outflow to identify anomalies such as tubing leaks or air ingress, prompting immediate corrective action. Together, these sensor technologies enhance the safety, accuracy, and personalization of dialysis therapy.

F. Dialysis Machines

Dialysis machines [19] are critical medical devices used to perform renal replacement therapy in patients with end-stage renal disease (ESRD) or acute kidney injury. These machines mimic the filtration function of healthy kidneys by removing waste products, excess fluids, and toxins from the bloodstream through a semi-permeable membrane. Hemodialysis, the most generic form, circulates blood through an external dialyzer, while peritoneal dialysis uses the patient's peritoneal membrane as the filtration surface. Dialysis machines tightly regulate parameters such as blood flow rate, dialysate composition, temperature, and ultrafiltration volume to ensure safe and effective treatment. Modern systems, such as the Fresenius 5008 CorDiax and Baxter's AK 200 ULTRA S, are equipped with real-time monitoring, integrated sensors, and customizable treatment protocols to improve patient outcomes. Integrated flow and volume sensors within these machines enhance safety by implementing air detectors, pressure monitors, and blood leak detectors to minimize risks of detecting air bubbles, pressure anomalies, and blood leaks, allowing for automatic system adjustments. Peritoneal dialysis machines, such as the Baxter Amia, use the peritoneal membrane for filtration and are designed for home use, offering patients greater flexibility and autonomy. Dialysis machines also store historical treatment data, aiding clinicians in personalizing therapy and tracking patient progress over time. The primary goal of these machines is to maintain fluid and electrolyte balance, reduce uremic symptoms, and improve survival and quality of life in patients with compromised renal function. Continued technological advancements aim to increase efficiency, portability, and patient comfort, making dialysis therapy more accessible and effective.

G. Method Calculations

Since this review serves as a collection of relevant research, it focuses on providing information that supports and sustains the discussion. Among the key topics, flow rate is widely assessed due to its versatility and extensive applications in flow and volume sensors. Understanding this concept is essential, as equation (1) defines the relationship between fluid velocity, cross-sectional area, and the volume of fluid passing through a point over time [20]:

$$Q = \frac{V}{S} \tag{1}$$

where Q represents the flow rate (e.g., blood flow), V denotes the average velocity, and S corresponds to the cross-sectional area of the fluid (e.g., blood).

Equation (2) expands upon flow rate by incorporating volume flow rate (Q_0), which can be modified depending on the specific application. For instance, when analyzing laminar blood flow in a rectangular channel, the volume flow rate is expressed as:

$$Q_0 = \frac{4ba^3}{3\mu}\left(-\frac{d\hat{p}}{dx}\right)\left[1 - \frac{192a}{\pi^5 b}\sum_{i=1,3,5,\ldots}^{\infty}\frac{\tan h\left(\frac{inb}{2a}\right)}{i^5}\right] \tag{2}$$

where b represents the width, a is the half-height of the channel, and μ signifies the fluid viscosity. The term $-\frac{d\hat{p}}{dx}$ refers to the pressure gradient within the channel, while $\sum_{i=1,3,5,\ldots}^{\infty}$ the summation term accounts for the influence of odd integers on the flow behavior. Additionally, $\tan h\left(\frac{inb}{2a}\right)$ represents the geometric characteristics of the channel.

Another essential equation used in flow and volume sensors is the Doppler equation (3), primarily utilized to measure the velocity of blood flow:

$$f_d = \left(\frac{V}{\lambda}\right)\left(\frac{4}{d}\right) = \frac{V}{d} \tag{3}$$

where f_d is denotes the Doppler frequency shift, V represents the velocity of blood flow, λ is the wavelength of the transmitted wave, and d is the distance.

In contrast to the Doppler equation, the wavelet spectrum equation (4) is applied to evaluate signals from flow and volume sensors:

$$W(s,\tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-\tau}{s} \right) \tag{4}$$

where $W(s,\tau)$ represents the wavelet transform of the signal, s is the scale parameter, $x(t)$ is the evaluated signal, τ corresponds to the time parameter, and ψ^* is the complex conjugate of the wavelet function.

Additionally, the non-dimensional temperature equation (5) is implemented in flow and volume sensors to adjust temperature measurements for improved accuracy:

$$T_{nondim} = \frac{T - T_{standard}}{\Delta T_{standard}} \tag{5}$$

where T_{nondim} represents the non-dimensional temperature, T is the measured temperature, $T_{standard}$ signifies the reference temperature, and $\Delta T_{standard}$ is the difference between two reference temperatures.

Finally, the flow sensitivity equation (6) is incorporated into flow and volume sensors to assess their responsiveness to variations in flow rate:

$$Sensitivity(\%) = \frac{\Delta T_{100mL/min} - \Delta T_{800mL/min}}{\Delta T_{800mL/min}} \times 100 \tag{6}$$

where $\Delta T_{100mL/min}$ represents the time change at a lower flow rate of 100mL/min, and $\Delta T_{800mL/min}$ corresponds to the time change at a higher flow rate of 800mL/min.

H. Outcomes of flow sensors

Experiments on flow sensors provided significant insights across various applications. For instance, MEMS flow sensors demonstrated a dynamic range of 2–200 ml/h, but showed output saturation near 200 ml/h, while IV system testing at 0.05 ml/min confirmed adaptability. Additionally, Doppler ultrasound flow sensors measured velocities between 110–122 cm/s with minimal variation, though estimates deviated by 5.9% across flow rates of 60–500 mL/min. Meanwhile, wearable flow sensors in clinical trials achieved physician agreement rates of 96%–99.2%, with 90% of patients recommending future use. In addition, laser Doppler flowmetry studies showed perfusion decreased when transitioning upright, but increased in a head-down position, with forehead measurements exhibiting minimal microcirculation changes. Notably, blood pressure and heart rate were consistently higher in vertical positions. Furthermore, epidermal blood flow sensors provided precise vascular access monitoring, showing a 12.2% deviation from Doppler ultrasound across flow rates of 100–600 ml/min, with a compact design suitable for hemodialysis. Lastly, anemometric flow sensors accurately monitored blood flow in CKD patients, adapting to AVF development, vascular stenosis, thrombosis, and access failure, while maintaining reliable performance despite minor setup imbalances. Ultimately, in vivo studies validated their precision across different flow conditions, with benchtop models confirming the impact of vessel structure on sensor sensitivity. These findings highlight the essential role of flow sensors in advancing patient monitoring and medical technology.

I. Technological Advancements and Innovations in Sensors

Recent advancements in dialysis technology have significantly improved the performance and integration of flow and volume sensors. *Miniaturization* has led to the development of smaller, more compact sensors that can be seamlessly embedded within dialysis machines, reducing the overall system size and enhancing portability. *Smart sensors*, powered by AI-based algorithms, now offer predictive analytics capabilities that anticipate potential complications and automatically adjust treatment parameters to enhance patient safety and optimize outcomes. Additionally, *wireless monitoring* has transformed clinical practice by enabling real-time, remote access to sensor data, allowing healthcare providers to oversee a patient's dialysis session without being physically present. These innovations are complemented by improved accuracy, achieved using advanced materials and technologies such as high-precision electromagnetic and miniaturized ultrasonic sensors, which ensure greater measurement reliability and clinical effectiveness.

J. Challenges and Limitations

Flow and volume sensors in dialysis systems, while essential for ensuring accurate and safe treatment, are subject to several limitations. *Sensor drift* is a common issue, where prolonged use leads to gradual loss of accuracy, necessitating routine recalibration to maintain performance. Additionally, *external interference*, including fluctuations in temperature, pressure, and changes in the chemical composition of blood or dialysate, can compromise the reliability of sensor readings. *Mechanical failures* also pose a significant risk; malfunctions can result in erroneous data that may threaten patient safety if not promptly detected. Furthermore, these sensors demand consistent *maintenance and cleaning* to prevent blockages or clogs, ensuring continuous, unobstructed operation and accurate monitoring throughout the dialysis process.

III. METHODOLOGY

This review focused on the assessment of mechanical and operational properties for flow and volume sensors using a diverse range of scientific literature and academic contributions. The primary sources included peer-reviewed journal articles, doctoral and master's theses, and conference presentations, all provided by researchers, and recognized scientific organizations. The objective was to gather comprehensive, high-quality information that reflects the current state of knowledge in the field. To ensure a comprehensive and inclusive literature review, an exhaustive search was conducted across American and European academic databases, emphasizing repositories affiliated with institutions specializing in biomedical engineering. The primary search focused on publications from 2021 to 2025 to capture the most recent advancements, utilizing databases such as PubMed, Scopus, IEEE Xplore, EBSCOhost, Google Scholar, and ScienceDirect. These platforms were selected for their broad coverage of biomedical and interdisciplinary research, allowing the identification of high-quality peer-reviewed articles, conference proceedings, and technical reports. Supplementary information from secondary sources, including engineering textbooks, technical manuals, handbooks, internet-based resources, and review articles, further enriched the contextual and technical depth of the review. To determine the most appropriate flow or volume sensor for a given clinical setting, several critical criteria must be considered according to the researched data evaluated from collected references. These include performance characteristics such as accuracy and reliability, and material properties like durability, biocompatibility, and ease of sterilization. Cost factors compassing initial investment, maintenance, and operational expenses, are also evaluated. Additionally, the simplicity of use, including training requirements and the ease of integration into existing dialysis systems, plays an important role in sensor selection. Real-time monitoring capabilities are essential for continuous assessment during the dialysis process. A comparative analysis of these criteria for each sensor type is presented in Table 1, with each criterion rated on a scale of Low, Medium, or High.

Tabla 1. Inclusion and Rejection Criteria.

Criteria	Key Questions	Rating (Low/ Medium/High)
Accuracy	How accurate is the sensor? What is the reliability of the sensor?	Refer to Tables 2 and 3 for a complete evaluation of flow and volume sensor criteria.
Material of Construction	What is the durability of the sensor? Is it biocompatible with other equipment? Is it easy to sterilize the sensor?	
Cost	What is the initial investment cost? What is the cost of maintenance? What is the cost for operation?	
Simplicity	How easy is it to use? What training does it require? How hard is it to integrate with the system?	
Invasiveness	Does it require direct access to blood or a vascular access point?	
Real-Time Monitoring	Does it provide real-time monitoring during the dialysis process?	
Clinical Maturity	Is it used in clinical dialysis centers or mostly in research settings?	

IV. RESULTS

Table 2 presents the flow sensor types analyzed and their distinctive characteristics, as well as their applications in health situations based on the information collected from the references obtained during this document's preparation.

Table 3 presents the volume sensor types analyzed and their distinctive characteristics, as well as their applications in health situations based on the information collected from the references obtained during this document's preparation.

According to the obtained results presented on Table 2, the best flow sensor option for hemodialysis mentioned on this paper should be Doppler Ultrasound flow sensor based on its high accuracy, real-time performance, non-invasive characteristics and clinically validated use. These characteristics prove the effectiveness in dialysis clinics for vascular access flow surveillance and early detection of complications like thrombosis and stenosis. For the other hand, MEMS flow sensors and wearable devices could enhance monitoring, especially for continuous, home-based settings, but they need more

Tabla 2. Flow Sensors Results.

Sensor Type	Accuracy	Durability	Cost	Ease	Invasive	Real-Time	Maturity	Clinical Application
MEMS	H	M	H	L	L	M	L	Experimental implantable blood flow monitors
Doppler Ultrasound	H	H	M	M	L	H	H	Vascular access blood flow measurement, stenosis detection
Wearable	M	M	M–H	H	L	L	L	Home/outpatient vascular monitoring
Laser Doppler Flowmetry	L	H	H	M	L	M	L	Monitoring superficial skin blood flow; not suitable for hemodialysis circuits
Epidermal	L–M	H	H	L	L	H	L	Skin perfusion monitoring, future vascular access checks
Anemometric	M	M	L–M	H	L	H	M	Prototypical dialysis blood flow monitoring

Legend: H = High, M = Medium, L = Low

Tabla 3. Volume Sensors Results

Sensor Type	Accuracy	Material Durability	Cost (USD)	Ease to Use	Invasiveness	Real-Time Monitoring	Clinical Maturity	Clinical Application
RVBM	M–H	H	L–M	H	L	H	H	Intradialytic blood volume tracking to prevent hypotension
BIA	M	H	L	H	L	L	H	Assessment of fluid overload pre-/post-dialysis
Ultrasound dilution	H	H	M–H	M	L	M	M–H	Blood volume and cardiac output monitoring during dialysis
NMR	H	H	H	L	L	L	L	Detailed body composition and hydration state
Biomarker	M	M	M–H	M	L	M	L	Monitoring biochemical markers related to hydration (natriuretic peptides)

Legend: H = High, M = Medium and L= Low

validation and ruggedization. Corresponding to obtained results presented on Table 3, the best volume sensor option for hemodialysis mentioned on this paper should RBVM (Relative Blood Volume Monitoring) volume sensor based on its real-time performance, non-invasive characteristics, cost-effective and clinically validated use. These characteristics prove the effectiveness for blood volume management during hemodialysis. For the other hand, Biomarker sensors and advanced NMR techniques could enhance fluid management in the future but are not yet practical for routine use. Along the course of the review, it was found that sensor accuracy is directly linked with sensitivity. This means that at a higher sensitivity, it can increase the performance of the sensor. In hemodialysis the incorporation of these sensors is crucial, because it can guarantee the well-being of the patient and at the same time ensure treatment effectiveness.

CONCLUSIONS

The review covered a comprehensive range of topics centered on flow and volume sensors and their applications in hemodialysis treatment. Each sensor type demonstrated specific strengths and limitations under various clinical conditions, yet all effectively fulfilled their intended roles in accurately monitoring blood flow and fluid dynamics. Flow and Volume sensors play a vital role in enhancing the precision of fluid management, thereby contributing to improved patient outcomes. The selection of an appropriate sensor depends on a combination of clinical requirements, resource availability, and cost considerations. Continued advancements in sensor technologies, especially regarding integration with dialysis systems and real-time monitoring capabilities, offer promising prospects for further improving the safety, efficiency, and overall effectiveness of hemodialysis therapy.

Moreover, interdisciplinary research efforts and collaborations between medical device manufacturers and healthcare providers are essential to accelerate innovation in this field. Future developments should focus on miniaturization, increased sensor sensitivity, and seamless integration with automated control systems to facilitate personalized treatment protocols. Such advancements will not only optimize hemodialysis procedures but also enhance patient comfort and reduce long-term healthcare costs.

Additionally, emerging trends emphasize the incorporation of artificial intelligence and machine learning algorithms into sensor technologies, enabling predictive analytics for early detection of complications such as clot formation, vascular access dysfunction, and fluid overload. These intelligent systems, already under exploration in advanced healthcare centers worldwide, have the potential to revolutionize hemodialysis management by providing data-driven insights for personalized treatment adjustments in real time. As seen in recent studies from leading institutions in the United States, Germany, and Japan, this technological convergence is paving the way for more adaptive and resilient dialysis systems, ultimately aiming to improve survival rates and quality of life for patients undergoing long-term treatment.

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REFERENCES

[1] U. P. Kehinde, O. J. Omotola, N. C. Igwebuike, E. S. Olubunmi, and T. O. Ruth, "Ultrafiltration volume: Surrogate marker of the extraction ratio, determinants, clinical correlates and relationship with the dialysis dose," *Journal of Clinical Nephrology and Renal Care*, vol. 7, no. 2, Sep. 2021.

[2] Y. Tian *et al.*, "Self-adaptive epidermal blood flow sensor for high-flux vascular access monitoring of hemodialysis patients," *Npj Flexible Electronics*, vol. 8, no. 1, p. 62, Oct. 2024.

[3] Y. Deng *et al.*, "A soft thermal sensor for the continuous assessment of flow in vascular access," *Nature Communications*, vol. 16, no. 1, p. 38, Jan. 2025.

[4] B. Beamer, "Pressure & flow sensor types for medical applications," https://www.arrow.com/en/research-and-events/articles/pressure-sensors-types-in-medical-applications, May 2024, online; accessed 2025-06-04.

[5] RACO Manufacturing, "Understanding flow sensors: Types, applications, and benefits," https://www.racoman.com/blog/understanding-flow-sensors-types-applications-and-benefits, Feb. 2025, online; accessed 2025-06-04.

[6] C. Yáñez, G. DeMas-Giménez, and S. Royo, "Overview of biofluids and flow sensing techniques applied in clinical practice," *Sensors*, vol. 22, no. 18, p. 6836, Sep. 2022.

[7] L. Zhang, Y. Yang, G. A. Bertos, C. Liu, and H. Hu, "Bio-inspired micromachined volumetric flow sensor with a big dynamic range for intravenous systems," *Sensors*, vol. 23, no. 1, p. 234, Dec. 2022.

[8] J. M. Cannata *et al.*, "Development of a flexible implantable sensor for postoperative monitoring of blood flow," *Journal of Ultrasound in Medicine*, vol. 31, no. 11, pp. 1795–1802, Nov. 2012.

[9] Y. Tomioka *et al.*, "Wearable, wireless, multi-sensor device for monitoring tissue circulation after free-tissue transplantation: A multicentre clinical trial," *Scientific Reports*, vol. 12, no. 1, p. 16532, Oct. 2022.

[10] A. A. Fedorovich *et al.*, "Body position affects capillary blood flow regulation measured with wearable blood flow sensors," *Diagnostics*, vol. 11, no. 3, p. 436, Mar. 2021.

[11] W. E. Vickery, S. M. Steinbach, and G. E. Moore, "Accuracy of crit-line® monitors in predicting hematocrit and change in blood volume of dogs during hemodialysis," *Journal of Veterinary Internal Medicine*, vol. 37, no. 6, pp. 2137–2144, Nov. 2023.

[12] A. Alayoud *et al.*, "Utility of a blood volume monitor in the management of anemia in dialysis by computing the total hemoglobin mass," *Hemodialysis International*, vol. 23, no. 4, pp. 419–425, Aug. 2019.

[13] S. R. Abbas, F. Zhu, G. A. Kaysen, P. Kotanko, and N. W. Levin, "Effect of change in fluid distribution in segments in hemodialysis patients at different ultrafiltration rates on accuracy of whole body bioimpedance measurement," *Journal of Applied Physiology*, vol. 116, no. 11, pp. 1382–1389, Jun. 2014.

[14] S. L. Goldstein and A. Allsteadt, "Ultrasound dilution evaluation of pediatric hemodialysis vascular access," *Kidney International*, vol. 59, no. 6, pp. 2357–2360, Jun. 2001.

[15] L. A. Colucci *et al.*, "Fluid assessment in dialysis patients by point-of-care magnetic relaxometry," *Science Translational Medicine*, vol. 11, no. 502, Jul. 2019.

[16] W. Y. Park, S. Park, Y.-W. Kim, and K. Jin, "Clinical efficacy of biomarkers for evaluation of volume status in dialysis patients," *Medicine*, vol. 99, no. 31, Jul. 2020.

[17] S. Zschätzsch, M. Stauss-Grabo, A. Gauly, and J. Braun, "Integrating monitoring of volume status and blood volume-controlled ultrafiltration into extracorporeal kidney replacement therapy," *International Journal of Nephrology and Renovascular Disease*, vol. 14, no. 1, pp. 349–358, Aug. 2021.

[18] B. A. Baharsyah, E. D. Setioningsih, S. Luthfiyah, and W. Caesarendra, "Analyzing the relationship between dialysate flow rate stability and hemodialysis machine efficiency," *Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics*, vol. 5, no. 2, pp. 86–91, May 2023.

[19] J. T. Daugirdas and J. E. Tattersall, "Automated monitoring of hemodialysis adequacy by dialysis machines: Potential benefits to patients and cost savings," *Kidney International*, vol. 78, no. 9, pp. 833–835, Nov. 2010.

[20] N. M. Krivitski, "Theory and validation of access flow measurement by dilution technique during hemodialysis," *Kidney International*, vol. 48, no. 1, pp. 244–250, Jul. 1995.

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Advances in zinc oxide nanobiosensors for medical diagnostics: morphologies, mechanisms and applications

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Abstract. Zinc oxide (ZnO) nanostructures present remarkable morphological, chemical and electrical properties, including a large surface area, semiconductor behavior and a high isoelectric point, positioning them as ideal for biosensing applications. This review outlines the recent advances (2022-2024) in ZnO-based nanobiosensors for medical applications, based on a selection of peer-reviewed, open-access experimental studies extracted from databases including IEE Xplore, Scopus and ScienceDirect. A variety of ZnO morphologies, including nanoflowers, nanorods, nanosheets and nanoparticles have made possible the development of piezoelectric, electrochemical, optical and field-effect transistor biosensors. Experimental data reveal that ZnO-based nanotechnologies achieve rapid detection of lactate, cancer biomarkers, glucose and infectious disease antigens, demonstrating lower detection limits and enhanced sensitivity. Emerging strategies, such as noble metal decoration and integration into wearable platforms or microfluids, have improved efficiency and clinical applicability. ZnO-based nanostructures therefore serve as a promising basis for the next generation of continuous monitoring and point-of-care systems.

Keywords: zinc oxide, nanobiosensor, medical diagnostic.

Avances en nanobiosensores de óxido de zinc para diagnóstico médico: morfologías, mecanismos y aplicaciones

Resumen. - Las nanoestructuras de óxido de zinc (ZnO) presentan buenas propiedades morfológicas, químicas y eléctricas, como gran área superficial, comportamiento semiconductor y alto punto isoeléctrico, lo que las hace ideales para biosensores. Esta revisión aborda avances recientes (2022–2024) en nanobiosensores de ZnO para diagnóstico médico, basándose en estudios experimentales peer-review y open-access de IEEE Xplore, Scopus y ScienceDirect. Diversas morfologías de ZnO como nanoflores, nanovarillas, nanoláminas y nanopartículas han permitido desarrollar biosensores piezoeléctricos, electroquímicos, ópticos y de efecto de campo. Los resultados muestran detección rápida de lactato, biomarcadores oncológicos, glucosa y antígenos patógenos, con límites de detección menores y sensibilidad mejorada. Estrategias emergentes, como decoración con metales nobles e integración en dispositivos portátiles o microfluidos, aumentan la eficiencia y viabilidad clínica. En conjunto, las nanoestructuras de ZnO se perfilan como plataforma prometedora para la siguiente generación de sistemas de monitoreo continuo y diagnóstico en el punto de atención.

Palabras clave: óxido de zinc, nanobiosensores, diagnóstico médico.

I. INTRODUCTION

Biosensors are analytical devices with the capability of combining a physiochemical transducer with an element of biological recognition for the detection of specific analytes and transforming this interconnection into a quantifiable signal [1]. This form of sensors represents a fundamental tool for modern medical diagnostics due to their high precision, Immediate respond and ability to provide real time and point of attention monitoring. Recent advancements in nanotechnology have caused an increment in the development of nanobiosensors, which incorporate nanomaterials mainly less than 100nm in size to strengthen the biosensors execution by enhancing the electron transfer rates, biomolecule immobilization efficiency and surface area [1].

Different types of nanomaterials like graphene, gold nanoparticles (AuNPs), carbon nanotubes (CNTs), and metal oxide nanostructures have shown remarkable benefits in biosensing applications [2]. These materials allow lower detection limits, a faster reaction time and higher sensitivity in comparison to traditional bulk materials. The nanoscale dimensions for these devices enable a productive transduction of biological signals and support the miniaturization process for the incorporation of wearable or portable diagnostic system devices. More precisely, such forms of nanotechnology have led to significant advancements in optical, piezoelectric and electrochemical biosensors [2].

In comparison to the large range of nanomaterials on the market, zinc oxide (ZnO) has proven to be a potential candidate for nanobiosensing technologies. ZnO provides a mixture of valuable characteristics, including a large bandgap ($\sim 3.3\,\text{eV}$), chemical stability, a high isoelectric point (~ 9.5)) and an excellent biocompatibility, contributing to its status as suitable for the immobilization of low isoelectric point (IEP) biomolecules like antibodies and enzymes [2]. In addition, ZnO can be engineered into a wide range of nanostructures like nanoflowers, nanowires, nanorods and nanosheets, using financially sustainable and industrially scalable methods for example: sol-gel processes, sputtering and hydrothermal synthesis [3][4] Furthermore, the variation on ZnO structures morphologically speaking helps with the increment of the surface area and promote stronger affinities with analytes, contributing to greater selectivity and sensitivity in biosensors made of ZnO nanostructures [4].

This review aims to provide an overview of recent advances (2022-2024) in ZnO-based biosensors used for medical diagnostics. On top of that, the review underscores properties that make ZnO-based biosensors highly favorable in a unique way, highlights key uses for glucose monitoring, cancer biomarker sensing, infectious disease detection, and explores methods for device fabrication and biomolecule functionalization. Lastly, this document describes current challenges in integration, reproducibility and stability, and addresses future scenarios for real-world implementation and clinical technology transfer of ZnO-based biosensing devices.

II. STRUCTURAL AND FUNCTIONAL BASIS OF ZNO NANOBIOSENSORS

A. Physiochemical properties of ZnO for biosensing

ZnO nanostructures have a unique mixture of electrical, chemical, and morphological properties that make them suitable for biosensor applications.

1. **High isoelectric point and biomolecule adsorption** – exhibits an isoelectric point of approximately 9.5, making its surface positively charged under physiological pH conditions [5]. This favors the electrostatic adsorption of enzymes and proteins resulting in a stable microenvironment, facilitating both preservation of biomolecular activity and efficient electron transfer.

2. **High surface-to-area-to-volume ratio** – this enables the anchoring of biological molecules, leading to enhanced detection of a specific target analyte [5]. The ability to modify morphology and surface chemistry plays a critical role in modulating the biosensor's selectivity, sensitivity, and operational range.

Table 1 presents the different morphologies of ZnO in biosensing applications. Each ZnO morphology offers unique structural and functional features that enhance biosensor performance. These structures vary in dimensionality, surface characteristics, and electron transport capabilities.

B. Electrical and optical properties for sensor stability

ZnO is a wide-bandgap semiconductor with a bandgap energy of 3.37 eV, which means it can operate at high voltages and under strong electric fields without undergoing electrical breakdown [6]. This property ensures the long-term electrical stability of biosensors, especially those used in biological fluids or high-impedance environments.

ZnO also exhibits strong photoluminescence for sensitive optical detection due to its high exciton binding energy (60meV) [6]. This photoluminescence emission typically occurs in the UV and visible blue range and is highly sensitive to changes at the surface of the nanostructure enabling real-time monitoring of biomolecular interactions.

C. Signal transduction mechanismss

1. **Electrochemical transduction** – electrochemical biosensors operate by converting biochemical interactions into electrical signals. The ZnO nanostructures act as electrode materials or electrode modifiers due to their moderate conductivity, high surface area, and ability to stabilize redox-active biomolecules. They facilitate efficient electron transfer between the enzyme's active site and the electrode [7].

2. **Optical transduction** – the ability to interact with light and produce measurable changes in their optical emission properties upon biomolecular recognition. When a target biomolecule binds to the ZnO surface, it modifies the surface electronic structure or local environment affecting the photoluminescence behavior [4, 8].

Tabla 1. Morphologies of ZnO in biosensing applications.

Morphology	**Dimensionality**	**Structure Description**	**Key Functional Features**	**Biosensor Application**
Nanoparticles (NPS) [4]	0D (zero-dimensional)	Spherical or quasi-spherical particles with nanoscale diameters	High density of surface atoms; excellent for maximizing surface interactions	Antibody /aptamer-based sensors; electrochemical detection
Nanorods/ Nanowires [4]	1D (one-dimensional)	Vertically aligned or elongated rod-shaped structures	Direct, continuous electron transport paths; fast redox reactions	Enzyme-based glucose, uric acid, and cholesterol sensors
Nanosheets [4]	2D (two-dimensional)	Thin, flat plate-like layers with polar surface exposure	Enhanced binding of charged biomolecules; flexible integration	Wearable patch sensors; DNA/protein electrochemical sensors
Nanoflowers / Porous structures [4]	3D (three-dimensional)	Branched assemblies with high surface area and inner voids	High target-binding molecule loading capacity; improved analyte diffusion and transport	SARS-CoV-2 gene sensors; cancer biomarker immunosensors

3. **Piezoelectric / acoustic transduction** – thin films or nanostructures act as mass-sensitive platforms causing an analyte (such as a protein or virus) when bonded to a functionalized ZnO surface, it causes a measurable mass change [9]. Due to ZnO's strong piezoelectric coefficient and high acoustic velocity, even minute changes in mass lead to detectable frequency shifts, enabling highly sensitive, label-free detection of biomolecules in real time.

4. **Field-effect transistor (FET) transduction** – ZnO nanowires or thin films form the semiconducting channel between the source and drain electrodes [6][10]. These channels are functionalized with biorecognition molecules. When a charged analyte (such as a protein, ion, or DNA) binds to the surface, it modifies the local electric field, affecting the charge carrier density in the ZnO channel and the conductivity of the device [6]. This results in a modulation of the drain-source current, which serves as the detection signal [11][12][13][14].

III. METHODOLOGY

This review is based on an extensive analysis of various scientific articles released between 2022 and 2024, directing attention to the applications of ZnO nanotechnologies in biosensors disease detection. Importantly, it covers both peer-reviewed reviews and open-access articles focusing on surface modification approaches for ZnO-based biosensors surface, key aspects of biosensing, and recent experimental investigations into its capabilities in optical and electrochemical sensors. The articles used in this review were selected based on their consistency with the study's focus [15], clinical relevance, and uniqueness, relying on sources like Springer, ScienceDirect, ELsevier and literature databases including IEEE Xplore and Scopus.

Tabla 2. Key contributions in ZnO-based biosensors

Ref.	Year	Key Contribution
[9]	2024	Development of a self-powered lactate biosensor based on the piezoelectric effect of ZnO nanowires
[10]	2023	Non-enzymatic glucose sensor using Ag-decorated ZnO nanorods, $\approx 1.3\ \mu$M, high sensitivity
[14]	2023	Electrochemical immunosensor for anti-PSA employing spherical ZnO structures, achieving nanomolar detection
[16]	2023	Microfluidic platform with ZnO nanorods for point-of-care dengue (DENV-3) immunofluorescent detection
[6]	2022	Review of 2D ZnO nanostructure-based biosensors, covering synthesis through device fabrication and performance metrics

IV. RESULTS

Recent studies have shown that ZnO structures can be adapted into several morphologies – from one-dimensional (1D) nanowires and nanorods to two-dimensional (2D) nanosheets and hierarchical nanoarchitectures – to improve the bio detection performance [11]. These modified forms of ZnO offer a large surface area and a high isoelectric point (favorable surface chemistry) for the immobilization of bioreceptors, which translates into high sensitivity and low limits of detection (LOD) in medical diagnosis [11]. This section in specific examines the experimental findings from 2022 to 2024 on ZnO-based biosensing devices targeted at a wide range of medically relevant analytes, including pathogens, glucose, cancer biomarkers and hormones. The emphasis of this section is placed on new ZnO-based nanostructures (e.g., 2D nanosheets, vertically aligned nanorods, flower-like hierarchical structures), various sensor configurations (optical, field-effect transistor, electrochemical), key performance indicators (LOD, linear range, sensitivity), and the demonstrated potential for real-life applications (point-of-care devices and wearable devices). Table 3 outlines exemplary findings from recent open-access studies.

Tabla 3. Performance comparison of ZnO-based biosensors

Analyte	ZnO Nanostructure	Detection Method	Linear Range	LOD	Sensitivity
H_2O_2 (enzymatic)	Waxberry-like ZnO microspheres [12]	Amperometric enzyme biosensor	0.15–15 mM	0.115 μM	–
H_2O_2 (non-enzymatic)	ZnO nanoparticles on MWCNTs [13]	Amperometric enzyme-free sensor	1–20 mM	–	–
Glucose	High-aspect-ratio ZnO nanorods [5]	Amperometric enzyme biosensor	–	–	Fastest response ($\sim$5s)
Glucose	Ag-decorated ZnO nanorods [10]	Amperometric enzyme-free biosensor	50–175 μM	1.3 μM	2792μA /(mM·cm^2)
Anti-PSA antibody	Spherical ZnO nanostructures [14]	Electrochemical immunosensor	–	$\sim$1–2 nM	Higher with spherical ZnO
CA-125	ZnO–Au hybrid nanorods [15]	Immunosensor (DPV)	–	$\sim$2.5 ng/μL	$\sim$100$\times$ better than ELISA
Dengue virus antigen	ZnO nanorods in microfluidic chip [16]	Immuno-fluorescence detection	$\sim$3.1$\times$10^{-4} – 3.1$\times$10^3 ng/mL	3.1$\times$10^{-4} ng/mL	2.7$\times$ higher signal vs flat glass
Lactate	ZnO nanowire array on Ti substrate [9]	Piezoelectric enzymatic biosensor	Up to 27 mM	$\sim$1.3 mM	Self-powered signal from LOx reaction

A. ZnO Nanobiosensors for Glucose and H_2O_2 Monitoring

Significant advances in biosensing have been led by ZnO-based nanostructures, especially in the detection of hydrogen peroxide (H_2O_2) and glucose. ZnO-based microspheres resembling waxberries and with a large surface area for enzyme immobilization, making possible a horseradish peroxidase (HRP) biosensor showing a linear range of 0.15–15 mM and a low detection limit of $\sim$0.115 μM for hydrogen peroxide [12]. In another study, it was showed that ZnO nanoparticles anchored onto carbon nanotubes produced stable, enzyme-free amperometric sensing of hydrogen peroxide, with the performance largely dictated by the ZnO structural form (spherical or rod-shaped) [13]. These investigations underscore how nanostructures design contributes to enhanced biosensor performance.

In addition, the morphology of ZnO nanorods for glucose sensing was modified, revealing that thinner, longer structures facilitated higher enzyme immobilization and resulted in the fastest amperometric response (5s) and the highest performance [5]. In recent studies, an enzyme-independent glucose sensor with the use of vertically aligned ZnO-based nanorods was modified with silver nanoparticles. Their device demonstrated an outstanding sensitivity (2792 μA/(mM·cm^2)), with a linear range from 50 μM to 175 μM and a low LOD of 1.3 μM [10]. These findings validate that ZnO surface and structure modification (e.g., noble metal decoration) play a critical role in biosensors efficiency.

B. ZnO-Based Sensors for Cancer Biomarkers

In a recent investigation, a ZnO-based sensor made for the detection of the anti-prostate-specific antigen (anti-PSA) antibodies was developed and this device achieved nanomolar detection limits, while evaluating and contrasting different types of ZnO morphology to enhance sensitivity [14]. Their results demonstrated that the morphology exhibiting superior sensitivity was the spherical nanostructures, outperforming rod-like forms. A design of ZnO-Au nanohybrid immunosensor for CA-125 (a biomarker for ovarian cancer) achieved a detection limit of 2.5 ng/μL, close to 100$\times$ more sensitive than conventional immunoblots [15]. These novel findings have shown the ZnO's growing impact in non-invasive cancer diagnosis.

C. ZnO Nanobiosensors for Infectious Disease Diagnostic

A notable example that illustrates the potential of ZnO nanomaterials in infectious disease diagnostics is developing a ZnO nanorod-integrated microfluidic immunofluorescence platform for the detection of Dengue virus serotype 3 (DENV-3) [16]. This study is especially relevant for low-resource settings and point-of-care diagnostics due to its sensitivity, speed, and minimal sample requirements.

The ZnO nanorods were synthesized via a seed-assisted hydrothermal growth process, resulting in vertically aligned structures with a predominant (002) crystal orientation. The ZnO nanorods functioned as an immobilization surface for specific monoclonal antibodies (mAbs) to the DENV-3 envelope protein. Functionalization was achieved using 3-glycidyloxypropyl trimethoxysilane (GPTMS) which is a silane linker that covalently bonds the antibodies to the ZnO surface. Among different surface treatments tested, ZnO modified with 4% GPTMS yielded the highest fluorescence intensity [16].

The mechanism of signal generation is based on optical transduction, where the amount of fluorescent signal directly correlates to the concentration of antigen present on the ZnO surface. The ZnO nanorods play a critical role by:

1. Providing a high surface area for mAb immobilization
2. Enhancing binding efficiency and signal amplification
3. Supporting stable, reproducible fluorescence output

This study is a strong example of how ZnO nanorod morphology can be strategically manipulated to improve biosensor performance through surface chemistry optimization and microfluidic integration. The work demonstrates that ZnO nanostructures not only enhance biomolecular binding but also enable label-based fluorescence detection at extremely low analyte concentrations.

D. Hormone and Metabolite Sensors with Nanostructures

A recent study presents a novel approach to lactate detection using a self-powered ZnO nanowire-based biosensor that represents the multifunctionality of ZnO in wearable diagnostics [9]. The authors developed a biosensing device in which ZnO nanowire arrays were hydrothermally grown on a titanium substrate. The ZnO surface was then functionalized with lactate oxidase (LOx), an enzyme that catalyzes the conversion of lactate into pyruvate and hydrogen peroxide [9]. What distinguishes this work is its use of the piezoelectric properties of ZnO to enable energy-autonomous sensing. The detection mechanism is based on the piezo-enzymatic coupling effect. Mechanical deformation (e.g., pressure or bending) of the ZnO nanowires generates a piezoelectric voltage due to lattice polarization. In the presence of lactate, the enzyme-catalyzed reaction alters the local ionic environment at the ZnO surface, which modulates the piezoelectric signal output. The magnitude of the output voltage correlates with lactate concentration, allowing real-time, quantitative measurement without external power or labeling agents.

This study represents an important advancement in self-powered biosensing and demonstrates the potential of ZnO as a material platform for mechanically responsive, label-free, and wearable diagnostics. The concept of piezo-enzymatic sensing offers a path forward for battery-free devices in personalized healthcare. Furthermore, the authors demonstrated a clear integration strategy between material design (ZnO nanowires), biofunctionalization (LOx), and mechanical actuation.

E. Toward Real-World Implementation

ZnO has been positioned as a leading material in next generation biosensors due to its compatibility with chemical stability, biocompatibility and scalable fabrication techniques (e.g., screen printing, hydrothermal growth). These ZnO-based nanobiosensors are more frequently tailored for wearables and point-of-care deployment. A thorough review by Zhou et al described ZnO-based enzyme biosensors and substantiated the material's broad relevance to clinical diagnostics.

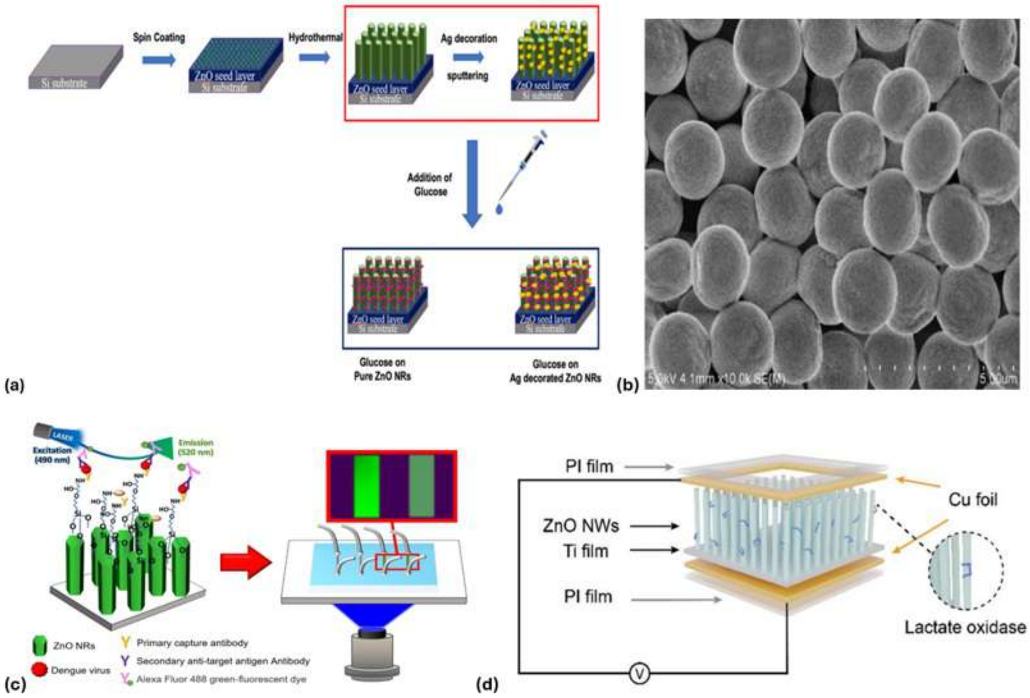

Fig. 1. Representative ZnO nanostructure morphologies and biosensor architectures.

CONCLUSIONS

ZnO nanobiosensors demonstrate exceptional physicochemical properties that position them as a root for the future development of advanced biosensing platforms. Their wide bandgap, high isoelectric point, and morphological diversity provide versatility for engineering medical diagnostic devices. The reviewed studies validate that strategic manipulation of ZnO nanostructures can significantly expand their applicability beyond traditional laboratory settings into real-time, portable, and point-of-care diagnostic settings.

The adaptability of ZnO opens pathways for developing next-generation biosensors capable of multiplex detection, self-powered operation, and miniaturization. Future exploration should focus on overcoming challenges related to long-term stability, scalability, and clinical validation to ensure successful translation into healthcare practice.

ZnO-based nanobiosensors not only offer promising routes for disease diagnosis but also inspire broader applications in personalized medicine, continuous health monitoring, and environmental sensing.

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REFERENCES

[1] P. Bhattarai and S. Hameed, “Basics of biosensors and nanobiosensors,” *Wiley Online Library*, pp. 1–22, Feb. 2020.

[2] M. L. M. Napi, S. M. Sultan, R. Ismail, K. W. How, and M. K. Ahmad, “Electrochemical-based biosensors on different zinc oxide nanostructures: A review,” *Materials*, vol. 12, no. 18, p. 2985, Sep. 2019.

[3] J. Theerthagiri *et al.*, “A review on zno nanostructured materials: Energy, environmental and biological applications,” *Nanotechnology*, vol. 30, no. 39, p. 392001, Jun. 2019.

[4] I. M. Maafa, “Potential of zinc oxide nanostructures in biosensor application,” *Biosensors*, vol. 15, no. 1, p. 61, Jan. 2025.

[5] Z. Zhao, W. Lei, X. Zhang, B. Wang, and H. Jiang, “Zno-based amperometric enzyme biosensors,” *Sensors*, vol. 10, no. 2, pp. 1216–1231, Feb. 2010.

[6] M. S. Krishna *et al.*, “A review on 2d-zno nanostructure based biosensors: From materials to devices,” *Materials Advances*, vol. 4, no. 2, pp. 320–354, Nov. 2022.

[7] Y. Zhao *et al.*, “Nanorod arrays composed of zinc oxide modified with gold nanoparticles and glucose oxidase for enzymatic sensing of glucose,” *Microchimica Acta*, vol. 182, no. 3–4, pp. 605–610, Sep. 2014.

[8] A. B. D. ć and Y. H. Leung, “Optical properties of zno nanostructures,” *Small*, vol. 2, no. 8–9, pp. 944–961, Jul. 2006.

[9] J. Lin, P. Yuan, R. Lin, X. Xue, M. Chen, and L. Xing, "A self-powered lactate sensor based on the piezoelectric effect for assessing tumor development," *Sensors*, vol. 24, no. 7, p. 2161, Mar. 2024.

[10] Y.-H. Lin, C. Sivakumar, B. Balraj, G. Murugesan, S. K. Nagarajan, and M.-S. Ho, "Ag-decorated vertically aligned zno nanorods for non-enzymatic glucose sensor applications," *Nanomaterials*, vol. 13, no. 4, p. 754, Feb. 2023.

[11] J. Zhou, N. S. Xu, and Z. L. Wang, "Dissolving behavior and stability of zno wires in biofluids: A study on biodegradability and biocompatibility of zno nanostructures," *Advanced Materials*, vol. 18, no. 18, pp. 2432–2435, Sep. 2006.

[12] C. Xia, N. Wang, L. Lidong, and G. Lin, "Synthesis and characterization of waxberry-like microstructures zno for biosensors," *Sensors and Actuators B: Chemical*, vol. 129, no. 1, pp. 268–273, Aug. 2007.

[13] M. B. Wayu *et al.*, "Morphology of hydrothermally synthesized zno nanoparticles tethered to carbon nanotubes affects electrocatalytic activity for h_2o_2 detection," *Electrochimica Acta*, vol. 97, pp. 99–104, Feb. 2013.

[14] V. Liustrovaite *et al.*, "Electrochemical immunosensor for the determination of antibodies against prostate-specific antigen based on zno nanostructures," *International Journal of Molecular Sciences*, vol. 24, no. 6, p. 5803, Mar. 2023.

[15] G. Gasparotto, J. P. C. Costa, P. I. Costa, M. A. Zaghete, and T. Mazon, "Electrochemical immunosensor based on zno nanorods–au nanoparticles nanohybrids for ovarian cancer antigen ca-125 detection," *Materials Science and Engineering C*, vol. 76, pp. 1240–1247, Feb. 2017.

[16] P. Pormrungruang *et al.*, "Metal oxide nanostructures enhanced microfluidic platform for efficient and sensitive immunofluorescence detection of dengue virus," *Nanomaterials*, vol. 13, no. 21, p. 2846, Oct. 2023.

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Advances in Technologies for the Soldiers of the Future

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Abstract. - Emerging technologies enhance soldiers' capabilities, improving safety, accuracy, and efficiency. Exoskeletons, AI, AR, biotechnology, nanotechnology, drones, smart materials, and communication technologies enable the optimization of strategies, decisions, resistance, and situational awareness, being key in modern armed forces. This review paper synthesizes the most relevant advances, their key technologies and the impacts they have on the efficiency of soldiers' strategies during their operations. A systematic PRISMA review was conducted across the SCOPUS, Web of Science, Taylor & Francis, PubMed, and ProQuest databases, identifying review articles on these advances, including practical cases of implementation in military forces in Latin America and Europe. The results show more recent advances such as drone swarms, biometrics for monitoring troops, and high-precision laser weapons. Despite challenges such as costs and technical training, these technologies transform defense, improving its effectiveness and security, driving greater capabilities, and providing competitive advantages in adverse events.

Keywords: emerging technologies, military innovation, technological innovation, security and defence.

Avances en Tecnologías Para los Soldados del Futuro

Resumen. Las tecnologías emergentes y avances en robótica actualmente potencian las capacidades, seguridad, precisión y eficiencia de los soldados. Exoesqueletos, tecnologías de realidad extendida, biotecnología, nanotecnología, drones, materiales inteligentes y las tecnologías de comunicación permiten optimizar estrategias, decisiones, resistencia y conciencia situacional, siendo clave para las operaciones de defensa de las fuerzas armadas modernas. Este trabajo describe los avances tecnológicos más relevantes, sus impactos en para los soldados durante sus operaciones, sus desafios y limitaciones. Se realizó una revisión sistemática PRISMA® identificando artículos en bases como SCOPUS, Web of Science, Taylor& Francis, PubMed y ProQuest además de casos reales de uso de estas tecnologías en fuerzas militares de América de Norte y Europa. La incorporación de tecnologías que incluyen enjambres de drones, biometría para monitoreo de tropas y armas láser de alta precisión impulsan ventajas competitivas ante el enemigo a gran distancia, a pesar de esto, persisten desafíos como el costos y formación técnica de los soldados.

Palabras clave: tecnologías emergentes, innovación militar, innovación tecnológica, seguridad y defensa.

I. INTRODUCTION

Currently, technology enhances aspects such as the effectiveness, security, and response capacity of soldiers, optimizing communication, surveillance, decision-making, and adaptability in combat, which is key to facing modern threats. The soldiers' use of technologies strengthens national defense, guarantees sovereignty, improves security, and positions countries in geopolitical competition. It also drives innovation, optimizes resources, and enables the efficient management of modern threats with reduced human risk. In this way, the impact of emerging technologies in the military field transcends the immediate operational benefits, contributing to the strengthening of institutional capacities and the promotion of global security. These innovations align with the Sustainable Development Goals (SDGs) [1], particularly SDG 16, which promotes the establishment of strong and resilient institutions, and SDG 17, as it requires partnerships to achieve its goals. Countries such as the United States, China, Russia, the United Kingdom, France, Israel, Germany, India, South Korea, and Japan are leading the way in integrating advanced technologies in military defense [2], while other nations are exploring their adoption to modernize their armed forces.

Technologies such as exoskeletons, artificial intelligence (AI), augmented reality (AR), brain-computer interfaces (BCIs), applied biotechnology, and 5G and 6G networks are shaping a paradigm shift in contemporary military strategies. These solutions strengthen situational awareness, optimize operational efficiency, and position technological innovation as a fundamental axis to ensure effectiveness in critical missions [3].

The modern soldier faces increasingly complex scenarios where the ability to adapt quickly and effectively utilize advanced technologies is essential for operational success. Solutions have been developed that improve mobility, physical endurance, and decision-making under dynamic conditions [4]. The adoption of technologies poses new ethical, technical, and strategic challenges that require clear regulatory frameworks and specialized training.

To understand the areas that have developed around the study of technologies for the soldiers of the future, Figure 1 has been made, which shows a bibliometric graph obtained from the analysis of 565 studies obtained in the SCOPUS database with the following text string: "*(future soldier OR soldier technology OR military technology OR combat systems) AND (wearable OR smart OR enhanced OR augmented) AND (communication OR networking OR connectivity OR data transfer) AND (sensors OR monitoring OR detection OR surveillance) AND (robotics OR autonomous OR drones OR unmanned) AND (training OR simulation OR education OR preparedness) AND (logistics OR support OR supply chain OR maintenance) AND (cybersecurity OR information security OR data protection OR threat assessment)*".

The bibliometric map in Figure 1 highlights that research on technologies applied to the soldiers of the future is addressed around two central axes: on the one hand, the development and application of advanced technologies such as artificial intelligence, robotics, sensors, nanotechnology, wearable devices, and communication systems; on the other, the analysis of the impact of these innovations on the physical, cognitive and decision-making capacities of military personnel. Concepts such as "*technology*", "*military operations*", "*military applications*" and "*soldier*" appear as predominant nodes, reflecting the importance of human-machine integration in the military field. The inter-

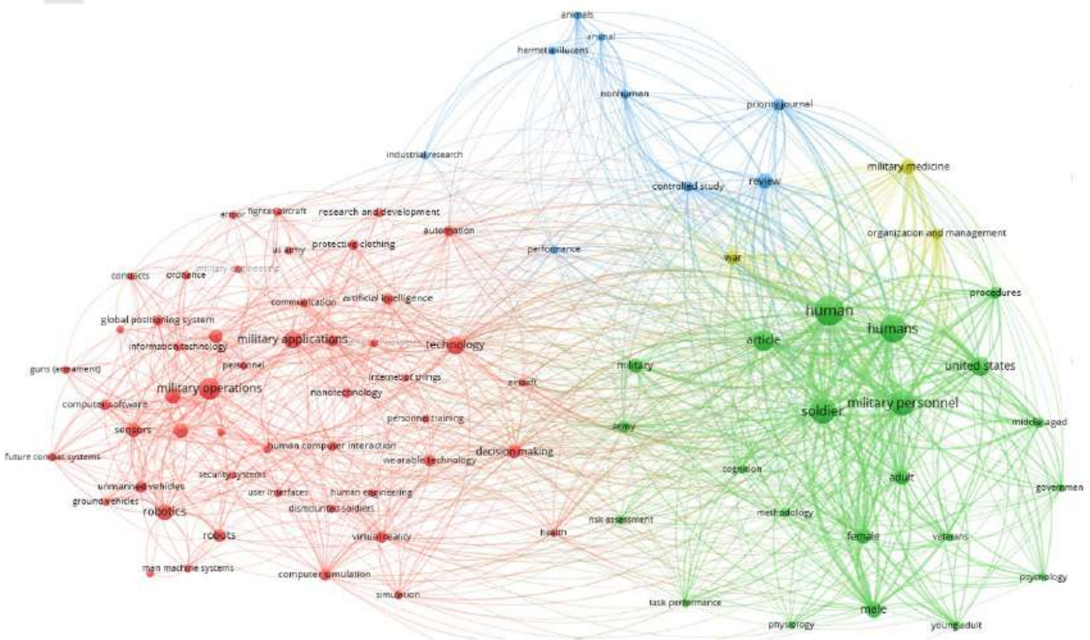

Fig. 1. Bibliometric graph highlighting studies related to technologies for soldiers of the future carried out with VOSViewer v.1.6.20.

connectedness between technological terms and human factors underscores the need to design solutions that not only enhance operational efficiency but also consider the health, performance, and safety of soldiers in complex environments. Additionally, the graph illustrates a growing interest in the scientific validation of these technologies through controlled studies, as well as in their institutional management and implementation, particularly in contexts such as military medicine and strategic defense organizations. All this points to a paradigm shift in the armed forces, where technological innovation and human adaptation are essential pillars to face the challenges of modern and future warfare.

The study of the advanced technologies addressed in Figure 1 and applied to the field of defence and security for soldiers may be of interest to researchers, academics, and professionals in the military, defence, and security fields, as well as developers of emerging technologies applied to tactical environments. The information provided may be relevant to defense policymakers, government institutions, companies in the military-technology sector, and international organizations seeking to optimize the readiness, security, and effectiveness of their armed forces through innovative solutions. Additionally, it can be useful for experts in ergonomics, occupational health, and the human factor who are interested in the impact of these solutions on the performance and well-being of soldiers.

This article aims to conduct a systematic review of the main technologies and development trends for soldiers of the future in the defense field, analyzing their operational impact, associated risks, and integration perspectives. The structure of the document addresses in Section 2 the methodology based on the guidelines of the PRISMA® methodology; Section 3 presents the results on (1) Technological developments for the soldiers of the future, (2) Impact of the use of technologies on the soldiers of the future, (3) Challenges in the use of technologies, and (4) Prospects in the use of technologies. Section 4 discusses technical, ethical, and strategic aspects related to the implementation and proper use of these technologies. Finally, the Conclusions are presented.

II. METHODOLOGY

The systematic review of this article was conducted following a protocol based on the PRISMA methodology, with the aim of identifying and analyzing the most relevant advances in emerging technologies applied to various areas of defense and combat for military personnel. Systematic reviews published in the last ten years in scientific journals and specialized conferences were considered. The primary research question guiding this review was: What technologies are being developed to enhance the performance of future soldiers? The number of studies identified through various databases and repositories, as well as their corresponding text strings for the search, is presented in Table 1.

Tabla 1. Text strings used for scientific literature search.

Database	**Search string**	**Number of studies**
Web of Science	`"future soldiers technologies" (Author Keywords) AND 2024 OR 2023 OR 2022 OR 2021 OR 2020 OR 2019 OR 2018 OR 2017 OR 2016 OR 2015 (Publication Years)`	95
Taylor & Francis	[Publication Title: ”future soldiers”] AND [Publication Title: ”technologies”] AND [Publication Date: (01/01/2019 TO 12/31/2024)]	25
Scopus	TITLE(”emerging” AND ”technologies”) AND PUBYEAR ¿ 2013 AND PUBYEAR ¡ 2025	110
ScienceDirect	Title, abstract, keywords: ”emerging technologies”	45
IEEE Xplore	(”Document Title”: ”emerging”) AND (”Document Title”: ”technologies”)	32
Total		**307**

This literature review was developed in three stages: (1) formulation of research questions, (2) definition of study scope, and (3) design of a search strategy to identify and select relevant documents. Priority was given to the most significant articles, followed by rigorous data extraction and analysis. The review was guided by five research questions: (1) What technologies enhance soldiers' operational effectiveness? (2) What key advances support future soldier solutions? (3) What are the impacts of these technologies? (4) What ethical and social challenges arise? (5) What are the future defense prospects? To assess article quality, evaluation criteria were applied as detailed in Table 2.

Figure 2 illustrates the workflow used for selecting reference documents. The search included the keywords: `("future soldier" OR "soldier technology" OR "military technology") AND ("wearable" OR "smart" OR "extended reality")`. Papers that analyzed relevant developments in emerging technologies over the past decade were included, while those that focused exclusively on specific technical aspects, such as algorithms or simulations, were excluded.

Tabla 2. Quality Assessment Questions

Quality Assessment Questions	**Answer**
Does the article describe technologies developed for use in military operations?	(+1) Sí / (+0) No
Does the paper address the impacts of these technologies on the effectiveness of defense operations?	(+1) Sí / (+0) No
Does the document include analyses of the ethical and social implications associated with emerging technologies?	(+1) Sí / (+0) No
Does the publication belong to a journal indexed in SJR?	(+1) Q1, (+0.75) Q2, (+0.5) Q3, (+0.25) Q4, (+0.0) Not classified

A. Inclusion criteria

Scientific articles, systematic reviews, technical reports, and case studies that addressed technologies applied to the optimization of soldiers' capabilities in military contexts, such as wearable devices, intelligent solutions, and extended reality technologies (AR, VR, and MR), were included for this study. The selected documents were published between 2015 and 2025, in English or Spanish, and were available in full text through recognized databases such as Scopus, Web of Science, Taylor & Francis, ScienceDirect, and IEEE Xplore, thus guaranteeing the quality and timeliness of the information analyzed.

B. Exclusion Criteria

Those documents, which despite addressing emerging technologies such as wearables or extended reality, did not have a direct application in the military field or in the development of capabilities for future soldiers, were excluded. Likewise, publications of an informative nature, reports without peer review, press releases, blogs and non-academic books were discarded. Duplicate documents or preliminary versions, as well as studies published before 2015, were also eliminated, as they were considered obsolete for the purpose of this analysis.

III. RESULTS

Technologies applied to the military field have multiple characteristics, impacts, and considerations in their use. In this section, the most representative advances, applications, and a description of their potential for defense activities are described.

A. Technological developments for the soldiers of the future

This section describes the technological advances that are redefining the operational capabilities of modern soldiers, offering innovative solutions that strengthen their performance and adaptability in complex scenarios. Technologies such as exoskeletons, robotic suits, augmented reality (AR), advanced biotechnology, 5G networks, and autonomous drones have established themselves as key tools in improving safety, efficiency, and effec-

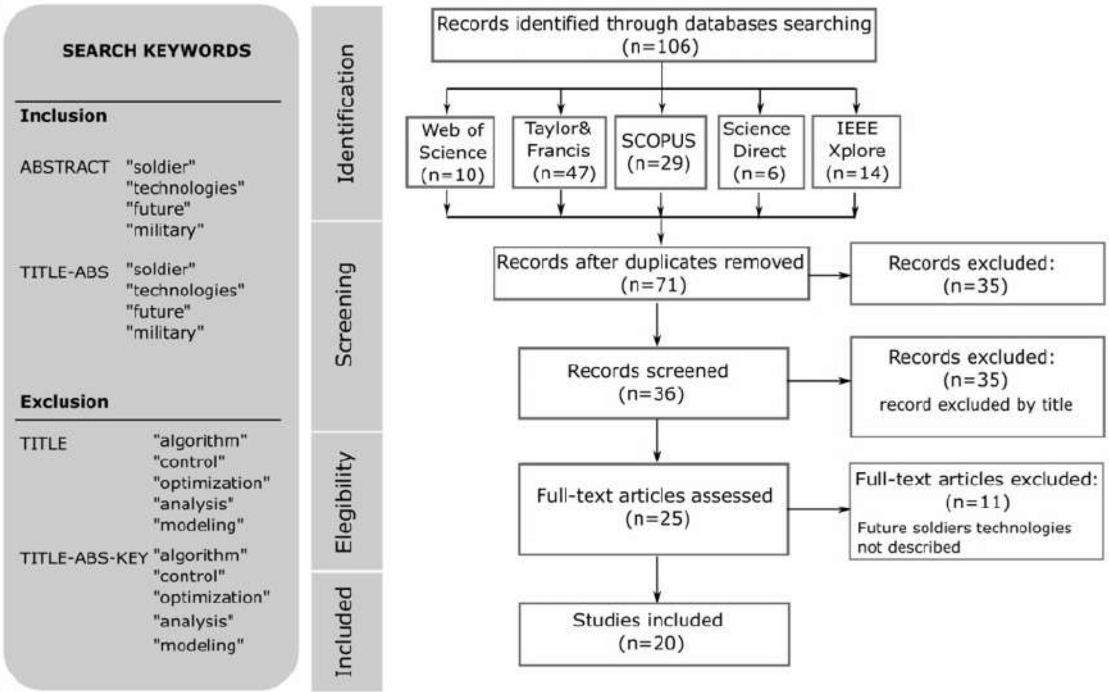

Fig. 2. Selection process of articles included in the study according to PRISMA® methodology.

tiveness on the battlefield [5][3][6]. Its applications, classifications and the ethical implications of its implementation are discussed below. Figure 3 summarizes and categorizes the technological advances addressed in this section.

Exoskeletons and robotic suits

The development of exoskeletons represents one of the most relevant advances in the physical strengthening of the modern soldier. These devices are designed to enhance strength, endurance, and stability, thereby minimizing muscle fatigue during prolonged operations and optimizing the combatant's energy efficiency. A prominent example is Lockheed Martin's ONYX Exoskeleton, which provides active knee support, improving mobility in challenging terrain and reducing muscle fatigue under prolonged load conditions **??**. Recent studies have shown that the use of exoskeletons, such as the ONYX, not only increases load capacity and reduces wear but also significantly decreases metabolic demand during walking, thereby increasing operational efficiency [7].

The new generation of robotic suits incorporates advanced biometric sensors for real-time monitoring of vital signs, thereby enhancing both performance and risk prevention during missions [8] (Figure 4). Additionally, soft exosuits offer greater flexibility and comfort, enabling extended use in demanding environments and broadening their tactical applications [9].

Artificial intelligence

Artificial intelligence (AI) is reshaping military operations by improving decision-making, real-time data analysis, and automating tactical tasks. It enables predictive threat analysis, multi-sensor detection, and action recommendations for units [10]. AI-powered drones and robots enhance reconnaissance and logistics with minimal human input,

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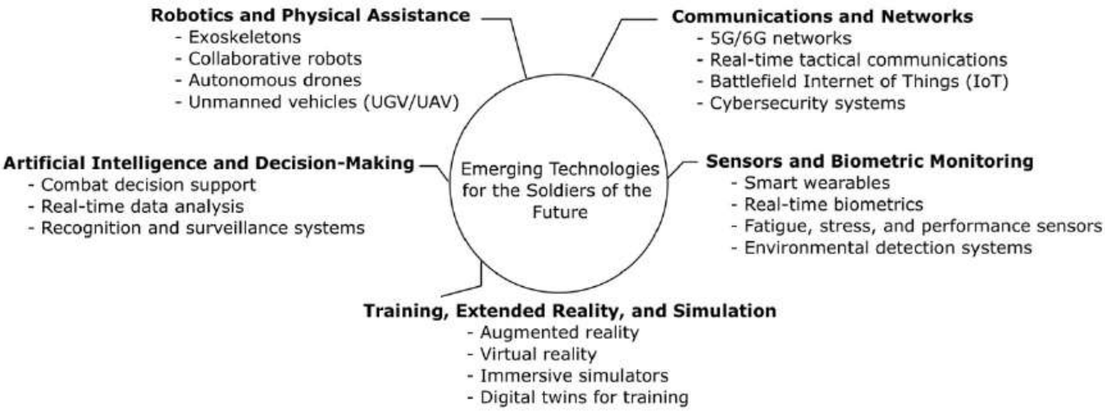

Fig. 3. Emerging technologies identified for use by soldiers in tactical and defense operations.

while sensor fusion creates real-time 3D battlefield views, improving awareness and reducing errors [11]. Ethical concerns include accountability and algorithmic bias. Figure 4 shows portable technologies such as physiological monitors, drones, communication power sources, and exoskeletons for mobility and protection.

Augmented and mixed realitye

Augmented reality (AR) and mixed reality (MR) have established themselves as key technologies to optimize tactical perception and operational efficiency in military environments. Advanced devices, such as the Microsoft HoloLens 2, allow strategic maps, evacuation routes, intelligence data, and critical environmental elements to be overlaid directly into the soldier's field of vision, significantly improving real-time decision-making [12].

The integration of these technologies facilitates the projection of 3D images and identification systems of enemies and allies, reducing cognitive overload in high-pressure situations. Through intelligent Head-Up Displays (HUDs), soldiers receive immediate alerts, strategic updates, and mission orders, thereby increasing their situational awareness and ability to respond quickly and accurately.

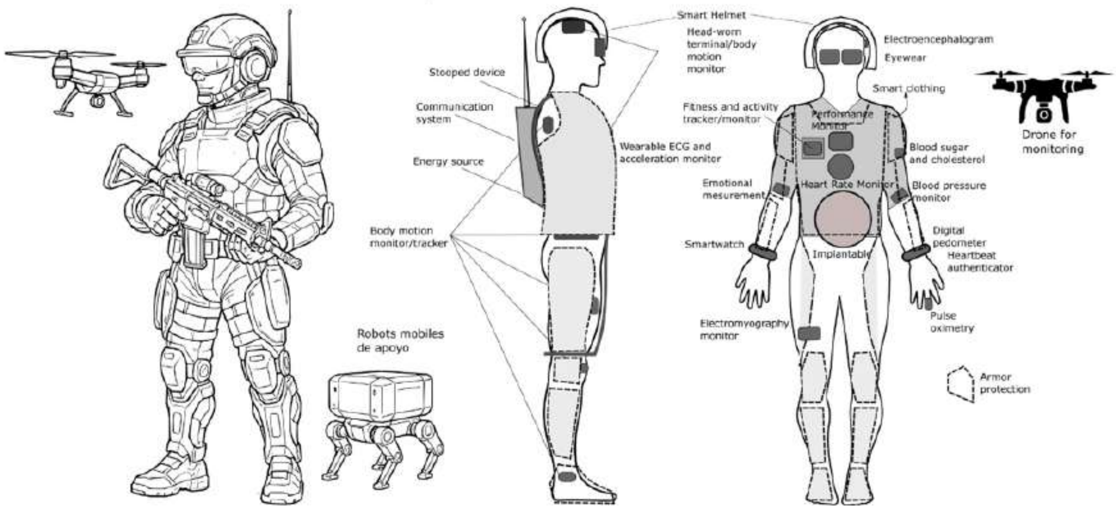

Fig. 4. Wearable devices for vital signs monitoring with the use of smart clothes, robots, and multiple sensors.

Virtual reality (VR) is widely used in military training, recreating realistic combat scenarios where soldiers practice skills like threat detection, navigation, and rescue operations. Studies show that incorporating VR and augmented reality (AR) significantly enhances tactical skill retention, mental resilience, and adaptability [11]. These immersive simulations provide high-fidelity environments that improve training effectiveness.

Biotechnology applied to the military field

Military biotechnology is reshaping how soldiers' health, performance, and recovery are managed in demanding scenarios. It includes advanced biometric sensors, gene therapies, and stress biomarkers to monitor and enhance physical and cognitive functions. Portable or implantable sensors track heart rate, oxygen saturation, hydration, and fatigue in real time, improving tactical and medical decisions [13][14]. Their use also accelerates recovery, reduces downtime, and increases troop availability in prolonged missions.

Gene therapy research explores ways to boost muscle endurance, speed up injury recovery, and improve cognitive adaptability in hostile settings. Tools like CRISPR are under evaluation to enhance physiological responses to extreme stress [15].

Early detection of stress biomarkers helps anticipate performance decline, aiding team management and mission planning. However, these advances raise ethical concerns around genetic modification, consent, and long-term effects. Thus, while biotechnology expands human potential, its application demands clear ethical frameworks and transparency.

Brain-Computer Interfaces (BCI)

Brain-Computer Interfaces (BCIs) are among the most disruptive technologies in today's military, enabling control of devices via neural signals without physical movement. Their use demands strict safety protocols and ethical oversight to ensure responsible deployment.

In combat, BCIs improve reaction time, silent communication, and control of autonomous systems—critical for high-demand missions [16]. DARPA has shown their potential in managing drones, robots, and weapons with neural commands, reducing latency. BCIs also monitor soldiers' cognitive and emotional states in real time, enabling early responses to fatigue or stress, vital for sustained operations [17]. Strategically, BCIs could transform military capabilities and future warfare dynamics [18]. However, they raise ethical concerns around mental privacy, consent, and cybersecurity. Strong ethical frameworks are essential for their responsible integration [19].

Nanotechnology and smart materials

Nanotechnology and smart materials are transforming soldiers' protection, mobility, and adaptability in demanding environments. Their integration raises concerns about sustainability, cost, and long-term toxicity, requiring strict regulation and safety protocols.

Key applications include smart fabrics in uniforms with self-healing, adaptive camouflage, and temperature regulation, enhancing survivability and comfort in extreme conditions [20]. Nanotech also enables ultra-light, high-resistance armor made from carbon and graphene nanotubes, offering superior ballistic protection with less weight [11].

Nanosensors embedded in gear detect chemical, biological, and radiological threats in real time, improving tactical responses. Research is advancing implantable nanodevices for monitoring physiological data and delivering drugs in response to fatigue or injury. Together, these innovations are central to strengthening future soldiers' protection and operational resilience.

5G Networkss

5G networks have enabled faster and more reliable connectivity on the battlefield, facilitating communication between units and the handling of advanced technological systems such as augmented reality devices and biometric sensors. This technology offers low latency and high data transmission capacity, improving coordination and real-time decision-making. In addition, 5G networks enable the efficient control of autonomous drone swarms and the integration of advanced artificial intelligence systems for tactical and strategic operations, increasing effectiveness in critical missions.

Tabla 3. Technologies, applications, benefits, and potential risks of using technologies for soldiers in the armed forces.

Technology	**Applications**	**Benefits**	**Potential risks**
Exoskeletons	Physical assistance, load support	Increased strength, reduced fatigue	Mechanical failures, technological dependence
Augmented reality (AR)	Tactical visualization, immersive training	Better situational awareness, effective training	Cognitive overload, misinterpretation
Artificial intelligence (AI)	Image analysis, threat prediction	Quick decisions, early detection	Data biases, cyberattacks
Bioengineering	Muscle and cognitive optimization	Greater resistance, better recovery	Ethical dilemmas, unforeseen effects
Brain–computer interface (BCI)	Device control by thought	Speed of communication, tactical advantage	Risk of invasion of mental privacy
Nanotechnology and Smart materials	Ballistic protection, climate adaptability	Lighter armor, self-healing fabrics	High costs, vulnerability in extreme conditions

Autonomous drones and smart swarms

Autonomous drones are transforming military operations by enabling surveillance, reconnaissance, and logistical support missions with minimal human intervention. Equipped with artificial intelligence, these devices are not only capable of operating synchronously in swarms but also of adapting to changes in real-time, optimizing coverage in the field and significantly improving operational efficiency [21].

Precision Laser Weapons

The development of laser weapons has expanded defensive and offensive capabilities by allowing the neutralization of threats with high accuracy and minimal collateral damage. These tools are crucial for countering airstrikes and safeguarding vital battlefield facilities [22].

A. Impact of the use of technologies on the soldiers of the future

The use of these technologies has improved the efficiency, safety, and operational performance of soldiers. For example, drone swarms enable the execution of complex tactical missions more effectively [21], while biometric sensors monitor troops' health in real-time, preventing medical emergencies [12]. Additionally, AR and MR enhance training by simulating real-time combat environments.

5G networks and autonomous drones have optimized communication and reconnaissance in missions, reducing risks and maximizing the success of operations. These tools also increase the ability to respond to unforeseen threats, strengthening the adaptability of troops [8].

B. Challenges in the use of technologies

The implementation of these technologies presents significant challenges. These include the high costs of development and implementation, as well as the need for specialized technical training for its effective use [5]. Ethical concerns also arise related to biometric data privacy and technological dependency, which could compromise autonomy in critical decisions.

The integration of AI into autonomous systems poses risks associated with potential errors in decision-making that occur without human intervention. This requires clear regulatory frameworks and strict oversight to ensure the safe and ethical use of these advanced tools.

C. Prospects of the technology use in soldiers of the future

The future of military operations will be marked by the integration of even more advanced technologies. The use of artificial intelligence (AI) is expected to extend to predictive systems capable of anticipating threats and providing more accurate real-time analytics [16]. In addition, biometric sensors will evolve into predictive devices capable of analyzing complex physiological patterns and anticipating health issues before they manifest.

Another expected advance is the adoption of 6G networks, which will offer higher speed and lower latency, allowing instant and coordinated communication between soldiers and autonomous systems [11]. Likewise, the development of lighter and stronger materials for exoskeletons will further improve soldiers' mobility and endurance on the battlefield.

International collaboration will be essential to establish ethical and normative standards to guide the responsible development of these technologies. Clear regulations and multilateral agreements will ensure their sustainable implementation, minimizing risks and maximizing benefits in the field.

D. Discussion

Emerging technologies—exoskeletons, robotic suits, BCIs, AR, AI, 5G, and autonomous drones—are redefining modern soldiers by enhancing individual performance and collective efficiency for faster, more adaptable deployments. However, their use raises ethical and strategic concerns. Biometric data, autonomous systems, and sensitive information require regulations to protect privacy, ensure consent, and uphold human judgment. Technological dependence also increases vulnerability to cyberattacks and system errors.

These innovations impact not only defense but also civilian sectors like biotech and communications, while raising fears of warfare dehumanization and widening geopolitical gaps. Future advances—such as miniaturized exoskeletons, 6G, accessible BCIs, and predictive AI—offer tactical benefits but increase systemic risks and bioethical challenges.

The future soldier goes beyond technology integration, using smart sensors, visors, laptops, and GPS to enhance real-time decision-making. Yet, prolonged conflicts may degrade capabilities, demanding versatile soldiers skilled in combat, stabilization, negotiation, and reconstruction.

Ethical dilemmas emerge with enhancing drugs, neurotech, and genetic modifications, particularly around consent and long-term health risks [15]. In a volatile global landscape, developing cognitive skills, emotional resilience, and tactical adaptability is crucial. Programs like the Comprehensive Soldier Fitness Program highlight the role of psychological strength in high-stress missions. Thus, technological advancement must be balanced with strategies that ensure operational resilience, protect human capabilities, and promote ethical reflection on the limits of military innovation.

CONCLUSIONS

The integration of emerging technologies—exoskeletons, AI, advanced communications, and extended reality—is redefining the modern soldier's capabilities. This synergy boosts tactical efficiency and real-time decision-making in complex, rapidly evolving scenarios. However, it also demands rethinking the human role in warfare, emphasizing physical, cognitive, and emotional resilience.

Military technological progress must be guided by ethical and strategic frameworks that protect human autonomy, particularly in areas like neurotechnology and genetic modification. Organizational resilience and long-term adaptability must be preserved to avoid overreliance on automation, ensuring readiness in low-tech or failure-prone environments. Innovation must align with principles of proportionality, transparency, and responsibility.

Future soldiers must be trained not only in advanced technologies but also in emotional resilience, technical expertise, and ethical reasoning. A holistic approach is essential to navigate highly automated and digitized combat settings, where human-machine collaboration will reshape the future of warfare and global security.

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REFERENCES

[1] V. Mai *et al.*, "The role of robotics in achieving the united nations sustainable development goals—the experts' meeting at the 2021 ieee/rsj iros workshop [industry activities]," *IEEE Robot. Automat. Mag.*, vol. 29, no. 1, pp. 92–107, Mar. 2022.

[2] A. A. E. Cubillos, J. A. A. Calderón, and Y. B. Suescún, "Innovaciones tecnológicas en las fuerzas militares de los países del mundo," *Rev. Cient. Gen. José María Córdova*, vol. 18, no. 29, pp. 213–235, Jan. 2020.

[3] G. Xiong, X. Ma, W. Li, J. Cao, J. Zhong, and Y. Su, "Brain computer interface technology for future battlefield," arXiv preprint arXiv:2312.07818, 2023.

[4] G. S. Sawicki, O. N. Beck, I. Kang, and A. J. Young, "The exoskeleton expansion: Improving walking and running economy," *J NeuroEngineering Rehabil*, vol. 17, no. 1, p. 25, Dec. 2020.

[5] A. A. E. Cubillos, J. A. A. Calderón, and Y. B. Suescún, "Innovaciones tecnológicas en las fuerzas militares de los países del mundo," *Rev. Cient. Gen. José María Córdova*, vol. 18, no. 29, pp. 213–235, Jan. 2020.

[6] J. Liu, S. Chen, F. Gao, Y. Long, Z. Wang, and B. Xi, "Development and application of robotics technologies in future intelligent soldier squad," in *2023 35th Chinese Control and Decision Conference (CCDC)*. Yichang, China: IEEE, May 2023, pp. 845–850.

[7] J. K. Proud *et al.*, "Exoskeleton application to military manual handling tasks," *Hum Factors*, vol. 64, no. 3, pp. 527–554, May 2022.

[8] A. J. Echevarria, "Putin's invasion of ukraine in 2022: Implications for strategic studies," *The US Army War College Quarterly: Parameters*, vol. 52, no. 2, pp. 21–34, May 2022.

[9] Y. Yoon and I.-J. Cho, "A review of human augmentation and individual combat capability: Focusing on mems-based neurotechnology," *Micro and Nano Syst Lett*, vol. 12, no. 1, p. 17, Sep. 2024.

[10] G. Xiong, X. Ma, W. Li, J. Cao, J. Zhong, and Y. Su, "Brain computer interface technology for future battlefield," arXiv preprint arXiv:2312.07818, 2023.

[11] R. A. Khalil, M. Haris, and N. Saeed, "Beyond line of sight defense communication systems: Recent advances and future challenges," arXiv preprint arXiv:2312.06491, 2023.

[12] M. M. Koop *et al.*, "The microsoft hololens 2 provides accurate biomechanical measures of performance during military-relevant activities in healthy adults," *Military Medicine*, vol. 188, no. Supplement_6, pp. 92–101, Nov. 2023.

[13] A. Yadav and K. Yadav, "Transforming healthcare and fitness with ai powered next-generation smart clothing," *Discov. Electrochem.*, vol. 2, no. 1, p. 2, Mar. 2025.

[14] Y. Chen, X. Jin, N. Weng, W. Zhu, Q. Liu, and J. Chen, "Simultaneous extraction of planetary boundary-layer height and aerosol optical properties from coherent doppler wind lidar," *Sensors*, vol. 22, no. 9, p. 3412, Apr. 2022.

[15] D. Bovens, E. V. Baarle, K. Ziesemer, and B. Molewijk, "The ethical dimension of personal health monitoring in the armed forces: A scoping review," *BMC Med Ethics*, vol. 25, no. 1, p. 88, Aug. 2024.

[16] S. Bhattacharyya, D. Valeriani, C. Cinel, L. Citi, and R. Poli, "Anytime collaborative brain–computer interfaces for enhancing perceptual group decision-making," *Sci Rep*, vol. 11, no. 1, p. 17008, Aug. 2021.

[17] X.-Y. Liu *et al.*, "Recent applications of eeg-based brain-computer-interface in the medical field," *Military Med Res*, vol. 12, no. 1, p. 14, Mar. 2025.

[18] X. Sun and B. Ye, "The functional differentiation of brain–computer interfaces (bcis) and its ethical implications," *Humanit Soc Sci Commun*, vol. 10, no. 1, p. 878, Nov. 2023.

[19] N. S. Jecker and A. Ko, "The unique and practical advantages of applying a capability approach to brain computer interface," *Philos. Technol.*, vol. 35, no. 4, p. 101, Dec. 2022.

[20] M. S. S. U. Patwary, "Smart textiles and nanotechnology: A general overview," *J Textile Sci Eng*, vol. 5, no. 1, 2015.

[21] P. Kozak and M. Vrsecka, "The use of drones in military conflict," in *2023 International Conference on Military Technologies (ICMT)*. Brno, Czech Republic: IEEE, May 2023, pp. 1–6.

[22] S. A. Ahmed, M. Mohsin, and S. M. Z. Ali, "Survey and technological analysis of laser and its defense applications," *Defence Technology*, vol. 17, no. 2, pp. 583–592, Apr. 2021.

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Evaluación comparativa de cementos Portland tipo I: implicaciones técnicas para la industria de la construcción

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Resumen. - El cemento es parte esencial de casi cualquier construcción. Su resistencia y versatilidad lo han convertido en un material protagonista en obras de todo tipo, desde estructuras simples hasta proyectos de gran envergadura. Este estudio busca comparar distintas marcas de cemento Portland tipo I, con la intención de ofrecer una mirada clara sobre cómo se comporta cada una y ayudar a tomar mejores decisiones al momento de elegir el material más adecuado. Para ello, se revisaron normas técnicas y se evaluaron propiedades clave como la resistencia del cemento, el tiempo que demora en fraguar, su nivel de finura, la expansión en agua y el contenido de aire. Todas las marcas analizadas cumplen con lo que exige la norma y algunas marcas ofrecen ventajas. Por eso, más que buscar un mejor cemento, se trata de identificar cuál se adapta mejor a cada necesidad específica en obra.

Palabras clave: cemento, construcción, resistencia, comparación.

Comparative evaluation of Portland cements type I: technical implications for the construction industry

Abstract. Cement is an essential part of almost any construction. Its strength and versatility have made it a key material in all types of projects, from simple structures to large-scale projects. This study seeks to compare different brands of Type I Portland cement, with the intention of offering a clear view of how each one performs and helping to make better decisions when choosing the most appropriate material. To this end, technical standards were reviewed and key properties such as cement strength, setting time, fineness, water expansion, and air content were evaluated. All the brands analyzed meet the standard's requirements, and some brands offer advantages. Therefore, rather than seeking the best cement, the goal is to identify which best suits each specific need on site.

Keywords: cement, construction, resistance, comparison.

I. INTRODUCCIÓN

El concreto es el material más utilizado en la construcción debido a su resistencia y adaptabilidad [1], siendo el cemento su componente fundamental, actuando como aglutinante y proporcionando las propiedades mecánicas necesarias para diversas aplicaciones. Debido a su alta versatilidad, el cemento es crucial en proyectos de infraestructura que exigen durabilidad y calidad, desde edificaciones residenciales hasta obras viales y de servicios a gran escala, consolidándose como esencial en el contexto de la expansión global de la construcción [2].

A nivel mundial, el consumo de cemento ha aumentado rápidamente, con China liderando la expansión de la industria cementera. En poco tiempo, el país ha establecido un número significativo de nuevas plantas de producción, superando ampliamente a las del resto del mundo. Este crecimiento está impulsado por la expansión del sector de la construcción, consolidando su posición como uno de los sectores más dinámicos de la economía global [3].

En América Latina, la diversidad de países en desarrollo genera una necesidad creciente de infraestructura a diferentes escalas, lo que conlleva a un alto consumo de cemento y concreto [4]. Este aumento en la demanda de materiales de construcción responde al crecimiento urbano y a proyectos de desarrollo como carreteras, hospitales y viviendas, fundamentales para mejorar la calidad de vida y el desarrollo económico en la región. En este contexto, la industria del cemento en el Perú representa uno de los sectores más significativos de la economía nacional, impulsada principalmente por el dinamismo de la actividad privada, que ha sido clave en la expansión del sector. Este crecimiento se refleja en la construcción de viviendas multifamiliares, centros comerciales, supermercados y hoteles, así como en el aumento de la inversión pública en la construcción y rehabilitación de carreteras, autopistas, hospitales, escuelas y otros proyectos de desarrollo e infraestructura [5].

El problema de elegir el cemento más adecuado para cada proyecto radica en la variabilidad de la calidad y desempeño del cemento Portland Tipo I en el Perú, material clave para el desarrollo de infraestructura. Las diferencias entre fabricantes pueden afectar la resistencia y durabilidad de las estructuras, especialmente en un país con condiciones geográficas diversas. La falta de estudios comparativos limita la capacidad de seleccionar materiales adecuados, comprometiendo la seguridad de las construcciones [6]. Realizar un análisis detallado de este tipo de cemento es fundamental para asegurar obras de calidad y tomar decisiones más acertadas dentro del sector.

Este estudio tiene como propósito identificar las posibles variaciones en propiedades y características del cemento Portland Tipo I, según la marca, con el fin de ofrecer información confiable que respalde decisiones bien fundamentadas en proyectos constructivos.

II. DESARROLLO

El cemento Portland Tipo I es, sin duda, uno de los más usados en el mundo de la construcción. Su popularidad se debe, principalmente, a su resistencia y a su capacidad para adaptarse a distintos tipos de obra. Según la norma ASTM C150 y otras equivalentes a nivel internacional, este tipo de cemento está pensado para construcciones en condiciones normales, donde no se necesita resistencia a agentes químicos agresivos ni otras propiedades especiales [7]. Por esa razón, está presente en gran parte de la infraestructura que vemos día a día.

En el caso del Perú, el mercado ofrece una variedad de marcas que comercializan cemento Portland Tipo I, lo que representa una ventaja para constructores e ingenieros, pero también un reto: no todas las marcas ofrecen el mismo nivel de calidad o desempeño [8]. Las diferencias pueden estar en aspectos como la resistencia mecánica, la finura del material o incluso el tiempo de fraguado. Por eso, resulta clave hacer una comparación detallada que permita identificar cuál es la opción más adecuada para cada tipo de proyecto, considerando tanto los resultados técnicos como la relación costo–beneficio.

Ahora bien, elegir un cemento no se trata solo de revisar fichas técnicas. Hay otros factores que también cuentan. El tipo de suelo donde se va a construir, el clima de la zona, e incluso qué tan fácil es conseguir una determinada marca en una región, pueden hacer una gran diferencia en el desempeño del concreto [9]. También influye la experiencia que han tenido otros usuarios con cada producto. Por todo ello, tomar en cuenta tanto los datos técnicos como el contexto real de uso permite tomar decisiones más acertadas y mejorar el resultado final de cualquier obra.

Por tal motivo, es necesario analizar factores como la trabajabilidad, la durabilidad y el costo del cemento Portland Tipo I producido en el Perú. Elementos como la calidad de las materias primas, el proceso de producción o incluso el lugar de fabricación pueden influir directamente en sus propiedades [10]. Este análisis permite identificar qué marcas se ajustan mejor a ciertos tipos de obra, ya sea por eficiencia, calidad o economía.

La presente investigación es de tipo básico, ya que busca generar conocimiento teórico sólido [11] sobre las propiedades del cemento Portland Tipo I de distintas marcas peruanas. El objetivo es analizar, comparar y organizar la información técnica disponible, para que pueda ser utilizada por profesionales del rubro o por quienes estén desarrollando estudios relacionados con este tipo de material [12].

El cemento Portland Tipo I es ampliamente reconocido como el cemento de uso general más empleado a nivel mundial, gracias a su capacidad para desarrollar resistencias mecánicas adecuadas en un amplio rango de aplicaciones estructurales y no estructurales. Según la norma ASTM C150, debe cumplir diversos requisitos físicos y químicos establecidos en dicha especificación. Su estructura química está dominada por la presencia de fases minerales como el silicato tricálcico (C_3S), silicato dicálcico (C_2S), aluminato tricálcico (C_3A) y ferrita tetracálcica (C_4AF), las cuales, al hidratarse, generan productos como el gel $C-S-H$ (silicato de calcio hidratado), responsable de buena parte de la resistencia y durabilidad del material [12]. La producción de este cemento involucra la calcinación de una mezcla de caliza y arcillas a temperaturas superiores a 1400 °C, seguida de una molienda controlada del clínker con yeso, dando como resultado un material con propiedades físicas estables (alta densidad, buena trabajabilidad y desarrollo progresivo de resistencia). Por su equilibrio entre rendimiento mecánico, disponibilidad global y respaldo normativo, el cemento Portland Tipo I continúa siendo un material fundamental en la ingeniería civil moderna [13][14].

III. METODOLOGÍA

La población estuvo compuesta por cinco marcas representativas: *Sol*, *Andino*, *Inka*, *Pacasmayo* y *Quisqueya*. Estas marcas fueron elegidas porque cuentan con un alto reconocimiento en el mercado y son ampliamente utilizadas en diversos proyectos de construcción. Su inclusión permite una comparación más amplia y realista de su desempeño, aportando una visión útil para el sector.

El análisis se desarrolló a partir de una revisión detallada de las especificaciones técnicas de cada marca, complementada con el estudio de la Norma Técnica Peruana (NTP) 334.009 que regula el cemento Portland Tipo I. Este enfoque permite comprender mejor los lineamientos que rigen su fabricación y uso, así como evaluar cómo se comporta cada marca en condiciones reales de obra [15].

Al considerar estos aspectos, es posible identificar de qué manera las diferencias entre marcas pueden impactar en la calidad y el rendimiento del cemento. Además, este análisis también toma en cuenta las regulaciones nacionales del Instituto Nacional de Calidad (INACAL) y del Ministerio de Vivienda, Construcción y Saneamiento (MVCS) que supervisan su producción y comercialización, lo cual es clave para garantizar la seguridad, durabilidad y eficiencia en las construcciones.

La distribución del cemento en el país se organiza de la siguiente manera: UNACEM y Caliza Cemento Inca abastecen la zona de la costa y la sierra central, mientras que Cementos Pacasmayo cubre el norte del país (Tabla 1).

Tabla 1. Marcas y empresas productoras de Cemento Portland Tipo I en el Perú.

Marcas de cemento	Compañía
Sol	Unión Andina de Cementos S.A.A. (UNACEM)
Andino	Unión Andina de Cementos S.A.A. (UNACEM)
Inka	Caliza Cemento Inca S.A.
Pacasmayo	Cementos Norte Pacasmayo S.A. (CNP)
Quisqueya	CEMEX

Cada una de estas empresas cuenta con sus propios procesos de producción y también con estándares de calidad, adaptados a las necesidades del mercado, lo que les permite ofrecer productos con características particulares, las cuales se evaluaron con el objetivo de analizar su idoneidad técnica en diversos contextos constructivos. Las variables estudiadas incluyeron: contenido de aire, finura (superficie específica Blaine), tiempos de fraguado inicial y final, expansión en agua (ensayo de autoclave) y resistencia a la compresión. La medición de estas propiedades se realizó mediante la revisión de fichas técnicas oficiales de cada fabricante, contrastadas con los requisitos establecidos por la NTP 334.009.

IV. RESULTADOS

A nivel nacional, la producción del cemento Portland Tipo I está regulada por normas como la NTP 334.002:2018, NTP 334.006:2019, NTP 334.004, NTP 334.051 y NTP 334.048, que garantizan una calidad uniforme del material. Sin embargo, pueden existir diferencias en los métodos de producción y en las materias primas utilizadas en cada planta de fabricación.

El Decreto Supremo N.º 001-2022-PRODUCE, que aprueba el Reglamento Técnico sobre Cemento Hidráulico utilizado en Edificaciones y Construcciones en General, regula el cemento Portland Tipo I en el Perú [16]. Este decreto establece los requisitos que deben cumplirse para asegurar la calidad de este material, teniendo como objetivo principal proteger la seguridad de las personas y prevenir prácticas engañosas que puedan perjudicar a los consumidores (Fig. 1).

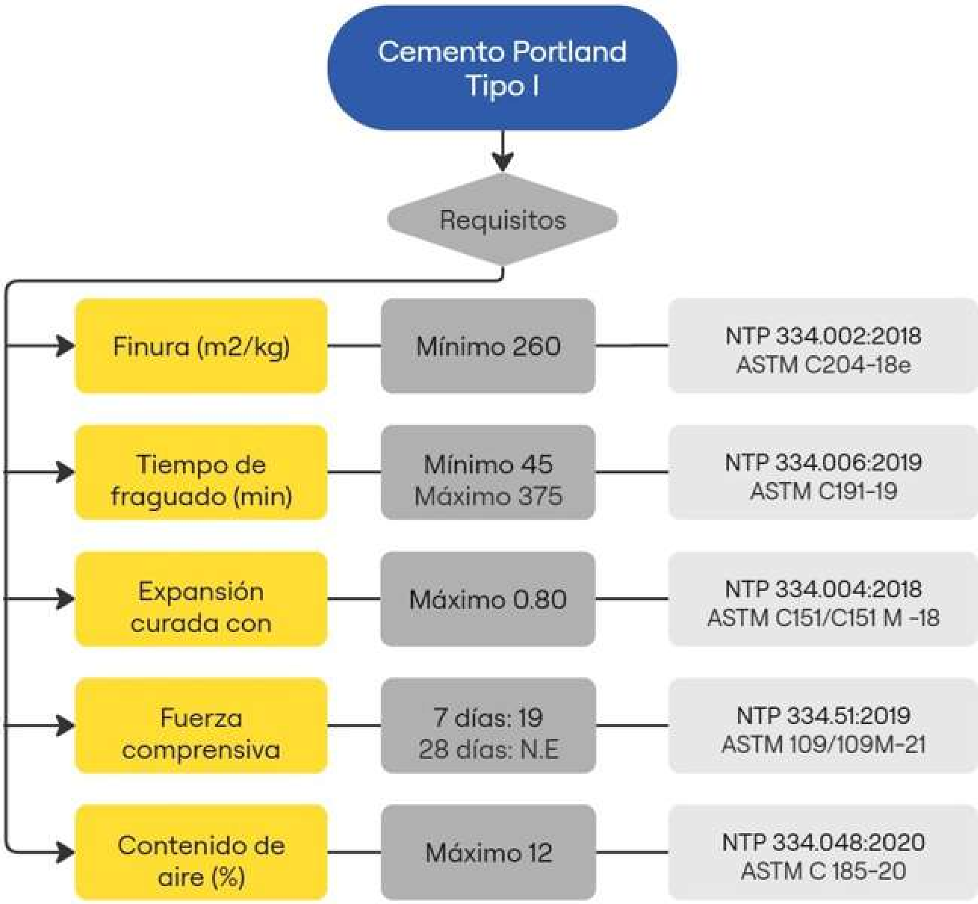

Fig. 1. Reglamento Técnico sobre el cemento Portland [16].

La normativa NTP 334.009 también detalla las características técnicas que debe cumplir el cemento Portland Tipo I, así como los procedimientos de evaluación de la conformidad y las disposiciones que deben seguir los fabricantes y distribuidores. Asimismo, resalta la obligación de cumplir con estas regulaciones para asegurar que el cemento se ajuste tanto a las normas nacionales como internacionales (Tabla 2).

El Instituto Nacional de Calidad (INACAL) es la entidad del Estado peruano encargada de establecer normas técnicas que ayuden a asegurar la calidad de los productos que se usan en distintos sectores, incluida la construcción [17]. Una de estas normas, la NTP 334.009:2020, define los criterios que debe cumplir el cemento Portland Tipo I para ser considerado seguro y eficiente en obra. Esta norma contempla aspectos esenciales como la finura del material, la cantidad de aire que contiene, su resistencia a la compresión y el tiempo que tarda en fraguar, entre otros.

Tabla 2. Requerimientos del cemento.

Propiedades	Método de ensayo	Tipo I
Contenido de aire (%)	NTP 334.048	Mínimo: —
		Máximo: 12
Finura (m^2/kg)	NTP 334.002	Mínimo: 260
		Máximo: —
Tiempo de fraguado (min)	NTP 334.006	Mínimo: 45
		Máximo: 375
Expansión curada en agua (%)	NTP 334.004	0,8
Resistencia a compresión (MPa)	NTP 334.051	3 días: 12
		7 días: 19
		28 días: —

Gracias a estos lineamientos, el INACAL no solo garantiza que el cemento cumpla con los estándares mínimos de calidad, sino que también ofrece una base técnica sólida para que ingenieros, constructores y fabricantes trabajen con mayor seguridad y confianza. Tener una norma clara facilita las labores de control de calidad, certificación de productos y seguimiento de procesos en campo, lo cual es clave en una industria tan exigente como la de la construcción.

Además, esta normativa impulsa mejoras en el propio sector cementero. Al establecer parámetros exigentes, motiva a las empresas a innovar y a ofrecer productos cada vez más eficientes, sostenibles y adaptados a las necesidades del mercado. Esto beneficia tanto a los fabricantes, que pueden competir con mejores estándares, como a los usuarios finales, que acceden a materiales confiables y de buen desempeño en sus proyectos.

La Tabla 3 presenta la existencia de variaciones notables entre las diferentes marcas disponibles en el mercado nacional; estas variaciones reflejan no solo el cumplimiento normativo mínimo, sino también las particularidades de los procesos de fabricación, el origen de las materias primas y el control de calidad de cada planta. En particular, se observan discrepancias en propiedades clave que influyen directamente en el desempeño del material en obra, el nivel de aire incorporado y el desarrollo de resistencia a largo plazo.

Tabla 3. Características físicas y mecánicas de las marcas de cemento Portland Tipo I [18].

Características físicas y mecánicas	Marcas de cemento Portland Tipo I				
	Sol	Andino	Inka	Pacasmayo	Quisqueya
Contenido de aire (%)	11,07	8,79	9,13	9,16	10,78
Finura (%)	96,36	96,49	97,21	72,84	91,90
Tiempo de fraguado (min)	195,00	215,00	195,00	190,00	210,00
Expansión curada en agua (%)	0,011	0,076	0,058	0,098	0,0116
Resistencia a la compresión (MPa) de 28 días	34,54	24,12	26,90	27,85	23,14

En cuanto a la finura del cemento, que afecta su reactividad y tiempo de fraguado, Inka muestra la mayor finura (97,21 %), lo que lo hace más reactivo, mientras que Pacasmayo, con una finura menor (72,84 %), podría presentar un fraguado más lento y una menor resistencia inicial [18]. Además, el tiempo de fraguado también varía significativamente entre marcas; Andino, con un fraguado más prolongado, es beneficioso en climas cálidos o en proyectos que requieren mayor tiempo de manejo.

Respecto a la expansión curada en agua, que mide la estabilidad dimensional, Pacasmayo presenta la mayor expansión (0,098 %), mientras que Sol y Quisqueya tienen los valores más bajos (0,011 % y 0,0116 %, respectivamente), lo que reduce el riesgo de deformaciones y los hace preferibles para estructuras que requieren alta estabilidad.

A los 28 días después de haberse moldeado y curado las probetas elaboradas con cada tipo de cemento, el cemento Sol presenta la mayor resistencia a la compresión con un valor de 34,54 MPa, clasificándolo como adecuado para estructuras que necesitan alta resistencia. Por otro lado, el cemento Quisqueya obtuvo una resistencia menor de 23,14 MPa, lo que podría ser más útil para construcciones con menores exigencias estructurales [19]. La resistencia a la compresión en cada caso se midió siguiendo normas técnicas, utilizando probetas de mortero previamente curadas en condiciones controladas de humedad y temperatura. Estas probetas fueron sometidas a carga en una prensa hidráulica hasta su ruptura, registrando la carga máxima soportada. Luego, se calculó la resistencia dividiendo esta carga entre el área de la sección transversal de la probeta, obteniendo así el valor en megapascales (MPa) [20].

Se observó que el cemento Portland Tipo I presenta diferencias según la marca, lo que les otorga características especiales para distintas aplicaciones y condiciones climáticas. Aunque cumplen con los estándares mínimos de calidad según la NTP 334.009, las variaciones que presentan permiten elegir la opción que mejor se adapte a las necesidades de cada proyecto, ayudando a garantizar que las edificaciones sean más duraderas y eficientes, ya que los ingenieros pueden seleccionar la marca de cemento más adecuada que ofrezca el mejor desempeño en cada tipo de construcción [19].

La Tabla 4 muestra una comparativa donde se expone el rendimiento técnico de cinco marcas de cemento Tipo I, centrándose principalmente en su resistencia a los 28 días y en una propiedad destacada que influye directamente en su desempeño en obra. Aunque todas las marcas cumplen con los requisitos mínimos establecidos por la normativa, existen diferencias importantes que pueden influir en su elección según las necesidades del proyecto.

Por ejemplo, la marca Sol sobresale al alcanzar la mayor resistencia a los 28 días (34,54 MPa), lo que la convierte en una opción confiable para estructuras sometidas a cargas elevadas o ubicadas en entornos exigentes. En contraste, Pacasmayo destaca por su tiempo de fraguado inicial más corto (119,75 minutos), siendo ideal para obras que requieren un avance rápido o se ejecutan en climas fríos. Quisqueya, si bien mantiene valores dentro del rango aceptable, muestra una resistencia final más baja, por lo que su uso sería más adecuado en construcciones de menor exigencia estructural.

Además, otras propiedades técnicas también influyen en el rendimiento general del concreto. En el caso de Inka, su alta finura (97,21 %) favorece una mejor hidratación y, por ende, una mayor durabilidad, lo que es especialmente útil en zonas húmedas o con ambientes agresivos. Por su parte, Andino, al presentar un menor contenido de aire

Tabla 4. Comparación de la resistencia a la compresión a 28 días entre marcas de cemento Portland Tipo I [18].

Marca	**28 días (MPa)**	**Análisis 28 días**	**Valor más resaltante**	**Dato específico / Análisis técnico detallado**
Quisqueya	23,14	Resistencia final baja, pero en el rango apto	Resistencia a 3 días	20,27 MPa. Supera el mínimo requerido (12 MPa); su bajo crecimiento posterior limita su uso estructural.
Pacasmayo	27,85	Resistencia aceptable para uso estructural general	Fraguado inicial más rápido	119,75 min. Reduce tiempos; ideal en climas fríos o plazos cortos.
Sol	34,54	Mayor resistencia final; ideal para estructuras exigentes o expuestas	Mayor resistencia a 28 días	34,54 MPa. Alta capacidad estructural y durabilidad.
Andino	24,12	Resistencia final moderada; apto para estructuras simples	Menor contenido de aire	8,79%. Mejor compacidad y acabado superficial.
Inka	26,90	Resistencia final adecuada; apto para estructuras no críticas o ambientes agresivos	Mayor finura del cemento	97,21%. Mayor hidratación y durabilidad; recomendable en ambientes húmedos/agresivos.

(8,79 %), ofrece una mezcla más compacta y con mejor acabado superficial, lo cual es ventajoso en elementos prefabricados o visibles.

CONCLUSIONES

Las cinco marcas de cemento Tipo I analizadas cumplen con los requisitos mínimos establecidos por la NTP 334.009; sin embargo, al observar sus resultados más a fondo, es evidente que no todas se comportan igual. La resistencia a la compresión a 28 días fue uno de los indicadores más relevantes en esta comparación. En este aspecto, la marca Sol mostró el mejor desempeño (34,54 MPa), lo que la convierte en una excelente alternativa para estructuras sometidas a grandes cargas o ubicadas en entornos exigentes. En cambio, Quisqueya, aunque dentro del rango permitido, alcanzó una resistencia menor (23,14 MPa), por lo que su uso se sugiere para obras con menor demanda estructural.

Cada marca presenta una característica que la hace más adecuada para ciertos contextos. Pacasmayo, por ejemplo, tuvo el fraguado inicial más rápido (119,75 minutos), una ventaja clara en obras con cronogramas ajustados o en zonas frías. Inka, con su elevada finura (97,21 %), favorece una mejor hidratación del cemento, lo cual se traduce en una resistencia más estable y mayor durabilidad, especialmente útil en ambientes húmedos o agresivos. Por su parte, Andino, al tener el menor contenido de aire (8,79 %), ofrece un concreto más compacto y con mejor acabado, ideal para elementos prefabricados o decorativos.

En definitiva, si bien todas las marcas cumplen técnicamente, cada una responde de manera distinta según las condiciones del proyecto. Por eso, elegir el cemento más adecuado no debe basarse solo en que "cumple la norma", sino en identificar qué propiedad es más relevante según el tipo de obra, su entorno y el ritmo de construcción. Esta elección bien fundamentada se traduce en estructuras más duraderas, procesos más eficientes y una mayor seguridad en el desempeño del concreto.

REFERENCIAS

[1] B. Mobasher, "Concrete construction industry-cement based materials and civil infrastructure," in *Proc. CBM-CI Int. Workshop*, 2007, pp. 73–90.

[2] M. Orozco, Y. Ávila, S. Restrepo, and A. Parody, "Factores influyentes en la calidad del concreto: una encuesta a actores relevantes en la industria del concreto," *Revista Ingeniería de Construcción*, vol. 33, no. 2, pp. 161–172, 2018.

[3] P. Mora, E. Gil, L. Sánchez, and B. Llamas, "Evolución de factores de emisión como herramienta para la mejora ambiental. estudio de caso del sector cementero español," *Revista Internacional de Contaminación Ambiental*, vol. 37, no. 1, p. 53991, 2021.

[4] M. Zajac, J. Skocek, M. Ben, and J. Deja, "Co_2 mineralization methods in cement and concrete industry," *Energies*, vol. 15, no. 10, p. 3597, 2022.

[5] R. Arrarte, "¿es competitiva la industria cementera peruana?" *Revista de la Facultad de Ciencias Contables UNMSM*, vol. 20, no. 37, pp. 106–122, 2012.

[6] J. C. Yam, R. Solis, and E. Moreno, "Influencia de los agregados pétreos en las características del concreto," *Ingeniería*, vol. 7, no. 2, pp. 39–46, 2003.

[7] M. Sanjuán and S. Chinchón, "Tipos de cemento. normalización y regulación," in *Introducción a la Fabricación y Normalización del Cemento Portland*, 1st ed. San Vicente del Raspeig: Publicaciones de la Universidad de Alicante, 2014, pp. 116–181.

[8] H. Panta, "Revisión sistemática de la literatura sobre la mejora de las propiedades físico-mecánicas del concreto con la adición de ceniza de cascarilla de arroz," *LATAM Revista Latinoamericana de Ciencias Sociales y Humanidades*, vol. 5, no. 3, pp. 2055–2062, 2024.

[9] C. Morales, K. Delgado, and M. Chevez, "Materiales alternativos para obras civiles: artículo de revisión bibliográfica," *COGNIS: Revista Científica de Saberes y Transdisciplinariedad*, vol. 1, no. 2, pp. 9–15, 2022.

[10] A. Jhatial, W. Goh, S. Sohu, S. Mangi, and A. Mastoi, "Preliminary investigation of thermal behavior of lightweight foamed concrete incorporating palm oil fuel ash and eggshell powder," *Periodica Polytechnica Civil Engineering*, vol. 65, no. 1, pp. 168–180, 2021.

[11] C. Ramos, "La investigación básica como línea propuesta de investigación en psicología," *Revista de Investigación Psicológica*, vol. 30, pp. 151–161, 2023.

[12] M. Ceroni, "Investigación básica, aplicada o simplemente investigación?" *Revista de la Sociedad Química del Perú*, vol. 76, no. 1, pp. 5–6, 2010.

[13] A. Cvetkovic, J. Maguiña, A. Soto, and J. L. Correa, "Estudios transversales," *Rev. Fac. Med. Hum.*, vol. 21, no. 1, pp. 164–170, 2021.

[14] C. Vivar, A. McQueen, D. Whyte, and N. Canga, "Cómo empezar en la investigación cualitativa: elaborando una propuesta de investigación," *Index de Enfermería*, vol. 22, no. 4, pp. 222–227, 2013.

[15] S. Hernández and D. Duana, "Técnicas e instrumentos de recolección de datos," *Boletín Científico de las Ciencias Económico Administrativas del ICEA*, vol. 9, no. 17, pp. 51–53, 2020.

[16] Ministerio de la Producción, *Decreto Supremo que aprueba el Reglamento Técnico sobre Cemento Hidráulico destinado a la Edificación y Construcción en General (DS Nº 001-2022-PRODUCE)*, El Peruano, Std., 2024.

[17] Instituto Nacional de Calidad (INACAL), *NTP 334.009:2020 Cementos. Cementos Pórtland. Requisitos*, Std., 2020.

[18] V. Guevara and M. Tantarico, "Evaluación comparativa de las características físico-mecánicas de las diferentes marcas de cemento portland tipo i, comercializadas en el norte y centro del perú (2018)," 2019.

[19] R. Gámez and J. Gutiérrez, "Estudio comparativo del concreto f'c = 210 kg/cm^2 de cinco cementos portland tipo i comerciales en la ciudad de trujillo," 2020.

[20] H. F. W. Taylor, *Cement Chemistry*, 2nd ed. Thomas Telford Publishing, 1997.

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$$(x+a)^n = \sum_{k=0}^{n} \binom{n}{k} x^k a^{n-k}$$

$$(1+x)^n = 1 + \frac{nx}{1!} + \frac{n(n-1)x^2}{2!} + \cdots$$

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