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EXPLAINABLE AI-BASED ASSESSMENT OF WEB ACCESSIBILITY IN ECUADORIAN PUBLIC INSTITUTIONS AS SOFTWARE QUALITY ATTRIBUTE

EVALUACIÓN BASADA EN IA EXPLICABLE DE LA ACCESIBILIDAD WEB EN LAS INSTITUCIONES PÚBLICAS ECUATORIANAS COMO ATRIBUTO DE CALIDAD DEL SOFTWARE

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ABSTRACT:

This study presents a quantitative evaluation of web accessibility as a non-functional software quality attribute in public institutions in Ecuador, using automated metrics and explainable artificial intelligence (XAI) techniques. The proposed approach assesses the degree of compliance of government websites with international accessibility standards, particularly WCAG, and analyzes differences across various institutional categories. Accessibility metrics were collected using automated tools such as Lighthouse and the WAVE AIM API, employing the AIM metric as a global indicator of accessibility performance. To enhance interpretability, XAI methods—specifically SHAP analysis—were applied to identify the contribution of each feature to the predicted accessibility score. The results reveal significant variability among institutions and highlight recurring quality issues related to color contrast, semantic structure, ARIA usage, and form accessibility. Furthermore, the findings suggest a negative relationship between page complexity and accessibility levels. By combining automated measurement with explainable models, this work provides a transparent and reproducible framework for software quality assessment, supporting evidence-based prioritization of improvements in large-scale web systems.

The findings of this study provide policymakers and software development teams with an objective framework to prioritize corrective interventions, which could significantly reduce barriers to accessing information and digital services for people with disabilities. Consequently, this research contributes to regulatory compliance, while actively promoting a more inclusive and equitable e-government, thus strengthening the principles of transparency and citizen participation in the Ecuadorian context.

Keywords: Web accessibility, Machine learning, XAI, Public institutions, Digital inclusion.

RESUMEN:

Este estudio presenta una evaluación cuantitativa de la accesibilidad web como atributo de calidad no funcional del software en las instituciones públicas de Ecuador, utilizando métricas automatizadas y técnicas de inteligencia artificial explicable (XAI por sus siglas en inglés). El enfoque propuesto evalúa el grado de cumplimiento de los sitios web gubernamentales con las normas internacionales de accesibilidad, en particular las WCAG, y analiza las diferencias entre las distintas categorías institucionales. Las métricas de accesibilidad se recopilaron mediante herramientas automatizadas como Lighthouse y la API WAVE AIM, utilizando la métrica AIM como indicador global del rendimiento en materia de accesibilidad. Para mejorar la interpretabilidad, se aplicaron métodos de XAI—concretamente, el análisis SHAP—con el fin de identificar la contribución de cada característica a la puntuación de accesibilidad prevista. Los resultados revelan una variabilidad significativa entre las instituciones

y ponen de relieve problemas de calidad recurrentes relacionados con el contraste de colores, la estructura semántica, el uso de ARIA y la accesibilidad de los formularios. Además, los resultados sugieren una relación negativa entre la complejidad de la página y los niveles de accesibilidad. Al combinar la medición automatizada con modelos explicables, este trabajo proporciona un marco transparente y reproducible para la evaluación de la calidad del software, lo que respalda la priorización, basada en pruebas, de las mejoras en los sistemas web a gran escala.

Los hallazgos de este estudio proporcionan a los responsables de políticas públicas y a los equipos de desarrollo tecnológico un marco objetivo para priorizar intervenciones correctivas, lo que podría reducir significativamente las barreras de acceso a la información y los servicios digitales para personas con discapacidad. En consecuencia, esta investigación contribuye al cumplimiento normativo, además promueve activamente una administración electrónica más inclusiva y equitativa, así fortalece los principios de transparencia y participación ciudadana en el contexto ecuatoriano.

Palabras clave: Accesibilidad web, Aprendizaje automático, XAI, Instituciones públicas, Inclusión digital.

INTRODUCTION

Web accessibility is a key element of digital inclusion and equitable access to online public services. Despite the existence of international standards such as the Web Content Accessibility Guidelines (WCAG), compliance remains inconsistent across different institutional contexts. In Ecuador, digital government initiatives have been implemented with the objective of promoting transparency and citizen participation. However, numerous institutional websites still present barriers that limit their use. In this context, the present study evaluates the accessibility of Ecuadorian public institutions' websites using automated metrics and Explainable Artificial Intelligence (XAI) techniques, with the aim of improving the interpretability of the results and supporting decision-making.

The use of automated metrics has facilitated the standardization of web accessibility assessments on a large scale. Nevertheless, questions remain regarding the reliability and validity of these metrics. As was noted in previous studies (Vigo & Brajnik, 2011), inconsistencies have been highlighted arising from reliance on tools and the sensitivity of metrics in different contexts. Moreover, user-centred approaches posit that accessibility should not be constrained by technical compliance, but should be informed by users' actual interactions with systems (Parmanto & Zeng, 2005). These perspectives underscore the necessity to augment automated evaluations with interpretable, user-oriented approaches.

In the Ecuadorian context, previous research has identified significant limitations in the accessibility of institutional websites. There have been recurrent reports of issues, including the absence of alternative text, inadequate color contrast, and deficiencies in the design of forms. These issues underscore noncompliance with standards such as ISO/IEC 40500 (Rodríguez et al., 2019). Concurrent studies in Latin America have demonstrated that automated assessment results frequently diverge from the actual experiences of users with disabilities, thereby underscoring the necessity to adopt integrated technical and user-centred approaches (Harari et al., 2025).

In this context, the present study combines automated metrics with XAI techniques to identify the factors influencing accessibility performance and generate interpretable results. The approach adopted aims to bridge methodological, practical, and interpretative gaps, thereby contributing to the development of data-driven strategies to improve web accessibility in Ecuador's public sector.

Web accessibility refers to the design and development of websites that can be used effectively by all individuals, including those living with disabilities. In accordance with the Web Content Accessibility Guidelines (WCAG), a website that is to be considered accessible must be perceivable, operable, understandable, and robust. The aforementioned principles ensure that users can interact with digital content without encountering any barriers. However, various studies indicate that accessibility is often addressed at a late stage, mainly during the testing phase, which limits its effectiveness and leads to reactive rather than preventive practices within the software development cycle (Ara et al., 2024).

Explainable Artificial Intelligence (XAI) can be defined as the set of methods designed to make machine learning models transparent, interpretable, and understandable to human users. Techniques such as SHAP and LIME facilitate the analysis of each variable's contribution to the model's predictions, thereby

enhancing the comprehensibility of the model's behavior . Within the domain of the public sector, the concept of explainability assumes particular significance, given its capacity to fortify trust, enhance transparency, and nurture decision-making processes that are grounded in empirical evidence, particularly in the context of artificial intelligence systems (Papadakis et al., 2024).

A number of studies have examined the evaluation of web accessibility using automated tools. Vigo and Brajnik's analysis of diverse accessibility metrics revealed discrepancies concerning tool dependency and the sensitivity of results, particularly in contexts characterized by limited accessibility (Vigo & Brajnik, 2011). These findings emphasise the limitations of approaches that are based exclusively on automated metrics.

From a user-centred perspective, Parmanto and Zeng proposed a task-based evaluation model, arguing that accessibility should be measured in terms of user performance and not merely technical compliance (Parmanto & Zeng, 2005). This approach underscores the discrepancy between normative validation and the actual user experience.

In Latin America, Rodríguez et al. (2019) evaluated the accessibility of university websites in Ecuador, identifying widespread non-compliance with standards, with frequent problems relating to contrast, the use of images, and content structure. Conversely, Harari et al. (2025) demonstrated that the results of automated evaluations may differ from the perceptions of users with disabilities, thus reinforcing the necessity for more comprehensive approaches.

Recent studies have incorporated machine learning and XAI techniques into accessibility assessment. Ara and Sik-Lanyi (2023) applied predictive models to identify accessibility issues, while Ara et al. (2024) proposed integrating accessibility throughout the development cycle. The extant literature demonstrates the potential of combining automated metrics with explainable models to improve the accuracy and interpretability of assessments.

Strengthening web accessibility in the public sector transcends the technical domain to constitute an ethical imperative and a matter of fundamental rights. In Ecuador, where a considerable percentage of the population reports some type of disability, the persistence of digital barriers on government portals not only limits the full exercise of citizenship but also deepens socioeconomic inequality gaps. The digital exclusion of people with visual, motor, or cognitive disabilities restricts their ability to access essential procedures, public information, and basic services, which contravenes the principles of equality and non-discrimination enshrined in the Ecuadorian Constitution and in international treaties such as the Convention on the Rights of Persons with Disabilities. In this sense, research such as the present study not only generates technical knowledge but also offers concrete tools to advance toward a more just, inclusive, and democratic public administration.

The social impact of this line of research materializes in the capacity to translate technical findings into effective public policies. By precisely identifying accessibility barriers and their underlying causes through explainable methods, decision-makers have empirical evidence to prioritize investments in digital infrastructure, design training programs for developers, and establish continuous monitoring mechanisms that guarantee the sustainability of improvements. Furthermore, the adoption of approaches based on explainable artificial intelligence fosters transparency and accountability by making the real state of accessibility of the State's digital services comprehensible to citizens. In this way, the research not only contributes to regulatory compliance but also promotes a cultural transformation toward digital inclusion as a cross-cutting axis of public management, especially benefiting historically marginalized groups and strengthening social cohesion in the country.

MATERIALS AND METHODS

The present study adopts a quantitative, non-experimental, descriptive-evaluative design, with the objective of assessing the level of web accessibility in Ecuadorian public institutions. The methodological approach integrates automatic metric extraction, data processing and explainable artificial intelligence (XAI) analysis to ensure both objectivity, and interpretability in the evaluation process. The overall workflow consisted of three main phases: data collection, metric calculation, and explainable analysis (Martins & Duarte, 2024).

The data source comprised the complete list of Ecuadorian public institutions officially published on the government website. The creation of the sample involved the development of a Python-based web scraping script, which was utilized to automatically extract the URLs of institutional websites from the official directory. The accessibility and functionality of each URL were verified, with those that were inactive, non-existent, or did not return a valid HTTP 200 response being excluded from the study. The final dataset comprised exclusively active institutional websites accessible to the public, thereby ensuring a reliable representation of the Ecuadorian public sector's digital ecosystem (Garcés-Freire et al., 2023).

The data collection process was divided into two primary stages. In the initial phase, a Python script was utilized to derive preliminary accessibility scores employing Google Lighthouse, a tool that provides an aggregate percentage of accessibility compliance. This step enabled an initial comparative assessment of the websites evaluated and offered a complementary perspective to specialized accessibility metrics. In the second stage, another Python script was developed to interact with the WAVE AIM subscription API, enabling the automatic extraction of detailed accessibility metrics for each valid URL (Souza et al., 2024). The WAVE API was selected on account of its full alignment with the Web Content Accessibility Guidelines (WCAG) 2.1 and the Ecuadorian standard NTE INEN ISO/IEC 40500:2012.

The metrics obtained from WAVE included the following: total errors, warnings, contrast errors, image errors, form errors, structural errors, link errors, ARIA-related errors, AIM score (out of 10), and total number of elements. The indicators thus furnished a multidimensional perspective on the accessibility status of each institutional website. On the basis of the aforementioned dataset, a further three

derived metrics were calculated with a view to enhancing the analytical interpretation:

- Percentage of dominant category
- Type of dominant category
- Percentage of compliance

The utilization of these derived indicators facilitated the classification of institutions according to their predominant accessibility issues and their relative compliance with WCAG principles.

Python was used for data processing and analysis, employing libraries such as requests, pandas, and openpyxl for data handling and matplotlib for visualization. Descriptive statistics were applied to identify the frequency of errors, the distribution of AIM scores, and the proportion of websites that met the minimum accessibility threshold. Correlation analyzes were performed to explore relationships between variables such as total element count, error count, and AIM scores. This provided insight into how structural complexity influences accessibility performance.

In the interpretability phase, XAI techniques were implemented to improve understanding of the behavior of accessibility metrics (Saarela & Podgorelec, 2024). Models such as SHAP (SHapley Additive Explanations) and LIME (Local Interpretable Model-agnostic Explanations) were employed to estimate the contribution of each metric to the overall AIM score, as well as to identify the most influential error categories. This explainable layer enabled the generation of recommendations that could be easily understood and acted upon to improve web accessibility.

The data analyzed were obtained from publicly available government websites. Therefore, no personal or sensitive data were processed and no ethical approval were required. The procedures complied with the terms of use of the WAVE API and Ecuador's Organic Law on Personal Data Protection. Combining web scraping, automated accessibility evaluation and explainable analysis ensures the methodology is reproducible, scalable, and aligned with open government principles that promote digital inclusion and transparency.

RESULTS AND DISCUSSION

This analysis provides an overview of the general level of accessibility of the websites of the Ecuadorian public institutions assessed, as measured by the Accessibility Impact Metric (AIM). Figure 1 shows a histogram illustrating the distribution of AIM values on a scale of 0 to 10. The results reveal considerable variability in accessibility performance across institutions, indicating a heterogeneous distribution (Ara & Sik-Lanyi, 2025).

The majority of websites achieved AIM scores between 4 and 7, indicating a moderate level of compliance with accessibility standards. However, a significant proportion of institutions scored below 3, indicating significant accessibility issues that could prevent users with disabilities from accessing the sites. Conversely, only a few institutions came close to the optimal accessibility threshold, with a smaller proportion of sites achieving scores above 8.

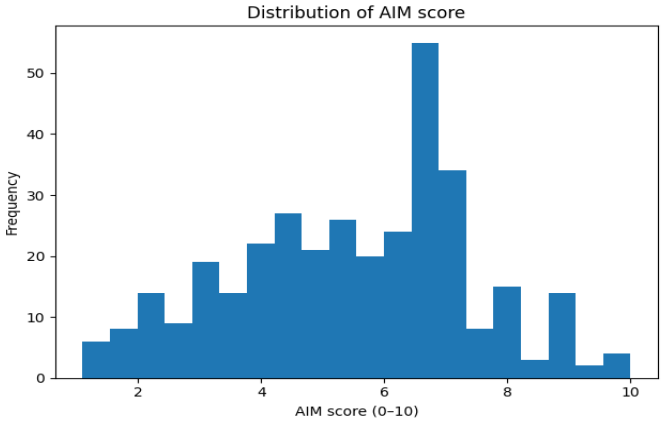

Fig 1: Distribution of AIM scores.

This variability indicates an inconsistent adoption of accessibility standards across the Ecuadorian public sector. Clustering of scores around the mid-range indicates partial compliance with Web Content Accessibility Guidelines (WCAG) criteria and is often associated with structural or perceptual accessibility issues, such as insufficient contrast, a lack of alternative text, or inadequate form labeling (Fischer et al., 2025). These findings lay the groundwork for further analysis aimed at identifying the most influential categories of errors and their contribution to overall accessibility scores.

The quantitative assessment of accessibility violations revealed significant disparities between error categories, as shown in Figure 2. Contrast-related errors (Err_Contrast) were by far the most common, accounting for the majority of issues detected on institutional websites. This type of error reflects persistent shortcomings in the color contrast between text and background elements, which critically affects readability for users with visual impairments.

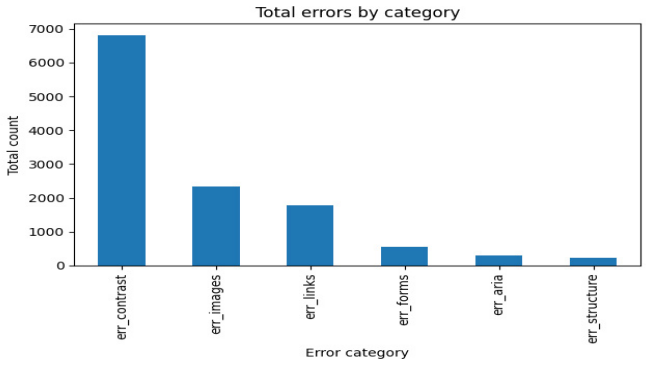

Fig 2: Totals by error category.

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After contrast errors, issues relating to images (Err_Images) and links (Err_Links) were the next most common. The former typically involve missing or incorrect alt text, while the latter involve non-descriptive or repetitive hyperlink labels. Both reduce the clarity of navigation for assistive technologies (Kaur et al., 2025).

Errors in forms (Err_Forms), ARIA attributes (Err_ARIA), and structural elements (Err_Structure) were less common, but were still significant in terms of usability. These errors often indicate deeper shortcomings in compliance with semantic structure or interactive components.

Overall, the distribution of errors shows that perceptual accessibility issues (e.g., insufficient contrast or lack of image alternatives) are the main barrier on the websites of Ecuadorian public institutions. This pattern aligns with global accessibility audit findings, which consistently highlight visual and perceptual issues as the primary challenges, despite the availability of established guidelines and automated testing tools (Ara & Sik-Lanyi, 2025).

Figure 3 shows the correlation between the total number of elements on each web page and their corresponding AIM scores, which was analyzed to examine the relationship between website complexity and accessibility performance. The scatter plot reveals a weak negative correlation, indicating that an increase in webpage complexity, as measured by the number of HTML elements, is associated with slightly lower accessibility scores (Kaur et al., 2025).

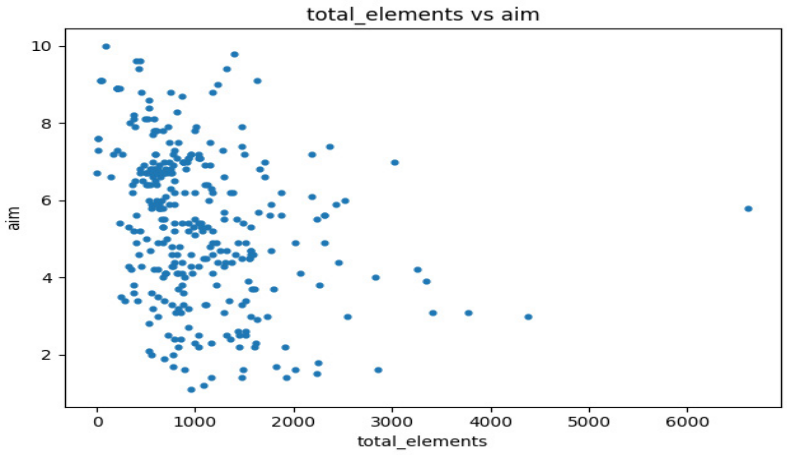

Fig 3: Total items vs. AIM score (10).

Most of the evaluated websites contained between 500 and 1,500 elements, within which range AIM scores predominantly fluctuated across a range of 3 points (from 4 to 7). This suggests that moderately structured pages can strike a balance between functionality and accessibility. However, websites with an excessive number of elements often exhibited poorer accessibility performance, potentially due to overloaded interfaces, redundant visual components, or non-semantic HTML structures hindering analysis by assistive technology.

Conversely, some lightweight websites with fewer than 500 elements also achieved low AIM scores. This implies that accessibility shortcomings are related not only to the volume of content, but also to design quality and adherence to accessibility principles. The dispersion of the points in the graph reinforces the idea that web accessibility is multifactorial and influenced by structural density and compliance with standards such as WCAG and ISO/IEC 40500 (Fischer et al., 2025).

To assess the contribution of each accessibility metric to the overall AIM score, a predictive model was trained using the Random Forest regressor, followed by the application of explainable artificial intelligence (XAI) techniques, specifically SHAP and LIME. These methods enabled us to interpret the model's internal logic and quantify the influence of each feature on the accessibility results (Ara & Sik-Lanyi, 2023).

The Random Forest model demonstrated satisfactory predictive performance. With a coefficient of determination (R^2) greater than 0.70 and a low mean absolute error, it was evident that the selected accessibility metrics collectively explained a significant proportion of the variation in the AIM scores. Combining both global (SHAP) and local (LIME) interpretability techniques provided complementary insights into the impact of each variable. The global LIME analysis (Figure 4) revealed that the total number of errors was the primary factor negatively impacting accessibility scores. This was followed by the total number of elements and warnings, which also exhibited a measurable influence. Thresholds derived

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by LIME (e.g., 'Errors > 44') reveal that websites exceeding these limits are highly likely to obtain low AIM scores. This highlights the sensitivity of accessibility performance to the cumulative presence of violations (Teixeira et al., 2025).

Similarly, the SHAP summary plot (Figure 6) and the average absolute SHAP importance plot (Figure 5) revealed similar patterns. Errors and Total Elements were the dominant predictors of accessibility, followed by Warnings and Contrast Errors. Higher error values consistently reduced the predicted AIM, as reflected in the negative SHAP values. Conversely, lower error rates and more straightforward page structures were associated with better accessibility performance (Ara & Sik-Lanyi, 2023).

Together, these results show that the quantity and complexity of accessibility issues have the greatest influence on overall accessibility outcomes. Integrating SHAP and LIME proved effective in revealing which metrics are most influential and the thresholds beyond which accessibility quality deteriorates (Ara & Sik-Lanyi, 2023).

In order to assess how the relevance of accessibility indicators varies depending on the organizational context, the importance of SHAP-based characteristics was analyzed by institutional category. The comparative results revealed significant differences among public bodies, suggesting that the variables influencing the accessibility indicator (AIM) depend on the institution's operational scope and digital structure.

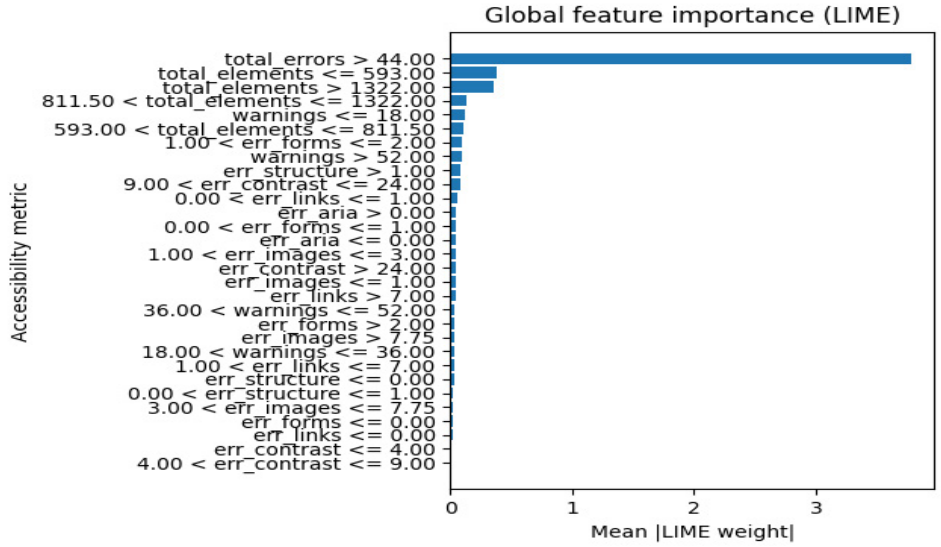

Fig 4: Global importance (LIME).

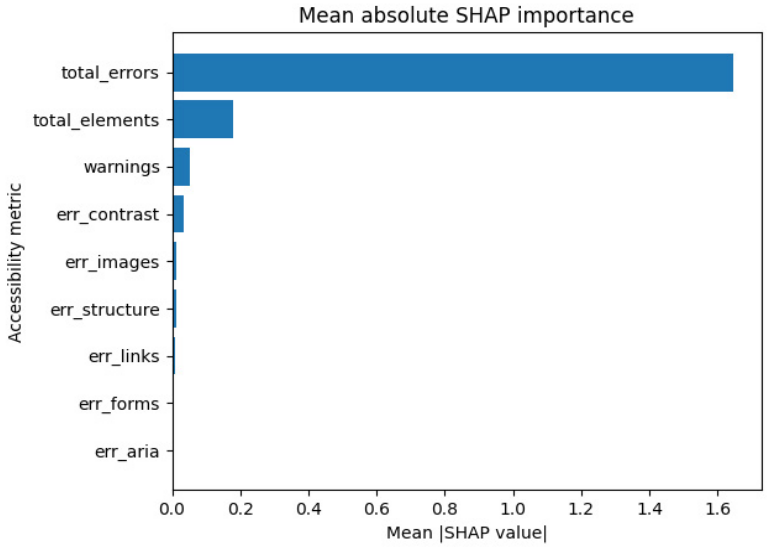

Fig 5: Absolute mean importance (SHAP).

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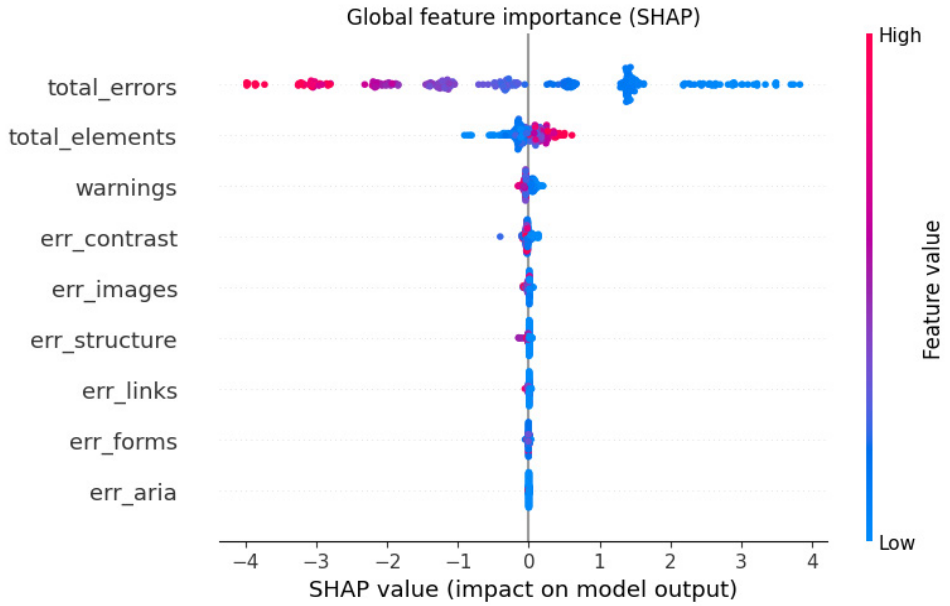

Fig 6: Global importance (SHAP).

For agencies, the most significant factors were warnings, errors, and image-related issues. This suggests that minor non-conformities and inadequate alternative text descriptions systematically lower accessibility scores. In contrast, government council websites demonstrated a reliance on errors and contrast issues, reflecting persistent perceptual barriers and visual inconsistencies (Ara & Sik-Lanyi, 2025).

In the case of decentralized autonomous governments, errors remained the dominant predictor, but the total number of elements and warnings also played a significant role. This suggests that interface complexity and modular design increase the likelihood of accessibility issues arising. Ministries presented a different profile, with total elements and warnings outweighing errors. This demonstrates that extensive content and dense structures, rather than coding errors, are the main limiting factors for government portals.

In higher education institutions, errors accounted for the majority of variance in the AIM, confirming the persistence of unresolved warnings on academic portals. In public enterprises, metrics related to contrast and image quality point to a combination of visual and semantic shortcomings. Finally, Superintendencies and other autonomous public bodies exhibited a pattern characterized by the prevalence of errors. Notably, form-related issues had a significant impact on the usability and compliance of data entry interfaces in the case of the former.

The findings presented have direct social implications that transcend the technical domain. The identification of contrast errors as the most prevalent barrier, along with deficiencies in images, links, and forms, reveals that the websites of Ecuadorian public institutions are designed without considering the needs of people with visual, cognitive, or motor disabilities. This reality implies that a significant percentage of citizens faces daily obstacles in accessing government information, completing online procedures, or exercising their right to citizen participation. The digital divide is not, therefore, a merely technological problem, but rather a manifestation of structural inequality that disproportionately affects the most vulnerable groups, limiting their autonomy and their ability to interact with the State on equal terms.

The approach based on explainable artificial intelligence (XAI) adopted in this study not only improves diagnostic accuracy but also provides decision-makers with transparent and justifiable tools to prioritize corrective actions with measurable social impact. By decomposing the contribution of each type of error to the overall accessibility score, policymakers can allocate resources efficiently, focusing first on barriers that affect a greater number of users or that generate more severe exclusions. For example, the priority correction of contrast and image errors, being the most frequent, could generate an immediate and widespread benefit for the population with visual disabilities. Likewise, the variability observed among institutional categories suggests that intervention strategies should be differentiated, addressing the particularities of each type of organization. Ultimately, this study offers an evidence-based roadmap to advance toward a more inclusive public digital ecosystem, where accessibility becomes a criterion of institutional quality and an indicator of the State's commitment to equity and social justice.

CONCLUSIONS

The findings of this study confirm that web accessibility in Ecuadorian public institutions remains well below the levels required to ensure equitable digital inclusion. This demonstrates that regulatory frameworks and standards alone are insufficient to guarantee effective compliance. Automated assessment of official public websites revealed systematic accessibility barriers, evident through multiple recurring technical violations affecting the ability of users with disabilities to interact effectively with digital government services. These findings reinforce the importance of accessibility being strengthened as a national, structural, crosscutting public policy rather than an isolated or voluntary technical effort.

The descriptive results obtained using the AIM metric provided a comprehensive overview of the extent to which accessibility is affected on public sector websites. This enabled the identification of the categories of institutions with the greatest impact. The prevalence of color contrast errors indicates that accessibility barriers are primarily design-related, highlighting the need for standardized design patterns aligned with WCAG guidelines. This is a particularly critical finding, as color contrast issues affect several groups of people with disabilities at once, making them a priority area for correction.

Integrating explainable artificial intelligence (XAI) methods through SHAP value analysis added value to this research by enabling the decomposition, interpretation, and prioritization of the variables that most impact accessibility. Unlike studies that focus exclusively on aggregating or scoring metrics, this approach makes the diagnostic process transparent by offering rational justifications for prioritizing improvements. This is a valuable contribution from both a scientific and a public administration perspective, as it supports evidence-based decision-making and objective interpretability rather than subjective perception or isolated heuristic judgment.

Furthermore, the variability observed across institutional groups reveals structural gaps in the adoption, internalization, and standardization of accessibility practices among different types of public organization. Ministries, supervisory bodies and regulatory agencies, for example, exhibited different patterns, and levels of deterioration in accessibility. This implies that administrative culture, development outsourcing models, internal technical maturity, and the level of regulatory enforcement produce varying outcomes in terms of compliance with accessibility requirements.

Finally, this study's broader implications suggest the need to transition from static measurement to continuous, proactive, and interpretable monitoring mechanisms that integrate accessibility throughout the entire web lifecycle, including design, development, deployment, maintenance, and evaluation. Future studies should explore hybrid models combining automated metric extraction, predictive modelling, online monitoring services, and XAI-based recommendation systems that can propose specific remediation strategies based on causal contribution analysis. In Ecuador, strengthening accessibility requires sustained institutional commitment, specialized training, regulatory reinforcement, and the integration of data-driven methodologies to ensure that public digital services are universally usable and equitable, and aligned with the rights of all citizens—particularly the most vulnerable population groups.

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CONFLICTS OF INTEREST

The authors declare that they have no financial, academic, or personal conflicts of interest that may have influenced the conduct or results of this research.

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