DOI: 10.24850/j-tyca-2026-06-05

Articles

Evaluation of equations for head losses due to friction in polyethylene pipes

Evaluación de ecuaciones para pérdidas de carga por fricción en tuberías de polietileno

Freddy Gavilánez-Luna[1], ORCID: https://orcid.org/0000-0002-7861-514X

Jesús Chavarría[2], ORCID: https://orcid.org/0000-0001-8868-394X

[1]Pontificia Universidad Católica del Ecuador-Sede Manabí, Manabí, Ecuador. Universidad Agraria del Ecuador, Guayaquil, Ecuador, fgavilanez3087@pucesm.edu.ec, fgavilanez@uagraria.edu.ec

[2]Pontificia Universidad Católica del Ecuador-Sede Manabí, Manabí, Ecuador, jechavarria@pucesm.edu.ec

Corresponding author: Freddy Gavilánez-Luna, fgavilanez@uagraria.edu.ec

Abstract

This study addressed the need to identify the most accurate formula for calculating friction head losses in pressurized systems with smooth pipes, evaluating the fit of expressions against experimental data. A test bench

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

was implemented with polyethylene pipes of 25, 32, 40 and 50 mm diameter and 50 m length. Piezometric loads of 10, 15, 20, 25 and 30 m were applied, measured with a digital manometer. The observed load losses were corrected for the unevenness of the terrain by topographic leveling. Eleven equations selected from the literature were evaluated, including Darcy-Weisbach with Colebrook-White. An absolute roughness of 0.0015 mm and a roughness coefficient of 150 for Hazen–Williams were used, in addition to a kinematic viscosity of 1.049 x 10^{-6} m^2/s. The relative error (RE), the Willmott concordance index (WCI) and the root mean square error (RMSE) of each expression were calculated. Likewise, analysis of variance was applied using Fisher's LSD test to determine significant differences. Experimental head losses were reported between 1.747 and 5.896 m, with flow rates between 2.93 x 10^{-4} and 3.525 x 10^{-3} m^3/s, with turbulent flow in all cases. All expressions reported an WCI > 0.97 and RMSE < 0.4 m; however, the Shaikh-Massan-Wagan formula obtained the lowest average RE (3.77 %), significantly (p < 0.05) different from the rest, standing out as the most accurate and precise for calculating pressure losses in smooth pipes such as those made of polyethylene.

Keywords: hydraulic equipment, hydrodynamics, plastics, equations, statistical analysis, measurement.

Resumen

Este estudio abordó la necesidad de identificar la fórmula más precisa para calcular pérdidas de carga por fricción en sistemas presurizados con tuberías lisas, evaluando el ajuste de expresiones frente a datos experimentales. Se implementó un banco de pruebas con tuberías de

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

polietileno de 25, 32, 40 y 50 mm de diámetro y 50 m de longitud. Se aplicaron cargas piezométricas de 10, 15, 20, 25 y 30 m, medidas con manómetro digital. Las pérdidas de carga observadas se corrigieron por el desnivel topográfico del terreno. Se evaluaron 11 ecuaciones seleccionadas de la literatura, incluyendo Darcy-Weisbach con Colebrook-White. Se empleó la rugosidad absoluta de 0.0015 mm y coeficiente de rugosidad de 150 para Hazen-Williams, además de una viscosidad cinemática de 1.049×10^{-6} m^2/s. Se calculó el error relativo (ER), el índice de concordancia de Willmott (ICW) y la raíz cuadrada del error cuadrático medio (RMSE) de cada expresión. Asimismo, se aplicó análisis de varianza con el test LSD de Fisher para determinar diferencias significativas. Se reportaron pérdidas de carga experimentales entre 1.747 y 5.896 m, con caudales entre 2.93×10^{-4} y 3.525×10^{-3} m^3/s, con flujo turbulento en todos los casos. Todas las expresiones reportaron un ICW > 0.97 y RMSE < 0.4 m; sin embargo, la fórmula de Shaikh-Massan-Wagan obtuvo el menor ER promedio (3.77 %), significativamente ($p < 0.05$) diferente al resto, destacándose como la de mayor exactitud y precisión para el cálculo de pérdidas de carga en tuberías lisas como las de polietileno.

Palabras clave: equipamiento hidráulico, hidrodinámica, plásticos, ecuación, análisis estadístico, medición.

Received: 13/10/2025

Accepted: 03/03/2026

Available ahead of print: 10/03/2026

Version of record: 01/11/2026

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Introduction

In the design of pressurized piping systems for water conveyance, whether for human consumption, industrial use, energy production, or irrigation, equations are commonly used to estimate friction-induced energy losses with a certain degree of inaccuracy. This lack of precision is not only associated with the empirical component embedded in the roughness coefficients of pipe materials (Sotelo, 1980), but also with the mathematical formulation of the equations themselves and the flow conditions under which they were developed. In practice, these limitations may lead to the over or underestimation of head losses, which in turn may result in the selection of pipe diameters that fail to meet maximum flow and pressure demands or, conversely, in increased costs due to pipe oversizing (Alegret-Breña & Martínez-Valdés, 2019).

Part of the uncertainty associated with the classical head loss equations can be explained by the fact that the roughness coefficients were calibrated nearly a century ago, based on the experiments of Nikuradse and the theoretical foundations established by Prandtl and von Kármán, which led to the development of the Colebrook-White (C-W) equation (Alfaro-Guerra & Olivares-Gallardo, 2019). These developments were primarily based on metallic conduits with artificially induced roughness, whose characteristics differ from the internal surfaces of modern plastic pipes. Although these formulations are applied in a general manner, the extrapolation of classical coefficients to materials such as polyethylene has not been sufficiently verified under specific experimental conditions. Furthermore, it has been noted that in plastic pipes the influence of roughness may vary with pipe diameter and flow velocity (Da Rocha *et al*., 2017). Therefore, it is pertinent to examine whether these

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

formulations adequately describe their hydraulic behavior or whether they introduce significant errors in the design of pressurized piping systems.

Expressions such as the Darcy-Weisbach (D-W) equation, in combination with the friction factor calculated using the C-W expression, enjoy the widest acceptance due to the rational basis of their derivation and the apparent accuracy they provide in the calculation of head losses under turbulent flow (Revilla, 1991), including transitional flow (Alegret-Breña & Martínez-Valdés, 2019; Arumugam *et al*., 2022). The latter applies to both hydraulically smooth and hydraulically rough conditions (Brkić, 2011; Saldarriaga, 2007). However, the accuracy of the results obtained using the D-W expression is also conditioned by the selection of the absolute roughness coefficient, which is established according to the pipe material. Since this parameter is often assigned discretionarily or obtained from tabulated values, it may influence the inherent margin of error in the estimation of head losses provided by the formula.

Given the mathematical complexity involved in using the D-W equation in combination with the C-W approach in the first decades of the 20th century —due to the latter's implicit nature (Ormsbee & Walski, 2016)— alternative formulas were devised for calculating head losses with a relatively intuitive basis and easy application because they are explicit. Additionally, to overcome the complexity of using the C-W expression to calculate the friction coefficient and to facilitate its determination, Moody (1944) incorporated this formula into a diagram that bears his name. While the resulting coefficients are determined through a process that speeds up calculations, they still suffer from uncertainty because they require "average" and approximate absolute roughness values (Sotelo, 1980), and there is also some subjectivity in their determination since it is a graphical method.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Among the purely empirically based alternatives, the Hazen-Williams (H-W) expression, proposed in 1906, stands out (Saldarriaga, 2007). Although it is widely used among engineers (Liou, 1998), its uncertainty is associated with a roughness coefficient that depends solely on the pipe material and with restrictive applicability conditions that tend to overestimate friction head losses (Gavilánez, 2019), which is why its use has even been discouraged (Achour & Amara, 2020). Alegret-Breña and Martínez-Valdés (2019) point out that their inaccuracy lies in the fact that the validity of their results is linked to laminar and transitional flows, while in practice turbulent regimes predominate. However, other authors (Abdulameer *et al*., 2022; Zhao & Gao, 2020) support its application under these latter conditions, even reporting a high correlation between H-W and the rational approach of D-W (Darweesh *et al*., 2024; Jamil, 2020), although from a theoretical perspective.

Considering that the aforementioned complexity of the C-W approach is due to the implicit form of the friction coefficient, whose calculation process requires numerical methods to obtain it, most explicit expressions are based on the C-W equation with different levels of empirical training (Anaya-Durand *et al*., 2014); hence, even though these consider the foundation of D-W, in the structures of many of them the postulates of Prandtl and von Kármán that gave rise to the rational expression of C-W have been left aside (Saldarriaga, 2007). One of the most recognized is the Swamee-Jain (S-J) equation (Swamee & Jain, 1976), recommended for application with Reynolds numbers from $5x10^3$ to $1x10^8$ and relative roughnesses between $1x10^{-2}$ to $1x10^{-6}$ (Anaya-Durand *et al*., 2014), which has received great acceptance for the degree of precision it can offer with respect to the C-W approach (Guerrero,

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

1995), showing errors of less than 1 % when compared with the latter equation (Kaseng *et al*., 2020; Saldarriaga, 2007).

Other approaches recommended due to the agreement of their estimates with the C-W expression are the equations of Pavlov (Anaya-Durand *et al*., 2014); Offor and Alabi (Pimenta *et al*., 2018); Barr-White (1981) (Saldarriaga, 2007); Haaland (1983) (Pérez-Pupo *et al*., 2020); Shaikh-Massan-Wagan (Beltrán, 2021), Round (1980), and Manadilli (Anaya-Durand *et al*., 2014). These explicit formulations are based, directly or indirectly, on the implicit C-W approach, seeking to simplify its solution; however, since they are derived from it, they share the uncertainty associated with the roughness estimation and the flow conditions considered. Likewise, the Blasius equation is recognized as suitable for hydraulically smooth pipes (Narváez, 2000), particularly in plastic conduits; however, its applicability is limited to the Reynolds number range between $3x10^3$ and $1x10^5$ (Tarjuelo, 1999).

With the purpose of identifying more accurate methods for the design of pressurized systems with smooth pipes, the present study evaluated the performance of the main expressions used in the calculation of friction head losses. To this end, an experimental bench was implemented with polyethylene pipes under controlled hydraulic conditions, a material which, in addition to the considerations previously stated, allowed the isolation of friction losses as it is a continuous conduit that minimizes the influence of local losses associated with joints. The experimental results were compared with the estimates of each formulation, in order to determine which, one offers greater accuracy and less error under real application conditions.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Materials and methods

Testing site

The experimental tests were carried out on the campus of the Agrarian University of Ecuador, Milagro extension, using an evaluation structure delimited by an area of 60 m x 20 m, on a relatively flat surface. The site has UTM coordinates of 17M 657668 9764284.

Installation of the test bench

To carry out the evaluations, a test bench was installed, the scheme of which is shown in Figure 1. This structure consisted of four extended pipes (low-density polyethylene [LDPE] hoses) 50 m long each, with nominal diameters of 25, 32, 40 and 50 mm. In each pipe, two-gauge pressure taps were placed, separated by the evaluation length (50 m), where the same gauge was located for pressure measurements according to the different piezometric loads previously established. The installation operated with an internal combustion pumping unit, with three inches in suction and discharge, and a pressure turbine.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

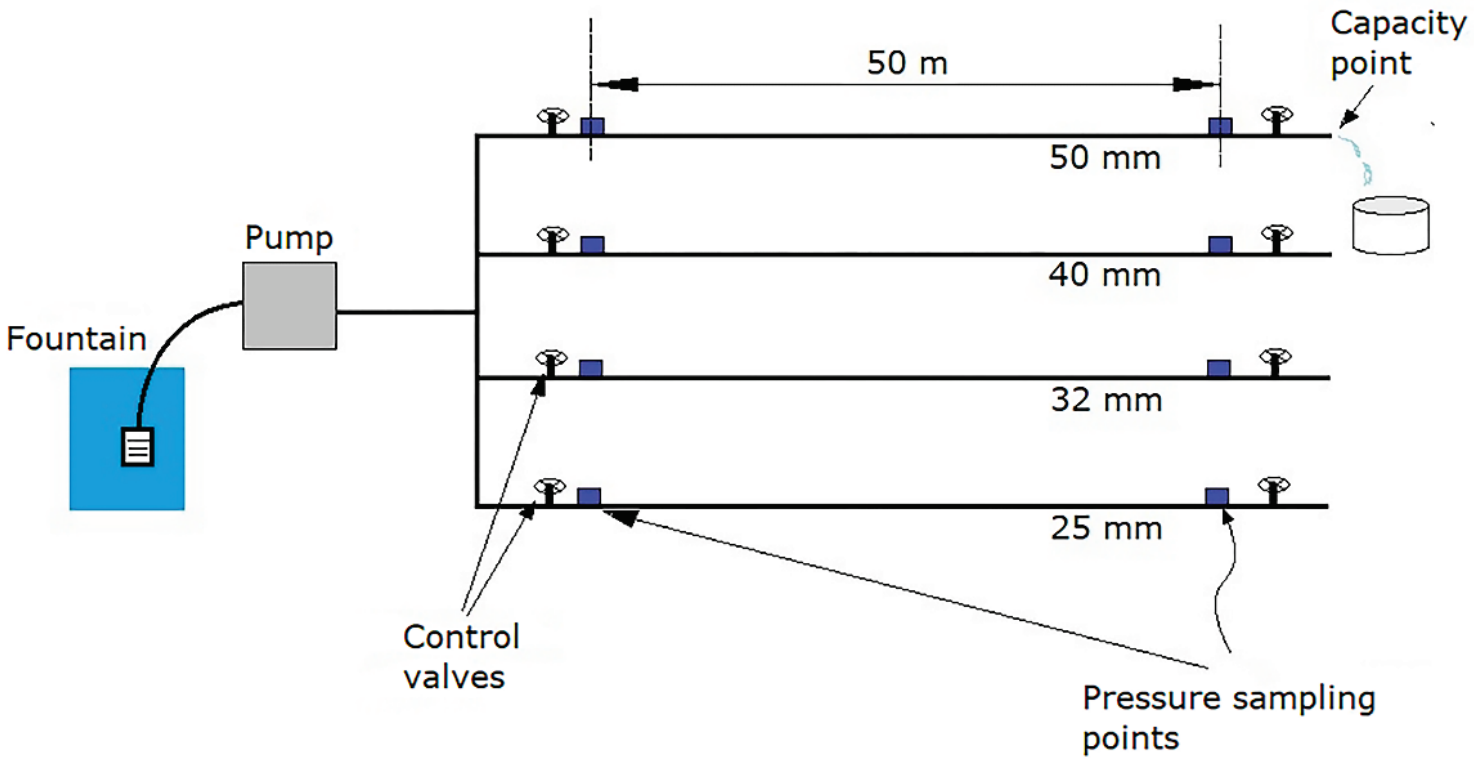


Figure 1. Diagram of the test bench for experimental measurement of energy losses due to friction.

Measuring equipment

A Winters brand digital manometer, 2.5 inches in diameter, with a recording capacity of 0 to 100 PSI, was used to measure the pressure. A digital thermometer was also used to measure the water temperature, both at the beginning and at the end of each of the tests; in such a way that the viscosity of the fluid could be obtained graphically, by means of a calibrated curve. A Vernier caliper was used to record the internal diameters of the pipes. The correction for the gravitational load differential due to the uneven ground was performed using a Sokkia brand topographic level.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Experimental evaluations

The experimental information was obtained by volumetrically evaluating the flow rates emitted in response to piezometric heads of 10, 15, 20, 25 and 30 m. In each load variation, the respective energy losses due to friction were recorded, due to the difference between the initial and final manometric readings in each of the pipes. Five repetitions were performed on each test load and their averages were corrected for the topographic unevenness of the ground where the tests were carried out.

For the theoretical estimation of the pressure losses using the expressions proposed and indicated in Table 1, especially in the calculation of the Reynolds number, the kinematic viscosity was established indirectly, using the in situ water temperature data to be able to use the Alambra viscosity calculator (Alambra, 2024). The value of 0.0015 mm was also used as the absolute roughness (ε) data for the polyethylene pipe (Saldarriaga, 2007).

Table 1. Theoretical expressions for calculating the friction coefficient f of the D-W equation.

Expression	Author	Conditions	References
$\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon/d}{3.71} + \frac{2.51}{R\sqrt{f}}\right)$	Colebrook - White	$R > 2000$ Hydraulically rough and smooth pipes	Colebrook & White, 1937.
$f = \frac{0.25}{\left[log\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{R^{0.9}}\right)\right]^2}$	Swamee - Jain	$5 \times 10^3 \leq R \leq 1 \times 10^8$ $10^{-6} \leq \varepsilon/d \leq 5 \times 10^{-2}$	Pérez-Pupo et al., 2020.
$f = \frac{0.3164}{R^{1/4}}$	Blasius	$R > 1 \times 10^5$	Sotelo, 1980.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Expression	Author	Conditions	References
		Hydraulically smooth pipes	
$f = \frac{0.25}{\left[log\left[\frac{\varepsilon}{3.7d} + \left(\frac{6.81}{R}\right)^{0.9}\right]\right]^2}$	Pavlov	$2 \times 10^3 \leq R \leq 1 \times 10^8$ $\varepsilon/d \leq 5 \times 10^{-2}$	Anaya-Durand et al., 2014.
$f = \frac{1}{3.24\left[log\left[\left(\frac{\varepsilon}{3.7d}\right)^{1.11} + \frac{6.9}{R}\right]\right]^2}$	Haaland	$4 \times 10^3 \leq R \leq 1 \times 10^8$ $10^{-6} \leq \varepsilon/d \leq 5 \times 10^{-2}$	Haaland, 1983.
$f = \frac{0.25}{\left[log\left[\frac{\varepsilon}{3.7d} + \frac{4.518log(R/7)}{R(1 + (R^{0.52}/29)(\varepsilon/d)^{0.7})}\right]\right]^2}$	Barr - White	$3 \times 10^3 \leq R \leq 3 \times 10^7$ $10^{-7} \leq \varepsilon/d \leq 10^{-1}$	Barr & White, 1981. (Saldarriaga, 2007)
$f = \frac{0.25}{\left[log\left[\frac{\varepsilon}{3.71d} + \frac{2.51\left(1.14 - 2log(\varepsilon/d)\right)^{0.75}}{R}\right]\right]^2}$	Shaikh, Massan & Wagan	$1 \times 10^4 \leq R \leq 1 \times 10^8$ $10^{-6} \leq \varepsilon/d \leq 5 \times 10^{-2}$	Shaikh, Massan & Wagan, 2015.
$f = \frac{0.25}{\left[log\left[\frac{\varepsilon}{3.7d} + \frac{95}{R^{0.983}} - \frac{96.82}{R}\right]\right]^2}$	Manadilli	$5 \times 10^3 \leq R \leq 1 \times 10^9$ Any relative roughness ε/d	Anaya-Durand et al., 2014.
$f = \frac{0.25}{\left[log\left[\frac{\varepsilon}{3.71d} - \frac{1.975}{R}\left[ln\left(\left(\frac{\varepsilon}{3.93d}\right)^{1.092} + \frac{7.627}{R + 395.9}\right)\right]\right]\right]^2}$	Offor & Alabi	$1 \times 10^3 \leq R \leq 1 \times 10^8$ $\varepsilon/d \leq 5 \times 10^{-2}$	Offor & Alabi, 2016.
$f = \frac{1}{3.24\left[log\left(\frac{R}{0.135R(\varepsilon/d) + 6.5}\right)\right]^2}$	Round	$4 \times 10^3 \leq R \leq 1 \times 10^8$ $\varepsilon/d \leq 5 \times 10^{-2}$	Round, 1980.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Formulas considered for the theoretical calculation of energy losses due to friction

The D-W and H-W expressions were evaluated, represented correspondingly by equations (1) and (2), where h_f is the friction head loss (m), L and d are the length and inner diameter of the pipe (m), respectively; v is the average flow velocity (m/s) and Q is the flow rate (m^3/s). The value of *C* is the H-W roughness coefficient limited to the pipe material, and to pre-established flow and fluid conditions (Saldarriaga, 2007), whose theoretical value, selected for plastic, was 150 (Sotelo, 1980). In the case of the D-W equation, 10 expressions were considered for calculating the semi-empirical component of this expression, represented by the friction factor f, taking into account aspects of precision (assessed in various works by other authors), Reynolds numbers (R), and relative roughness (ε/d) for plastic material. The formulas used to calculate f are detailed in Table 1:

$$h_f = f \cdot \frac{L}{d} \cdot \frac{v^2}{2g} \quad (1)$$

$$h_f = 10.674 \left(\frac{Q}{C}\right)^{1.852} \frac{L}{d^{4.87}} \quad (2)$$

Calculation of precision

The accuracy of each of the selected expressions was defined by the relative error (RE) with respect to the experimental readings of the pressure losses, applying expression 3, in which x_i is the experimental

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

(observed) value and y_i is the theoretical value obtained with the selected expressions:

$$RE = \frac{100|x_i - y_i|}{x_i} \quad (3)$$

Additionally, to observe concomitantly and in aggregate the accuracy of each expression, the Willmott concordance index (WCI) (Willmott, 1981) was also calculated, along with the root mean square error ($RMSE$), using equations (4) and (5), respectively:

$$WCI = 1 - \frac{\sum(x_i - y_i)^2}{\sum(|y_i - \bar{x}| + |x_i - \bar{x}|)^2} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum(y_i - x_i)^2}{n}} \quad (5)$$

An analysis of variance was also applied to the relative error data, and the comparison of means of this variable was performed using Fisher's LSD test (Gutiérrez & De-la-Vara, 2008) between each of the expressions considered.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua

OPEN ACCESS

Check for updates

Results

In all the pipes evaluated, the direct relationship between the increase in the initial load and the increase in corrected friction head losses (CHL) was confirmed, as a consequence of the greater circulating flow under test pressures between 10 and 30 m (Table 2). For each load condition, the greatest losses were recorded in the smaller diameters, reflecting the combined effect of the internal diameter and average velocity on the hydraulic gradient. Thus, at an initial head of 10 m, the 25 mm pipe showed the greatest loss (2.396 m), while the 50 mm pipe registered the least (1.747 m); this trend was maintained at 30 m, indicating that, even though the flow rates are not identical between diameters, the reduction of the cross-sectional area in the smaller pipes increases the velocity and, consequently, the friction losses.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Table 2. Experimental results.

ND (mm)	ID (mm)	IH (m)	FH (m)	OHL (m)	PLD (m)	CHL (m)	Q (m^3/s)	V (m/s)	R*
25	21.2	10	8.00	2.00	0.396	2.396	0.000293	0.830	16 764.7
		15	12.20	2.80		3.196	0.000367	1.039	20 992.8
		20	16.20	3.80		4.196	0.000434	1.230	24 866.5
		25	20.10	4.90		5.296	0.000493	1.397	28 231.7
		30	24.50	5.50		5.896	0.000526	1.489	30 094.6
32	28.2	10	8.10	1.90	0.255	2.155	0.000651	1.043	28 039.7
		15	12.50	2.50		2.755	0.000742	1.189	31 955.4
		20	15.80	4.20		4.455	0.000996	1.594	42 861.2
		25	20.60	4.40		4.655	0.001011	1.619	43 513.5
		30	25.00	5.00		5.255	0.001032	1.652	44 416.7
40	35.2	10	8.20	1.80	0.345	2.145	0.001157	1.189	39 897.4
		15	12.80	2.20		2.545	0.001286	1.322	44 346.9
		20	16.60	3.40		3.745	0.001587	1.631	54 729.1
		25	20.40	4.60		4.945	0.001882	1.934	64 896.5
		30	24.60	5.40		5.745	0.002040	2.096	70 347.5
50	45.0	10	8.60	1.40	0.347	1.747	0.001856	1.167	50 051.2
		15	13.20	1.80		2.147	0.002284	1.436	61 616.7
		20	17.10	2.90		3.247	0.002701	1.698	72 845.6
		25	20.80	4.20		4.547	0.003486	2.192	94 018.6
		30	25.60	4.40		4.747	0.003525	2.216	95 069.4

ND = Nominal diameter
ID = Internal diameter
IH = Initial head
FH = Final head
OHL = Observed head loss
PLD = Positive level difference
CHL = Corrected head loss
Q = Flow rate
V = Velocity
R = Reynolds number.
*Calculated with a kinematic viscosity of 1.049×10^{-6} m^2/s, established for an average water temperature of 18.2 °C.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

The increase in the initial load produced concomitant increases in flow rate (Q), average velocity (V) and Reynolds number (R), with variations reaching up to 90 % in the 50 mm pipe and 58 % in the 32 mm pipe between the extreme pressures evaluated. In all cases, Reynolds values far exceeded the 4 000 threshold, placing the flow in turbulent regime (Munson *et al*., 2013). This behavior confirms that the measured losses correspond predominantly to the fully developed turbulent regime, a relevant condition for the subsequent comparative evaluation of the theoretical expressions, given that most of them were formulated precisely for this flow interval.

From the joint analysis of the theoretical head losses (THL) and the relative errors (RE), in the 25 mm pipe the Shaikh-Massan-Wagan equation stands out as the most accurate, with the THL closest to the observed ones and minimal errors between 0.2 and 2.5 %, especially from 15 m (Table 3), which suggests a better adaptation under higher head conditions. Although Hazen-Williams also showed low errors at high loads (0.2 % at 25 m and 0.9 % at 30 m), its high error at 10 m (15.9 %) limits its overall reliability. Expressions such as Colebrook-White, Swamee-Jain, Barr-White and Manadilli showed consistent performance, with errors between 4.5 and 7.6 %, and very close pressure losses between them, without being the most accurate. In contrast, Blasius presented the highest THL and errors of up to 9.3 %, mostly showing the lowest precision.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Table 3. Head losses (m) and relative error (%) of each expression in the 25 mm pipe.

Equation	10 m		15 m		20 m		25 m		30 m	
	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)
Colebrook-White	2.252	6.0	3.345	4.7	4.510	7.5	5.646	6.6	6.323	7.2
Swamee-Jain	2.251	6.1	3.339	4.5	4.499	7.2	5.629	6.3	6.303	6.9
Blasius	2.300	4.0	3.409	6.7	4.585	9.3	5.726	8.1	6.403	8.6
Pavlov	2.238	6.6	3.320	3.9	4.474	6.6	5.599	5.7	6.270	6.3
Haaland	2.238	6.6	3.319	3.9	4.471	6.6	5.593	5.6	6.261	6.2
Barr - White	2.249	6.1	3.341	4.5	4.506	7.4	5.640	6.5	6.317	7.1
Shaikh-Massan-Wagan	2.168	9.5	3.201	0.2	4.299	2.5	5.367	1.3	6.003	1.8
Manadilli	2.254	5.9	3.349	4.8	4.516	7.6	5.653	6.7	6.332	7.4
Offor-Alabi	2.238	6.6	3.319	3.9	4.471	6.6	5.593	5.6	6.261	6.2
Round	2.212	7.7	3.284	2.7	4.427	5.5	5.542	4.6	6.207	5.3
Hazen - Williams	2.014	15.9	3.055	4.4	4.180	0.4	5.287	0.2	5.952	0.9

THL: Theoretical head loss, RE: Relative error.

In the 32 mm pipe (Table 4), the Shaikh-Massan-Wagan equation showed a favorable combination of accuracy and stability, THLs very close to those observed and moderate relative errors, which ranged between 3.0 and 6.7 % throughout all the analyzed loads. The Hazen-Williams formulation showed the smallest errors at low loads (2.4 and 2.0 %), but increased its deviation at intermediate loads (up to 8.7 %), showing a non-uniform fit. In contrast, the Blasius equation, along with those of Manadilli and Offor-Alabi, consistently generated the highest THLs and errors of up to 13.4 %, demonstrating a tendency toward overestimation.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Meanwhile, Colebrook-White, Swamee-Jain, Pavlov, Haaland, and Barr-White yielded uniform results, with errors between 7.0 and 12.6 %, and THLs that were quite close to each other. Finally, Round's equation showed decreasing errors until reaching 0.0 % at the maximum load evaluated, standing out at the upper end of the analyzed range.

Table 4. Head losses (m) and relative error (%) of each expression in the 32 mm pipe.

Equation	10 m		15 m		20 m		25 m		30 m	
	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)
Colebrook-White	2.357	9.4	2.970	7.8	5.002	12.3	5.138	10.4	5.330	1.4
Swamee-Jain	2.356	9.3	2.969	7.8	5.000	12.2	5.136	10.3	5.328	1.4
Blasius	2.404	11.5	3.022	9.7	5.052	13.4	5.187	11.4	5.377	2.3
Pavlov	2.344	8.7	2.953	7.2	4.975	11.7	5.110	9.8	5.301	0.9
Haaland	2.343	8.7	2.951	7.1	4.968	11.5	5.103	9.6	5.293	0.7
Barr - White	2.362	9.6	2.978	8.1	5.018	12.6	5.155	10.7	5.347	1.8
Shaikh-Massan-Wagan	2.257	4.7	2.837	3.0	4.754	6.7	4.883	4.9	5.063	3.7
Manadilli	2.366	9.8	2.983	8.3	5.028	12.9	5.166	11.0	5.358	2.0
Offor-Alabi	2.364	9.7	2.980	8.2	5.023	12.8	5.160	10.9	5.353	1.9
Round	2.319	7.6	2.923	6.1	4.929	10.6	5.064	8.8	5.253	0.0
Hazen - Williams	2.207	2.4	2.811	2.0	4.843	8.7	4.980	7.0	5.173	1.6

THL: Theoretical head loss, RE: Relative error.

At the 40 mm diameter (Table 5), the Shaikh-Massan-Wagan equation again showed the best overall fit, with head losses between 2.156 m and 5.884 m and low and stable relative errors (0.5-3.1 %)

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

throughout the load range, demonstrating accuracy and consistency. The Hazen-Williams formulation showed acceptable performance, with errors between 1.3 and 8.1 %, standing out in low and moderate loads, although with greater variability than the previous one. However, equations such as Colebrook-White, Swamee-Jain, Blasius, Barr-White, and Manadilli tend to overestimate head losses, reaching values of up to 6.256 m and errors exceeding 9 %, reflecting a greater deviation from experimental data. Round's equation showed intermediate behavior, with errors between 3.7 and 7.4 % and head losses of up to 6.139 m, positioning itself as an acceptable alternative, although without reaching the level of adjustment of Shaikh-Massan-Wagan.

Table 5. Head losses (m) and relative error (%) of each expression in the 40 mm pipe.

Equation	10 m		15 m		20 m		25 m		30 m	
	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)
Colebrook-White	2.268	5.7	2.738	7.6	3.985	6.4	5.405	9.3	6.246	8.7
Swamee-Jain	2.258	5.3	2.725	7.1	3.965	5.9	5.378	8.8	6.215	8.2
Blasius	2.291	6.8	2.757	8.3	3.984	6.4	5.368	8.6	6.182	7.6
Pavlov	2.246	4.7	2.711	6.5	3.945	5.4	5.352	8.2	6.185	7.7
Haaland	2.245	4.7	2.709	6.4	3.940	5.2	5.343	8.0	6.173	7.4
Barr - White	2.267	5.7	2.736	7.5	3.982	6.3	5.402	9.2	6.242	8.7
Shaikh-Massan-Wagan	2.156	0.5	2.598	2.1	3.767	0.6	5.097	3.1	5.884	2.4
Manadilli	2.271	5.9	2.741	7.7	3.990	6.5	5.413	9.5	6.256	8.9
Offor-Alabi	2.269	5.8	2.739	7.6	3.986	6.4	5.408	9.4	6.249	8.8
Round	2.225	3.7	2.686	5.5	3.912	4.5	5.310	7.4	6.139	6.9
Hazen - Williams	2.172	1.3	2.642	3.8	3.900	4.1	5.347	8.1	6.209	8.1

THL: Theoretical head loss, RE: Relative error.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

For the 50 mm diameter (Table 6) a general trend towards overestimation of theoretical load losses compared to those observed is confirmed, especially under higher loads. The Colebrook-White, Swamee-Jain, Barr-White, Manadilli, and Offor-Alabi equations recorded relative errors greater than 9 % at several points, with THL up to 5.128 m, demonstrating a systematic overestimation of flow resistance. Shaikh-Massan-Wagan showed the smallest errors at high loads (minimum of 1.5 % and THL up to 4.817 m), although its deviation increased at low loads (up to 11.8 %), suggesting an adjustment dependent on the hydraulic condition. Round showed an intermediate behavior (4.0-8.9 %), while Blasius and Pavlov offered more conservative estimates, with THL not exceeding 5.070 m and moderate errors, emerging as alternatives with less tendency to overestimate.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Table 6. Head losses (m) and relative error (%) of each expression in the 50 mm pipe.

Equation	10 m		15 m		20 m		25 m		30 m	
	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)	THL (m)	RE (%)
Colebrook-White	1.623	7.1	2.352	9.5	3.174	2.3	5.019	10.4	5.121	7.9
Swamee-Jain	1.614	7.6	2.339	9.0	3.157	2.8	4.993	9.8	5.094	7.3
Blasius	1.631	6.7	2.346	9.3	3.145	3.1	4.915	8.1	5.012	5.6
Pavlov	1.606	8.1	2.328	8.4	3.142	3.2	4.970	9.3	5.070	6.8
Haaland	1.605	8.1	2.326	8.3	3.138	3.4	4.960	9.1	5.060	6.6
Barr - White	1.622	7.2	2.351	9.5	3.172	2.3	5.017	10.3	5.118	7.8
Shaikh-Massan-Wagan	1.541	11.8	2.226	3.7	2.996	7.7	4.722	3.9	4.817	1.5
Manadilli	1.624	7.0	2.354	9.7	3.178	2.1	5.027	10.6	5.128	8.0
Offor-Alabi	1.623	7.1	2.353	9.6	3.175	2.2	5.022	10.4	5.123	7.9
Round	1.591	8.9	2.308	7.5	3.117	4.0	4.936	8.6	5.036	6.1
Hazen - Williams	1.575	9.8	2.315	7.8	3.156	2.8	5.062	11.3	5.168	8.9

THL: Theoretical head loss, RE: Relative error.

Viewed holistically across the four evaluation diameters, the numerical values of the relative error indicate that the Shaikh-Massan-Wagan equation presents the lowest RE in all pipes (Figure 2), especially in 40 mm (1.74 %) and 25 mm (3.05 %), showing a high degree of agreement with the experimental data. Subsequently, the Round and Hazen-Williams equations also stand out in performance, maintaining low errors, especially in diameters from 25 to 40 mm. Conversely, commonly accepted expressions such as those of Blasius, Swamee-Jain and Colebrook-White present systematically larger errors, exceeding 7.0 % in

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

several cases, which calls into question their direct applicability in real conditions with polyethylene pipes. Therefore, for conditions similar to those of the present study, less traditional equations such as the Shaikh-Massan-Wagan equations can offer greater accuracy in estimating friction head losses.

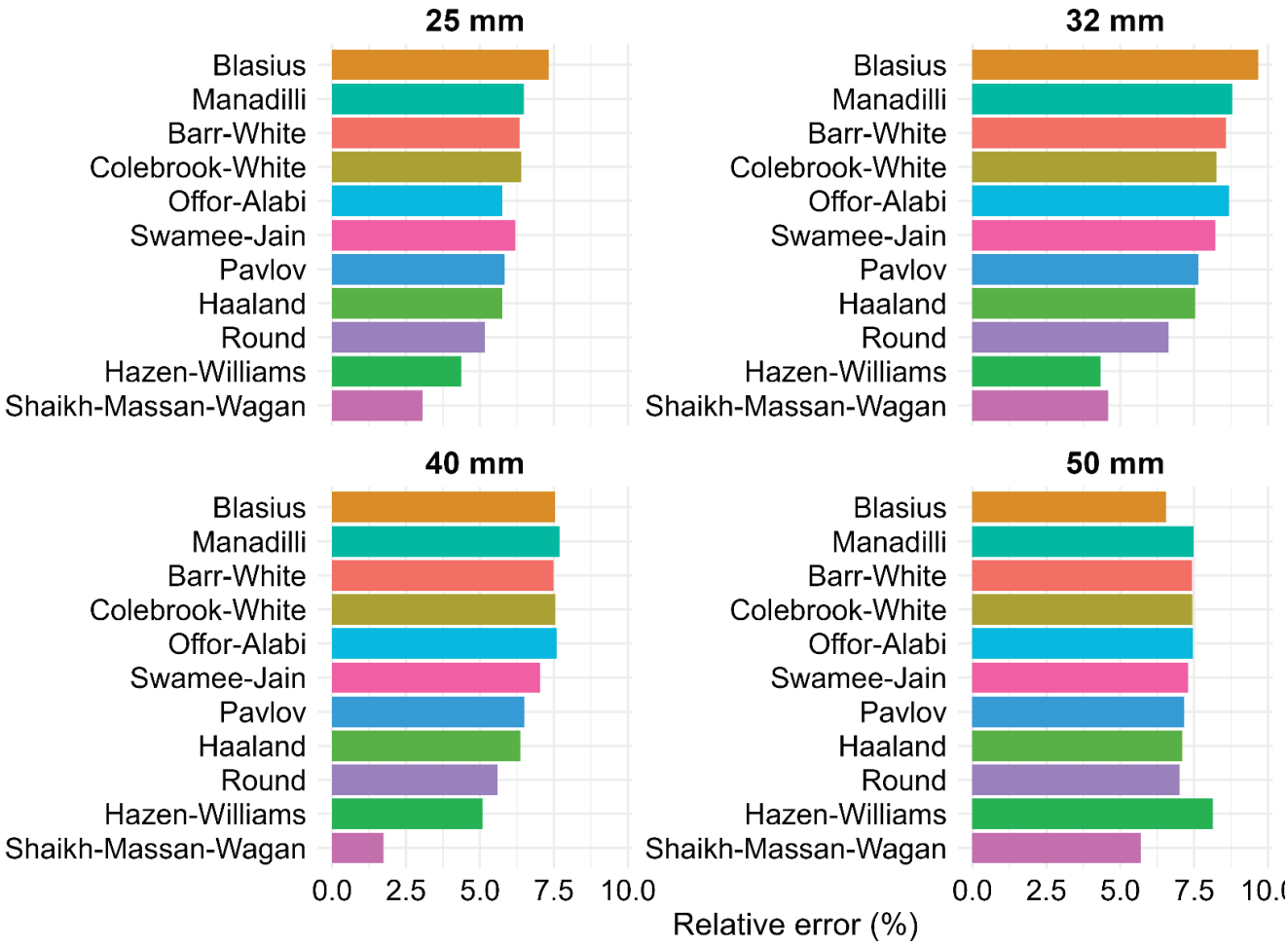


Figure 2. Relative error (%) of the expressions for calculating friction head losses in polyethylene pipes for different diameters.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

The relationship between the increase in hydraulic load and the loss of load due to friction showed an approximately linear behavior in the four diameters evaluated (Figure 3), showing a direct proportionality throughout the analyzed range. Although the different expressions adequately reproduce the general trend of the observed data, discrepancies in the magnitude of the fit are noted; in one case a relative error of up to 15.9 % was reached under a load of 10 m. Consistently, from 20 m of load onwards, several formulations tend to slightly overestimate energy losses, systematically placing themselves above experimental values, which suggests the presence of a common positive bias in theoretical estimates.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

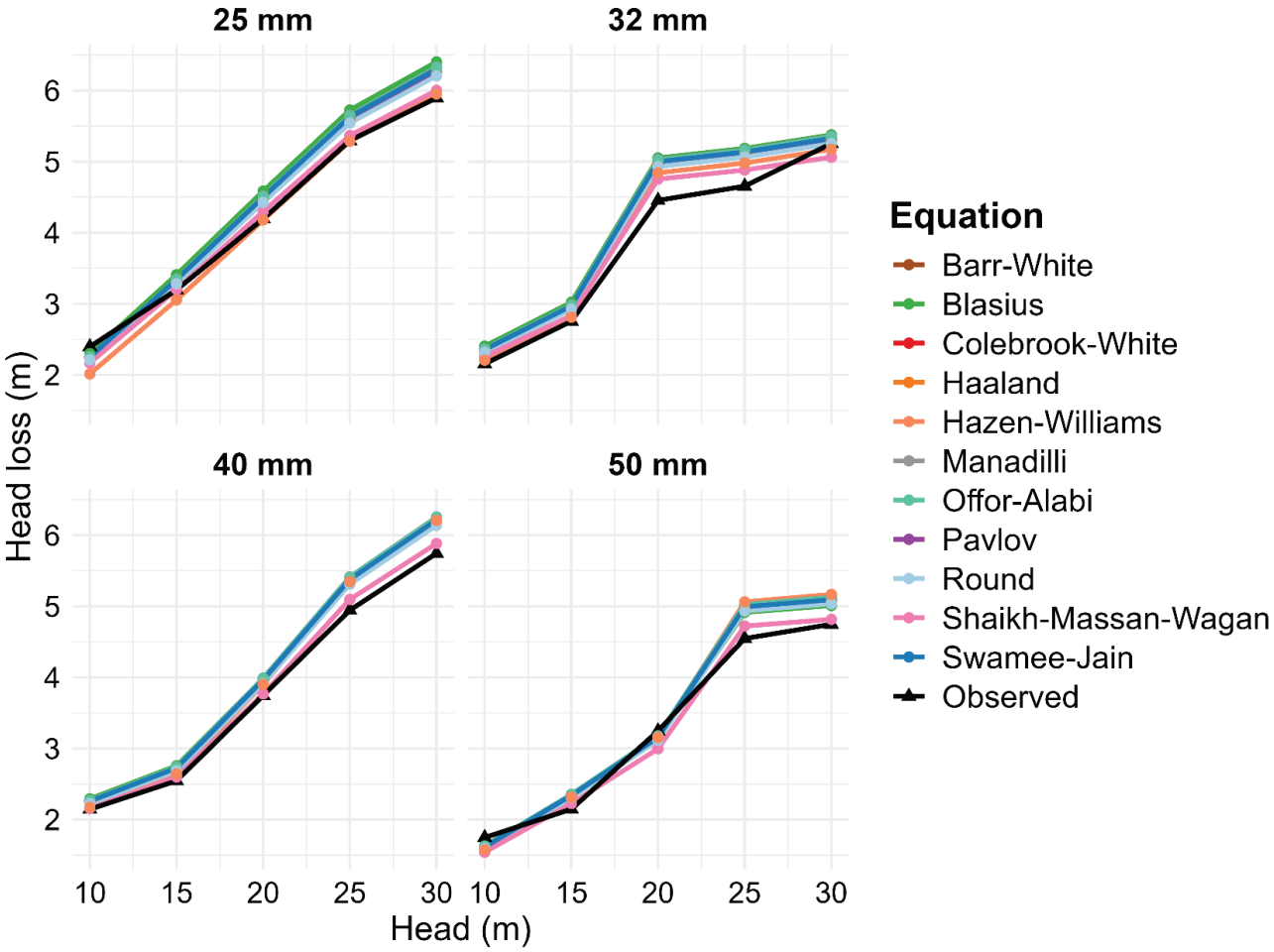


Figure 3. Trends in estimated pressure losses using the different evaluated expressions and in experimentally observed pressure losses.

While all expressions reported excellent agreement (WCI>0.95) (Pimenta *et al*., 2018) with respect to experimental head losses, it is noteworthy that, of this group of equations, the Shaikh-Massan-Wagan equation presented the best fit to the experimental values, with the highest WCI indices (between 0.993 and 0.999), supported by the lowest RMSE values in all the diameters analyzed (Table 7), which indicates a high predictive capacity and minimal dispersion with respect to the

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

observed data. In contrast, classic expressions such as Blasius or Colebrook-White, although they reported relatively high agreement indices (WCI>0.97), exhibited significantly higher RMSE values, implying a greater deviation from the actual measurements.

Table 7. Willmott concordance index (WCI) and root mean square error (RMSE) values.

Equation	25 mm		32 mm		40 mm		50 mm	
	WCI	RMSE	WCI	RMSE	WCI	RMSE	WCI	RMSE
Colebrook-White	0.988	0.299	0.979	0.354	0.986	0.339	0.988	0.292
Swamee-Jain	0.989	0.286	0.979	0.352	0.988	0.317	0.989	0.276
Blasius	0.983	0.360	0.974	0.397	0.988	0.314	0.992	0.232
Pavlov	0.991	0.264	0.981	0.333	0.990	0.296	0.990	0.263
Haaland	0.991	0.260	0.982	0.328	0.990	0.288	0.990	0.258
Barr - White	0.989	0.295	0.978	0.366	0.987	0.336	0.988	0.290
Shaikh-Massan-Wagan	0.998	0.126	0.993	0.198	0.999	0.096	0.995	0.172
Manadilli	0.988	0.304	0.977	0.373	0.986	0.345	0.987	0.296
Offor-Alabi	0.988	0.299	0.977	0.370	0.986	0.340	0.988	0.293
Round	0.993	0.184	0.985	0.232	0.992	0.287	0.991	0.319
Hazen - Williams	0.995	0.225	0.991	0.299	0.990	0.262	0.986	0.246

The graph of RMSE values makes evident the greater accuracy of the Shaikh-Massan-Wagan equation in estimating head losses, by describing the smallest errors in all the diameters analyzed (Figure 4). In contrast, most of the other equations tend to overestimate the

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

experimental values, reflecting a lower degree of fit to the actual hydraulic behavior of the polyethylene pipes evaluated.

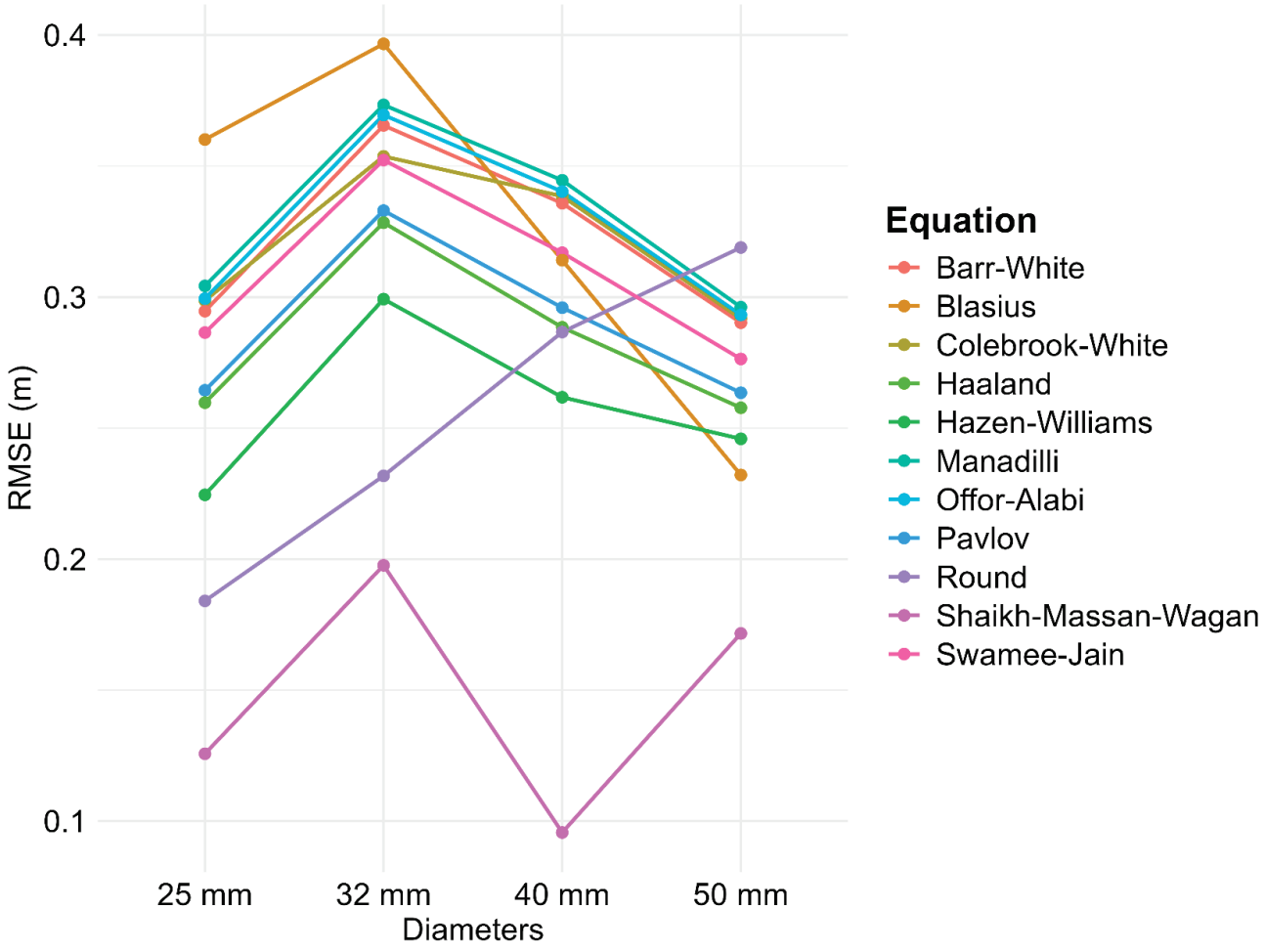


Figure 4. Average RMSE values (m) of the evaluated equations.

The analysis of variance showed statistically significant differences ($p<0.05$) in the relative error between the evaluated equations, indicating that the predictive performance was not homogeneous. Fisher's LSD test discriminated three levels of fit, where the Shaikh-Massan-Wagan equation presented the lowest mean RE (3.77 %) and formed a

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

statistically distinct group (letter c), showing a superior fit compared to the rest (Table 8). At the opposite extreme, equations such as Blasius, Manadilli, Barr-White and Colebrook-White presented the highest RE values (between 7.78 and 7.41 %), with no significant differences between them (group a), indicating a less accurate fit to the experimental data. The remaining equations are in an intermediate group (letters ab or bc), reflecting moderate precision. Overall, the statistical comparison supports the greater predictive capacity of Shaikh-Massan-Wagan in estimating friction head losses in polyethylene pipes.

Table 8. Comparative analysis of the mean relative error (%) according to Fisher's LSD test.

Equations	Mean* RE values (%)
Blasius	7.78 a
Manadilli	7.61 a
Barr-White	7.45 a
Colebrook-White	7.41 a
Offor-Alabi	7.37 a
Swamee-Jain	7.18 ab
Pavlov	6.79 ab
Haaland	6.69 ab
Round	6.10 ab
Hazen-Williams	5.48 bc
Shaikh-Massan-Wagan	3.77 c

* Means with the same letter do not differ significantly ($p > 0.05$).

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Discussion

Experimental evidence confirms that increasing the initial hydraulic load resulted in a systematic increase in friction head losses in all the pipes evaluated. This behavior is consistent with the fundamental principles of fluid mechanics, where a higher hydraulic gradient generates increases in flow rate and, consequently, greater shear stresses on the inner wall of the pipe (Streeter *et al*., 1998). In this sense, the results obtained do not constitute an isolated finding, but rather align with the energy formulation established by the Darcy-Weisbach equation and its functional dependence on the flow velocity.

The influence of the internal diameter was consistently manifested at all load levels. Smaller diameter pipes recorded greater head losses, even though flow rates differed between diameters, confirming the dominant role of the relationship between average velocity and energy dissipation (Munson *et al*., 2013). This pattern confirms that, in turbulent flow, the diameter not only affects the magnitude of the conducted flow, but also the rate of conversion of mechanical energy into friction losses, in accordance with theoretical developments for turbulent flow in pressurized conduits (Jamil, 2019; White, 2011).

The Reynolds number analysis showed values greater than 4 000 in all cases, confirming that the tests were carried out in a fully turbulent regime (Falkovich, 2011; White, 2011). This condition is relevant because the validity and accuracy of many explicit equations depend precisely on the turbulence range for which they were formulated. Therefore, the comparison between expressions was not carried out in a transitional or uncertain scenario, but within the typical operating domain of real conduction systems in plastic pipes such as polyethylene.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Under this hydraulic context, the contrast between equations acquires technical meaning. The Shaikh-Massan-Wagan expression showed the lowest relative error and the best overall fit indicators, positioning itself as the most accurate alternative within the evaluated context. This performance is consistent with that reported by Beltrán (2021), who identified this equation as one of the most accurate among multiple explicit formulations, and with that indicated by its own authors (Shaikh *et al*., 2015), who developed it as an optimized explicit approximation of the Colebrook-White equation, highlighting its better behavior than other expressions in a wide range of Reynolds numbers and relative roughnesses. Consequently, the experimental results support its robustness not only theoretically, but also practically in polyethylene pipes under turbulent flow.

Conversely, traditional equations such as Blasius, Manadilli, Barr-White, Offor-Alabi, and Swamee-Jain showed larger relative errors, although statistically similar to Colebrook-White. This consistency suggests that, although the formulation may differ in complexity or empirical basis, they maintain a convergent behavior in turbulent regime, as has been documented by several authors (Pérez-Pupo *et al*., 2020; Pimenta *et al*., 2018; Tolentino & González, 2023). However, the fact that they have not shown clear comparative advantages over the implicit reference limits their contribution when seeking to optimize accuracy.

The Haaland, Pavlov, and Round equations occupied an intermediate position, combining simplicity with relatively low errors. In separate documents, the literature has highlighted these expressions as practical alternatives due to their balance between ease of implementation and acceptable precision (Anaya-Durand *et al*., 2014; Beltrán, 2021; Brkić, 2011). However, under the specific conditions

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

evaluated, they did not consistently outperform the Shaikh-Massan-Wagan formulation, reinforcing the idea that comparative performance depends on the Reynolds range and the relative roughness considered.

One particularly relevant result was the behavior of the Hazen-Williams equation. Despite not being derived from universal principles of turbulent flow and its theoretical restrictions for certain diameters (Alegret-Breña & Martínez-Valdés, 2019; Mott, 2006), it showed a competitive relative error and even lower than several classical expressions. This finding can be explained because the experimental conditions were within the operating range where the equation has shown good empirical performance (Liou, 1998; Monís, 2020; Munson *et al*., 2013), especially in moderate turbulence and typical distribution system speeds. Therefore, rather than contradicting its theoretical limitations, the results suggest that, under controlled conditions and within its empirical domain, it can offer satisfactory estimates.

It is necessary to point out that, even in turbulent regime, the hydraulic behavior near the wall of the conduction medium is governed by the existence of a laminar sublayer whose thickness regulates the interaction between the internal roughness and the turbulent core of the flow (Munson *et al*., 2013; White, 2011). If surface irregularities are contained within that sublayer, the conduit behaves as hydraulically smooth; when roughness exceeds it, fully developed turbulence is reached, and in intermediate conditions a transition regime occurs (Çengel & Cimbala, 2014). Given that plastic pipes such as polyethylene have low relative roughness, it is reasonable that in the evaluated scenarios a behavior close to the hydraulically smooth regime predominates, which helps to explain the similarity between several expressions derived from the Colebrook-White formulation, as well as the

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

better fit of those equations that reproduce that theoretical basis more faithfully.

Overall, the discussion allows us to establish that, although multiple equations exhibit consistent behavior in turbulent regime, the Shaikh-Massan-Wagan expression showed the greatest ability to reduce the relative error without sacrificing practical applicability. Its explicit nature also constitutes an operational advantage over the implicit nature of Colebrook-White, particularly in hydraulic modeling processes where repetitive calculations or extensive simulations are performed (Offor & Alabi, 2016). Consequently, under the experimental conditions evaluated, this expression emerges as the technically most robust alternative for estimating pressure losses in polyethylene pipes.

Conclusions

All the evaluated expressions showed excellent agreement (WCI>0.95) with respect to the experimental head losses and relative errors less than 10 %; however, the Shaikh-Massan-Wagan equation stood out in terms of accuracy, as well as precision, in all the evaluated diameters, presenting the lowest RMSE values and a significantly lower average RE than the rest of the equations. Therefore, the use of this explicit expression is recommended for calculating pressure losses in polyethylene pipes with nominal diameters of 25, 32, 40 and 50 mm.

Acknowledgments

To the Department of Agricultural Engineering of the Agrarian University of Ecuador, especially to the engineers Jeremy Azú, Crístofer Íñiguez and

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Jefferson Inga, for the equipment and support provided in carrying out the tests.

Funding

This study was funded by one of the authors and the Agrarian University of Ecuador.

Declaration of conflicts of interest

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this article.

Statement on the use of AI

In this article, AI was used solely to improve linguistic fluency in certain paragraphs; all such changes were thoroughly reviewed by the corresponding author prior to their inclusion in the manuscript.

References

Abdulameer, L. S., Dzhumagulova, N., Algretawee, H., Zhuravleva, L., & Alshammari, M.H. (2022). Comparison between Hazen-Williams and Darcy-Weisbach equations to calculate head loss through conveyancing treated wastewater in Kerbala City, Iraq. *Eastern-European Journal of Enterprise Technologies*, *1*(115), 36-43. https://doi.org/10.15587/1729-4061.2022.251385

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Achour, B., & Amara, L. (2020). Theoretical considerations on flow regime dependency of the Hazen-Williams coefficient. *Larhyss Journal*, (42), 53-62. https://www.larhyss.net/ojs/index.php/larhyss/article/view/727

Alambra, K. (2024, agosto 27). *Calculadora de la viscosidad del agua*. Omni Calculator. https://n9.cl/m9zwq

Alegret-Breña, E., & Martínez-Valdés, Y. (2019). Coeficiente de Hazen-Williams en función del número de Reynolds y la rugosidad relativa. *Ingeniería Hidráulica y Ambiental*, *40*(3), 41-55. https://www.researchgate.net/publication/343573793_Hazen-Williams_coefficient_as_a_function_of_Reynolds_number_and_relative_roughness

Alfaro-Guerra, M., Guerra-Rojas, R. & Olivares-Gallardo, A. (2019). Evaluación experimental de la solución analítica exacta de la ecuación de Colebrook-White. *Ingeniería Investigación y Tecnología*, *20*(2), 1-11. https://doi.org/10.22201/fi.25940732e.2019.20n2.021

Anaya-Durand, A., Cauich-Segovia, G., Funabazama-Bárcenas, O., & Gracia-Medrano-Bravo, V. (2014). Evaluación de ecuaciones de factor de fricción explícito para tuberías. *Educación Química*, *25*(2), 128-134. https://doi.org/10.1016/S0187-893X(14)70535-X

Arumugam, A., Kibrom, H., Gebreamlak, M., Teame, M., & Mengstu, M. (2022). Comparative analysis and validation of selected explicit equation models for determination of Darcy friction factor to estimate major head loss for a pressurized flow system. *Science & Technology Asia*, *27*(3), 216-235. https://ph02.tci-thaijo.org/index.php/SciTechAsia/article/view/241771

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Barr, D., & White, C. (1981). Solutions of the Colebrook-White function for resistance to uniform turbulent flow. *Proceedings of the Institution of Civil Engineers*, *71*(2), 529-535. https://doi.org/10.1680/iicep.1981.1895

Beltrán, L. (2021). *Validación de las ecuaciones del factor de fricción en tuberías a presión* [Tesis de grado, Universidad Católica de Colombia]. RIUCaC. https://hdl.handle.net/10983/26576

Brkić, D. (2011). Review of explicit approximations to the Colebrook relation for flow friction. *Journal of Petroleum Science and Engineering*, *77*(1), 34-48. https://doi.org/10.1016/j.petrol.2011.02.006

Çengel, Y. A., & Cimbala, J. M. (2014). *Fluid mechanics: Fundamentals and applications* (3rd ed.). McGraw-Hill.

Colebrook, C. F., & White, C. M. (1937). Experiments with fluid friction in roughened pipes. *Proceedings of the royal society A*, *161*(906), 367-381. https://doi.org/10.1098/rspa.1937.0150

Da Rocha, H. S., Marques, P. A., de Camargo, A. P., Frizzone, J. A., & Saretta, E. (2017). Internal surface roughness of plastic pipes for irrigation. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *21*(3), 143-149. https://doi.org/10.1590/1807-1929/agriambi.v21n3p143-149

Darweesh, M. S., Salah, W. A., Awwad, T. A., Ragad, E. M., & Ahmed, A. A. (2024). An improved form of Hazen-Williams equation for pressurized flow. *Engineering, Technology & Applied Science Research*, *14*(3), 14640-14644. https://doi.org/10.48084/etasr.7511

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Falkovich, G. (2011). *Fluid Mechanics: A Short Course for Physicists*. Cambridge University Press. https://doi.org/10.1017/CBO9780511794353

Gavilánez-Luna, F. (2019). Incidencia de la presión sobre el coeficiente de rugosidad C de Hazen-Williams. *Tecnología y ciencias del agua*, *10*(5), 214-225. https://doi.org/10.24850/j-tyca-2019-05-08

Guerrero, J. (1995). Ecuación modificada de Colebrook-White. *Ingeniería hidráulica en México*, *10*(1), 43-48.

Gutiérrez, H., & De-la-Vara, R. (2008). *Análisis y diseño de experimentos* (2ª ed.). McGraw-Hill Interamericana, S. A.

Haaland, S. E. (1983). Simple and explicit formulas for the friction factor in turbulent pipe flow. *Journal of Fluids Engineering*, *105*(1), 89-90. https://doi.org/10.1115/1.3240948

Jamil, R. (2020). Frictional head loss relation between Hazen-Williams and Darcy-Weisbach equations for various water supply pipe materials. *International Journal of Water*, *13*(4), 333-347. https://doi.org/10.1504/IJW.2019.106047

Kaseng, F., Bayona, R., & Rodríguez, C. (2020). Alternate formula for calculating the Darcy coefficient in turbulent flow in pipes. *3C Tecnología. Glosas de Innovación Aplicadas a la Pyme*, *9*(3), 99-109. https://doi.org/10.17993/3ctecno/2020.v9n3e35.99-109

Liou, C. P. (1998). Limitations and proper use of the Hazen-Williams equation. *Journal of Hydraulic Engineering*, *124*(9), 951-954. https://doi.org/10.1061/(ASCE)0733-9429(1998)124:9(951)

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Monís, J. (2020). *Historia, análisis y expresión gráfica de las fórmulas de pérdidas de carga utilizadas en la ingeniería hidráulica* [tesis doctoral, Universidad de Córdoba]. Helvia: Repositorio Institucional de la Universidad de Córdoba. http://hdl.handle.net/10396/20203

Moody, L. F. (1944). Friction factors for pipe flow. *Transactions of the American Society of Mechanical Engineers*, *66*(8), 671-678. https://doi.org/10.1115/1.4018140

Mott, R. (2006). *Mecánica de fluidos* (6ª ed.). Pearson Educación.

Munson, B. R., Okiishi, T. H., Huebsch, W. W., & Rothmayer, A. P. (2013). *Fundamentals of fluid mechanics* (7th ed.). John Wiley & Sons.

Narváez, P. (2000). Ecuaciones de flujo para líquidos: desarrollo histórico y características fundamentales. *Revista Ingeniería e Investigación*, (45), 33-38. https://doi.org/10.15446/ing.investig.n45.21313

Offor, U., & Alabi, S. (2016). An accurate and computationally efficient explicit friction factor model. *Advances in Chemical Engineering and Science*, *6*(3), 237-245. https://doi.org/10.4236/aces.2016.63024

Ormsbee, L., & Walski, T. (2016). Darcy-Weisbach versus Hazen-Williams: No calm in West Palm. In: *World Environmental and Water Resources Congress 2016* (pp. 455-464). https://doi.org/10.1061/9780784479865.048

Pérez-Pupo, J., Navarro-Ojeda, M., Pérez-Guerrero, J., & Batista-Zaldívar, M. (2020). On the explicit expressions for the determination of the friction factor in turbulent regime. *Revista Mexicana de Ingeniería Química*, *19*(1), 313-334. https://doi.org/10.24275/rmiq/Fen497

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Pimenta, B. D., Robaina, A. D., Peiter, M. X., Mezzomo, W., Kirchner, J. H., & Ben, L. H. (2018). Performance of explicit approximations of the coefficient of head loss for pressurized conduits. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *22*(5), 301-307. https://doi.org/10.1590/1807-1929/agriambi.v22n5p301-307

Revilla, J. (1991). Factores de pérdidas por cortante para flujo de agua en tuberías. *Ingeniería hidráulica en México*, *6*(3), 9-17.

Round, G. F. (1980). An explicit approximation for the friction factor in turbulent pipe flow. *The Canadian Journal of Chemical Engineering*, *58*(1), 122-123. https://doi.org/10.1002/cjce.5450580119

Saldarriaga, J. (2007). *Hidráulica de tuberías*. Alfaomega Bogotá.

Shaikh, M., Massan, S., & Wagan, A. (2015). A new explicit approximation to Colebrook's friction factor in rough pipes under highly turbulent cases. *International Journal of Heat and Mass Transfer*, *88*, 538-543. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.006

Sotelo, G. (1980). *Hidráulica general*. Editorial Limusa, S. A.

Streeter, V. L., Wylie, E. B., & Bedford, K. W. (1998). *Fluid mechanics* (9th ed.). McGraw-Hill.

Swamee, P. K., & Jain, A. K. (1976). Explicit equations for pipe-flow problems. *Journal of the Hydraulics Division*, *102*(5), 657-664. https://doi.org/10.1061/JYCEAJ.0004542

Tarjuelo, J. (1999). *El riego por aspersión y su tecnología* (2ª ed.). Ediciones Mundi-Prensa.

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Tolentino, S. L., & González, O. (2023). Correlación para el cálculo de la fricción turbulenta en tuberías. *Ingenius, Revista de Ciencia y Tecnología*, (30), 54-63. https://doi.org/10.17163/ings.n30.2023.05

White, F. M. (2011). *Fluid mechanics* (7th ed.). McGraw-Hill.

Willmott, C. J. (1981). On the validation of models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213

Zhao, Z., & Gao, J. (2020). Robustness of water hammer protection of different formulas of frictional head loss. *Desalination and Water Treatment*, *187*, 172-177. https://doi.org/10.5004/dwt.2020.25314

2026, Instituto Mexicano de Tecnología del Agua. Open Access bajo la licencia CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/)