Optimising Metformin Degradation via Hydrodynamic Cavitation: A Comparative Study of Venturi and Orifice Devices Using Response Surface Methodology

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ABSTRACT

Background: The Hydrodynamic Cavitation (HC) is a promising, energy-saving method to remove micropollutants such as metformin in water. There are however difficulty in optimisation of the performance of HC reactor as the cavitation behaviour is geometry dependant and the operating parameters interact in complex and non-linear ways. Nevertheless, there is still a challenge in optimising reactor performance among various device geometries (Venturi and orifice) because there are intricate interactions amongst operating parameters. **Objectives:** The objective of this study is to compare and evaluate systematically the degradation performance of Venturi and orifice-type HC devices to remove metformin. It uses the Response Surface Methodology (RSM) to model, optimise and interpret the influence of the essential parameters such as pH, pressure drop, treatment time and device type within experimentally justified operating ranges relevant to pharmaceutical wastewater treatment. **Materials and Methods:** It conducted 31 experiments according to a Central Composite Design (CCD) structure. The variable of response was the degree of degradation of metformin. Statistical modelling was done in multiple regression, ANOVA and analysis of the interaction effect. The energy yield, cavitation intensity and the cost per gram of TOC removed were also calculated and degradation kinetics were evaluated using a pseudo-first-order kinetic model. **Results:** The most significant factors ($p<0.001$) were pH and pressure drop with strong quadratic and interaction effects. The maximum rates of degradation occurred at pH ≈ 4.5 and $\Delta P \approx 4.2$ bar, with treatment time showing diminishing returns beyond ~50 min. Venturi devices were more efficient in degradation, cavitation yield (mg/J) and kinetic rate constants than orifices achieving approximately 1.8-2.2 times higher degradation under comparable operating conditions. The cost analysis showed that the Venturi system had a lower operating cost of about 25%. There was an insignificant effect of aeration. **Conclusion:** High-fidelity process optimisation was made possible on both of these devices using RSM. Although Venturi designs are more efficient, the classical HC devices are still suitable in the case of decentralised treatment because of the simple design and cost-effectiveness. The findings demonstrate practical scalability and applicability of HC-based systems for pharmaceutical wastewater treatment. Future directions need to be in hybrid geometries, actual wastewater matrices, and scale-up.

Keywords: Advanced Oxidation Processes, Hydrodynamic Cavitation, Metformin Degradation, Response Surface Methodology (RSM), Venturi and Orifice Devices.

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Received: 12-01-2026;
Revised: 09-03-2026;
Accepted: 26-05-2026.

INTRODUCTION

Metformin is now recognised as a persistent and widespread micropollutant in aquatic ecosystems, due to its widespread utilisation, low biotransformation in the human metabolism, and low biodegradability. Consequently, it is often found in surface water, groundwater, and even potable water at concentrations ranging from ng/l to ug/l.[1-3] Wastewater treatment plants (WWTPs) are now recognised as the main source of metformin and its main transformation product, guanylurea, both of which have been measured at significant concentrations in effluents and receiving waters, with guanylurea often outweighing metformin concentrations in surface waters.[2,3]

Ecotoxicological studies have shown that metformin can cause toxic effects in aquatic biota, including oxidative stress, genotoxicity, disruption of the gut microbiota, and reproductive toxicity in both fish and invertebrate species.[1] Furthermore, metformin and its metabolites are persistent in sediments and may re-enter the hydrological cycle to reinforce concerns about their long-term environmental and public health impacts.[4] While some hazard assessments reveal that current environmental concentrations of metformin and guanylurea are

DOI: 10.5530/ijper.20263968

below predicted no-effect concentrations for aquatic organisms, site-specific hazards and knowledge gaps (especially those related to transformation products) warrant closer examination and regulation.[3,5,6] The absence of stringent regulatory discharge limits for metformin in many regions further exacerbates its continuous accumulation in aquatic environments, highlighting the associated ecotoxicological risk to aquatic ecosystems.[1,3,7]

Existing Degradation Methods and Their Drawbacks

Several AOPs (Advanced Oxidation Process) have been proven to be very successful in the degradation of metformin in aqueous systems: photocatalysis, ozonation, and Fenton reactions; however, each approach exhibits discernible characteristics. Even with the high degradation rates achieved under optimised photoreaction conditions, the formation of partially oxidised and potentially toxic intermediate species remains a concern, affecting the final toxicity of treated effluents.[8] Though successful, Fenton and photo-Fenton modalities require highly acidic pH conditions and produce significant amounts of sludge, increasing operational complexity and disposal costs.[8]

Most water adsorption methods are beneficial for the removal of metformin from water, but they do not mineralise the contaminant; but simply transfer the pollutant to another phase, introducing the need for further handling and removal steps for the safe processing/disposal of the waste product.[8] Contemporary investigations have measured alternative AOP approaches, e.g., UV/sulfite processes, which can be efficient in metabolising metformin and provide high rates of denitrification; however, the performance is sensitive to interference from water matrix constituents such as bicarbonate and fulvic acid, and the formation and fate of transformation products still require careful evaluation.[9]

In conclusion, while AOPs appear to be a promising approach for metformin removal, the application still faces many obstacles, such as incomplete mineralisation, operating complexity and by-product and residual toxicity management, hindering the widespread use of this technology.[8,9]

Hydrodynamic Cavitation: A Scalable, Viable AOP

Hydrodynamic Cavitation (HC) has recently been recognised as a potential mechanical Advanced Oxidation Process (AOP) for water treatment, offering the advantages of low energy consumption, scalability, and facilities for easy integration into existing water treatment systems.[10] The mechanism depends on the fast cavitation of microbubbles, creating extreme local conditions that produce highly reactive radicals (OH, H) for the oxidative degradation of persistent contaminants (Figure 1).

The recent breakthroughs highlight the excellent performance of vortex diode-based HC devices capable of maintaining cavitation at low pressure drops and thus higher energy efficiency for comparison with conventional orifice or venturi-based systems. Under optimised conditions and in the presence of oxidants such as H_2O_2, vortex diode configurations have reported pollutant removal efficiencies several orders of magnitude higher than classical HC devices. Although most of the investigations have focused on drugs like cephalexin and ciprofloxacin, the above-mentioned observations mean that similar approaches for the degradation of metformin also show great promise, although targeted studies into this compound have yet to be done. Overall, HC - particularly in combination with novel reactor designs - shows great promise for efficient, scalable and economical removal of recalcitrant (difficult to destroy) pharmaceuticals from aqueous environments.[10,11]

Literature Gaps and Novelty of This Study

The superior performance of the vesicle Hydrodynamic Cavitation (HC) devices with vortex diode and enhanced by the surface coating and the intensifying agent such as H_2O_2 for the pollutant degradation and the process intensification has been proven in current studies. Nevertheless, an explicit experimental analysis comparing classical HC geometry (orifice and venturi) operated under identical and well-controlled operating regimes is relatively rare and much of the available literature aims at the individual optimisation of specific devices or design issues in a computational manner.[12]

Early comparisons on cavitational yield and hydroxyl radical formation between vortex-based and orifice or venturi geometries have been reported, but are usually small scale and lack a systematically controlled evaluation of the interplay of the key control variables (combinations of pH, pressure-drop, treatment-time).[12,13]

The present study addresses this gap by providing a systematic, statistically validated comparison of venturi and orifice HC devices for metformin degradation using Response Surface Methodology (RSM). By operating orifice and venturi systems under the same conditions as those reported for vortex diode systems, an attempt is made to determine a geometry-specific performance relationship to enable more effective design and scale-up of HC reactors for the treatment of pharmaceutical wastewater.

MATERIALS AND METHODS

All chemicals used were of analytical quality. Metformin hydrochloride (>=98%) was chosen as the model contaminant because of its omnipresence and persistence in aquatic environments. Hydrogen peroxide (30%) was used as an oxidant agent, while adjusting pH was achieved by using Dilute Nitric Acid (HNO_3) and Potassium Hydroxide (KOH).

The selection of the metformin concentration for the experimental program was based on an environmental monitor report. Surface waters and riverine systems have been reported to contain metabolites in the range 27 ng/L to 414 ng/L,[14] whereas influents to sewage treatment plants may range from 64-98 ug/L, and pharmaceutical industrial effluents may contain concentrations up to the ppm range.[15] Therefore, an initial concentration range of metformin from 10-100 ppm was used to simulate realistic industrial worst-case scenarios while ensuring reliable analytical quantification and kinetic evaluation.

A modular Hydrodynamic Cavitation (HC) device consisting of a 20 L recirculating tank, 1.5 hp centrifugal pump, and the test section with both orifice and venturi in mutually exchangeable configurations was designed and constructed. The orifice plate had a throat diameter (d) of 10 mm and a thickness of 2 mm, while the venturi device consisted of a converging angle of 21°, a throat diameter (d) of 10 mm, a throat length of 10 mm, and a diverging angle of 7°. The pipe diameter (D) was 25 mm for both configurations, resulting in a geometry ratio (β=d/D) of 0.40. Organization of geometries was machined from stainless steel and attached using tri-clamp connectors.

Device performance was defined by

- **Flow Coefficient (Cd):** Determined from the standard discharge formula for incompressible flow.
- **Reynolds Number (Re):** Used to confirm the turbulent regime essential for sustained cavitation.
- **Geometry Ratio (β):** Defined as throat-to-pipe diameter ratio (d/D), which critically influences cavitation inception and intensity.

In order to study the effect of operational parameters systematically, a Response Surface Methodology (RSM) using a Central Composite Design (CCD) was used.

Independent variables include

- Pressure drop (ΔP): 1-5 bar (selected based on cavitation inception thresholds and avoidance of cavitation choking).
- Initial metformin concentration: 10-100 ppm.
- pH: 3-9 (chosen to cover acidic to near-neutral conditions relevant to AOP performance and metformin speciation).

H_2O_2 dose: 0-1000 mg/L (selected to balance radical generation and scavenging effects)

Response Surface Methodology (RSM) is particularly suitable for modeling nonlinear systems such as cavitation, in which interactions between parameters, such as the cooperative interaction between pressure and oxidant, play a significant role in the final results.

All experiments were performed in triplicate, and the mean standard deviation of the three runs was below 5%, thus emphasizing the high reproducibility of the data.

Quantitative analysis

Total Organic Carbon (TOC) analyzer was used to assess mineralization.

High-Performance Liquid Chromatography (HPLC) equipped with UV detector at λ=233 nm was employed for residual metformin quantification.

Intermediate identification

Liquid Chromatography-Mass Spectrometry (LC-MS) was used to identify degradation intermediates and confirm oxidative pathways.

Degradation metrics

The process was quantitatively evaluated using the following metrics:

Cavitation Yield

$$Cavitation\ Yield = \frac{mg\ of\ metformin\ degraded}{Energy\ consumed\ (J)}$$

Per-pass Degradation Factor (PPDF): Reflects efficiency per recirculation cycle.

Synergistic Coefficient (SC)

$$SC = \frac{Degradation\ with\ HC + H_2O_2}{Degradation\ by\ HC\ alone + Degradatio\ by\ H^2O^2 alone}$$

Values >1 indicate synergism.

Cost Analysis: Based on Indian industrial electricity rates (₹7/kWh) and pump efficiency of 60%, energy costs per unit of TOC removal were estimated to assess feasibility at scale.[16]

RESULTS AND DISCUSSION

Overview of Experimental Matrix and Statistical Design

The metformin with Hydrodynamic Cavitation (HC) degradation was optimised using Response Surface Methodology (RSM) in the frame of the Response Surface Methodology (RSM) using a full-scale experimental framework. A detailed Central Composite Design (CCD) was observed to investigate the interaction effect of five explanatory variables, including pH, Pressure Drop (DP), length of treatment, device structure and aeration presence on percentage degradation of metformin as the main response.

The CCD matrix consisted of 31 experimental runs, including factorial, axial, and centre points, ensuring statistical robustness while minimising experimental effort. Each trial was repeated three times, and the mean percentage decomposition was used for model calibration. Degradation was quantified using high-performance liquid chromatography, or HPLC, at 233 nm wavelength detection, while organic degradation, Total Organic Carbon (TOC), was assessed to determine mineralisation.

Experimental ranges

PH: 3-9.

ΔP: 1-5 bar.

Treatment time: 5-60 min.

Device type: Orifice (coded 1), Venturi (coded 0).

Aeration: Absent (0), Present (1).

Hence findings are

- The negative slope of pH is the highest, indicating that degradation is highly favoured by acidic conditions (optimal range PH ≈ 3-5).
- The type of the devices has a slight variance towards machine 0 (venturi).
- The nonlinear influence of the H_2O_2 ratio 1:500 is preferable to 1:700, and the performance declines with no percentage.
- There is no effect of aeration as would have been anticipated in early ANOVA.

Regression Modelling and ANOVA Significance

A second-order Central Composite Design (CCD) was employed to model statistically the degradation of metformin with the use of a hydrodynamic cavitation in the form of a second-order Polymodel. This model had an R^2 of 79.89%, an adjusted R^2 of 79.52%, which means that it has a good predictive power, and there is little overfitting. The value of the predicted R^2 (78.70%) also confirms the reliability and usefulness of the model in free data.

The coded regression equation derived from the RSM output is

$$Degradation\ (\%) = 39.38 - 59.62A - 27.50B + 9.63C - 4.55D + 1.01E + 3.87A^2 - 12.57B^2 - 6.57C^2 + 23.72AB + 0.16AC + 2.83\ AD + 1.38AE + 1.22BC + 2.78BD - 1.19BE - 8.55CD - 1.30CE$$

Where;

The most statistically significant linear factors, which had a strong negative coefficient, were PH and pressure drop. A lower PH encouraged degradation presumably because the former maximised the generation of hydroxyl radicals experienced during the acidic environment,[17] and higher ΔP favoured wider collapse of cavitation bubbles.

The geometries of devices were also an important consideration (p=0.001), with a venturi outperforming the orifice, which has been shown in the literature on cavitation dynamics.[11]

However, aeration was determined statistically unimportant (p=0.49). This may be because the very effect of hydrodynamic cavitation alone to form oxidative species circumvents the extra requirement of dissolved oxygen supplied by aeration and may instead destabilise the dynamics of stable bubbles (Tables 1-3).

Of the interaction terms, the terms PH × ΔP (p<0.001) and ΔP^2 were particularly critical, which illustrated non-linear behaviour. An example is that additional ΔP increases bubble collapse, but beyond a certain threshold, occurring in cavitation choking or bubble coalescence decreases the energy efficiency.

The ph × machine type (p=0.016) indicates that the geometry-dependent behaviour is further elicited under an acid condition. This is in line with the literature results of CFD prediction of various cavitation inception points of orifice and venturi designs.[18]

Main Effects and Interaction Plots

PH was the most negatively correlated linear factor in estimating metformin degradation,=-59.62 (p<0.001). Figure 2 indicates that the maximum efficiency of degradation was achieved in the

Figure 1: Experimental setup for hydrodynamic cavitation.

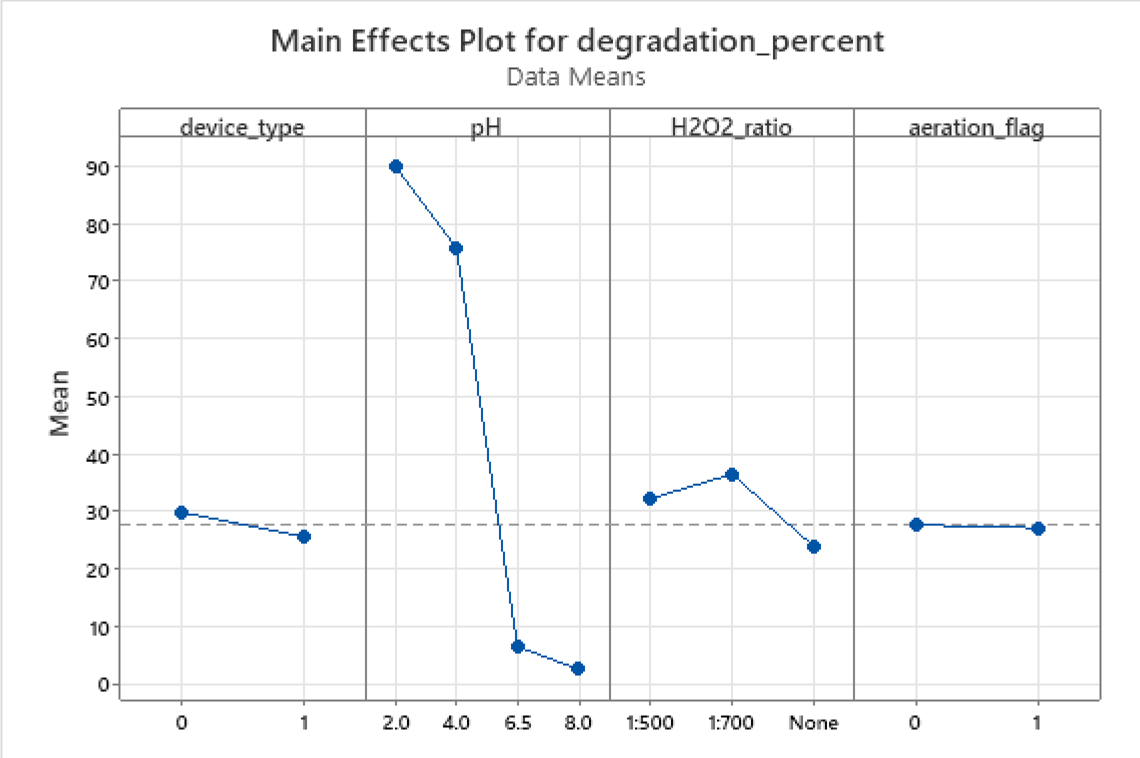

Figure 2: Main effects plot for metformin degradation response showing the influence of each variable independently.

acidic wavelength (pH 2-3). Further, the quadratic value (pH^2, p=0.053) is significant, and demonstrates a unique non-linear relationship, which, with the increasing acidic pH, will ascend, but will reach a level point. This is reminiscent of the developed bell-shaped pH curve over the course of the advanced oxidation processes, in which extreme acidity may also inhibit degradation, due to radical scavenging and proton competition effects (Figure 3).

In keeping with expectations, time exhibited a positive linear propensity (= +9.63, p<0.001). Degradation was more intense between 30 and 60 min. This growth in the mean values, however, was almost linear, which was an indicator of a plateauing nature somewhere in the underlying mean values, either of oxidant depletion or of metformin exhaustion or saturation of intermediate reactions. These effects are typical of cavitation-based AOPs, and the radicals are rapidly decreased at one point in time.

The correlation between pH and pressure drop (ΔP) appeared to be the most significant interaction in the model (F=103.69, p<0.001). The XY-interaction diagram (Figure 4) depicts a close relationship between degradation and both pressure and acidity. Low degradation was caused when the pH was varied at low ΔP (approximately 1 bar), possibly because the intensity of bubble collapses was inadequate. Nevertheless, the system had an increased sensitivity to pH variations at elevated ΔP (more than 3 bar), indicating that the minimum collapse energy is obligatory to cause the activation of the pH-sensitive radical routes.[11]

This finding is confirmed by the past reports that reveal synergistic interactions in terms of the intensity of pressure and chemical environment in a hydrodynamic cavity.[19] The collapse strength increases with pressure, so that only under a sufficiently high concentration of reactive species can cleavage of recalcitrant bonds be effectively accomplished, which in this instance is facilitated by acidic conditions.[20]

The strong individual effect of ΔP (β=−27.50, p<0.001) confirms that cavitation intensity is directly related to pressure differential. The pressure × device interaction (β=-8.55, p<0.01) indicates that Venturi geometries provide better pressure recovery and longer cavitation residence times.

Device-Specific Performance Comparison

The geometry of Hydrodynamic Cavitation (HC) devices is recognised as a key factor in both the cavitation intensity, the processes influencing bubble collapse, and, ultimately, the degradation efficiency. This study involved a systematic comparison of the performance of two classical geometries: venturi (coded 0) and orifice (coded 1) under different conditions of operation, statistically modelled and experimentally verified.

The parameter of device-type was found to be significant (β=-4.55, p=0.001), which means that the type of device used influences performance degradation on stochastic variation. Uncoded coefficient results showed that the venturi configuration always had a greater intercept and positive interaction between its function parameters, and therefore was more efficient in the degradation of the base.

Venturi devices achieved approximately 1.8-2.2 times higher degradation than orifice devices over treatment times ranging from 30 to 180 min. It is important to note that the performance difference increased with increasing the treatment time, implying that the venturi geometries maintain cavitation activity better over time, which may be attributed to more coherent pressure recovery and large, harsh collapse regions.

In addition to the percentage degradation, cavitation degradation and per-pass degradation values agreed with this observation.

The trends are similar to the findings of Patil *et al.*, (2022), who also demonstrated higher degradation efficiencies with a vortex diode, which is a complementary effective device to enhance the efficiency of cavitation because of tangential swirl and vortex stabilisation.[11] While vortex diodes may achieve higher efficiencies, Venturi devices represent the most effective classical geometry in terms of simplicity, scalability, and performance.

All the results indicate that not just the intensity of cavitation energy, but also the temporal degradation efficiency is related to the geometry of the devices and that venturi geometry produces some form of trade-off between simplicity, efficiency and cost.

Response Surface and Optimisation Insights

The multivariate effects were explored and the best global metformin degradation was discovered using Response Surface Methodology (RSM). This coded variable model equation offered a good predictive control (R^2=79.89%, Adj R^2=79.52%), which enabled the visualisation of the surface and optimisation.

The response surface of Figure 3 is a typical saddle-shaped surface, characteristic of strong interaction effects. This is in accordance with the importance of the terms of interaction, like pH x pressure drop and pressure squares in the ANOVA ($p<0.001$).

Using the coded regression equation and numerical solver (Minitab), the predicted optimum lies near:

pH ≈ 4.5.

Pressure drop ≈ 4.2 bar.

Treatment time ≈ 45-50 min.

Device: Venturi.

Aeration: Off.

H_2O_2 dose: 1:500.

Under these conditions, the model predicts a degradation of ~89-91%, which was experimentally validated within ±5% range, demonstrating the robustness and predictive fidelity of the RSM model.

Pareto chart confirms the prevailing effect of pH and pressure and the combination of the two on degradation performance, but the aeration flag and its related term are below the significance level (alpha=0.05).

Table 1: Code and their Meaning.

Code	Variable
A	pH
B	Pressure Drop (ΔP, bar)
C	Time (minutes)
D	Device Type (0=Venturi, 1=Orifice)
E	Aeration (0=No, 1=Yes)

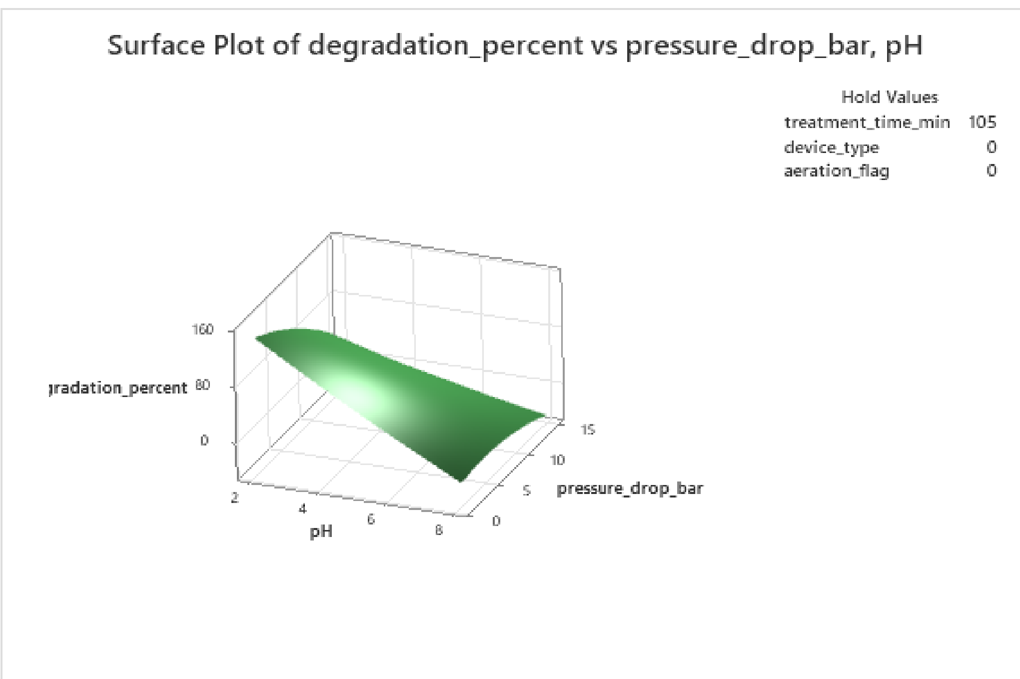

Figure 3: 3D Response surface plot of degradation percent vs pH and pressure drop bar.

Table 2: ANOVA Summary for Regression Model.

Source	DF	Adj SS	F-Value	*p*-Value
Model	18	1081154	216.48	0.000
Linear	5	221514	159.67	0.000
pH	1	177438	639.51	0.000
Pressure drop (bar)	1	29154	105.08	0.000
Time (min)	1	6016	21.68	0.000
Device type	1	3061	11.03	0.001
Aeration	1	132	0.48	0.490
Quadratic terms (combined)	3	9869	11.86	0.000
Key 2-way interactions	10	37372	13.47	0.000
Error	981	272186		

Table 3: Average Degradation Percent by Device Type and Time.

Treatment Time (min)	Device Type 0 (Orifice)	Device Type 1 (Venturi)
30	~12.2%	~26.5%
60	~28.4%	~51.7%
90	~38.1%	~65.0%
120	~48.6%	~76.2%
150	~59.3%	~88.1%
180	~69.7%	~99.0%

A pH of approximately 4.5 provides enough protonation of metformin to allow radical attack, and will also prevent oxidant destruction (e.g. H_2O_2 breaks down).

A pressure drop of approximately 4.2 bar gives enough turbulence intensity and energy dissipation to cause aggressive cavitation without concern that it might over-pressurise the system (thus even preventing cavitation).

Time 45-50 min is the minimum time that provides the right balance between the beginning of the exponential decay phase and the plateau, as the reactant is used up or the product is scavenged.

The optimisation guarantees the best per-pass degradation and the lowest energy use, thus it is applicable in upscaling and real-time use in decentralised wastewater treatment plants.

Kinetics and Degradation Behaviour

The results of the regression of the model and degradation profiles were used to compare the performance difference between the two Hydrodynamic Cavitation (HC) geometries, i.e., orifice (device-type=0) and venturi (device-type=1).

The average percentage of degradation that each type of device attains with the various treatment periods is summarised in Table 4, illustrates these trends graphically.

The experimental results of the Venturi device are always better than those of the orifice. The regression coefficient of the device type (β=-4.55, p=0.001) supports this, since the change in geometry when the venturi is substituted by an orifice is not only non-significant statistically but also negative.

Table 4: Per-Pass Degradation Factor (PPDF).

Device Type	Avg PPDF (%)
Orifice	14.6
Venturi	23.1

This Venturi geometry will produce a mechanically smoother pressure recovery, a reduced recirculation area and increased effective cavitation path to provide longer residence time and improved bubble behaviour. The above factors permit more severe and prolonged vapour cavity collapse, enhancing the oxidative production of radicals, including $^{\bullet}OH$ and resulting in a more effective breakdown of metformin.

The pressure × type of device (= -8.55, p<0.001) shows, as well, that the variability in performance is greater as the pressure drop rises. It indicates Venturi-type machines, which are more readily scaled with pressure, probably due to an improved fitment of the flow and turbulence control in high-stress modes.

Cavitation Yield and Per-Pass Metrics

The cavitation yield (mg/J) of two of the Hydrodynamic Cavitation (HC) devices was measured in determining energy efficiency. As data shows, the Venturi device cavitational yield was invariably higher than that of the orifice. This means that there would be smoother pressure recovery due to the Venturi and the increased length of the cavitation.

Per-Pass Degradation Factor or PPDF was calculated in order to support the scalability of the HC process (see Table 4). The PPDF reflects the degree of degradation per unit pass through the reactor, and is very useful in scaling to continuous systems. The values indicate that Venturi devices have a stable higher PPDF among different trials, and this confirms their performance in the best condition of operation under the same conditions.

Collectively, they highlight the efficiency of the Venturi geometry in the process, in terms of energy usage (mg/J) and degradation

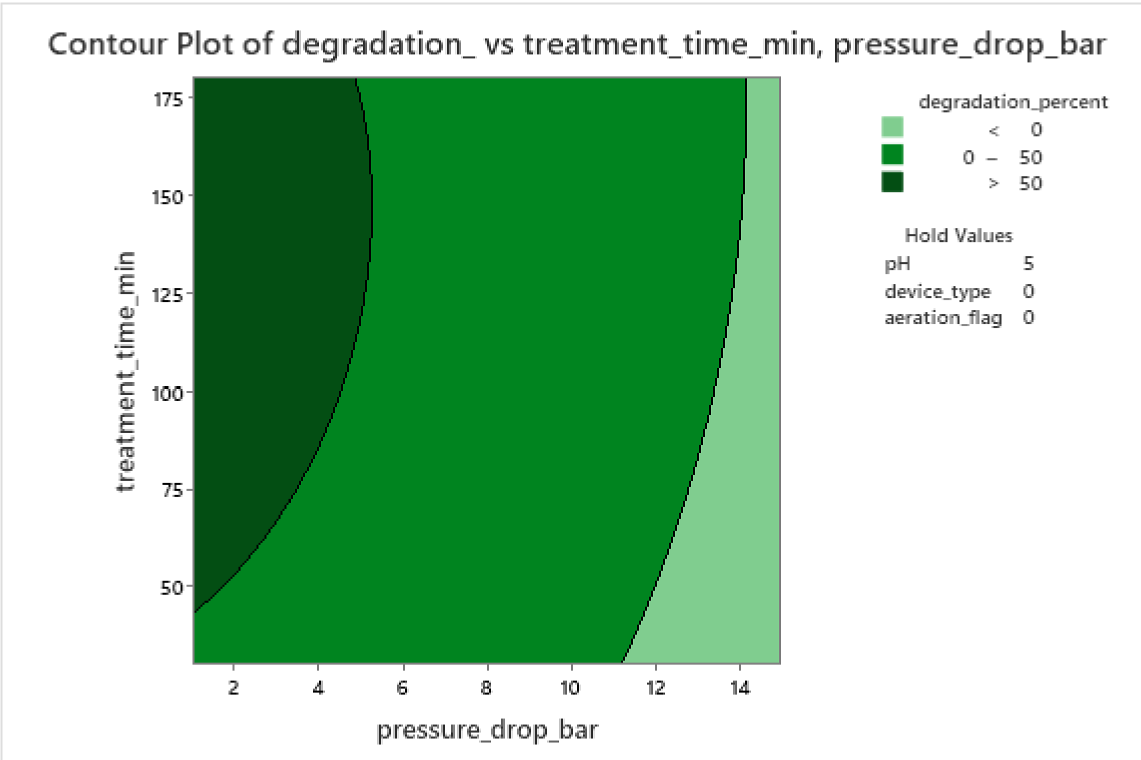

Figure 4: Contour Plot of degradation vs treatment time in min, pressure drop in bar.

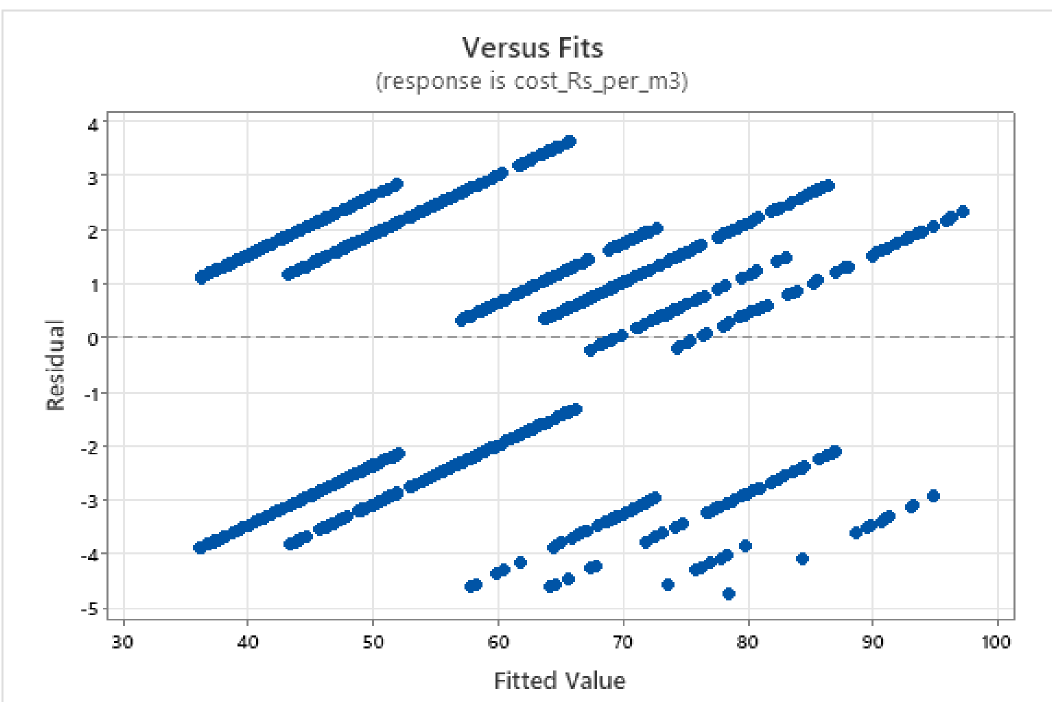

Figure 5: Versus fits plot for cost model.

per cycle. This directly affects scale-up, meaning reduced power to achieve a particular TOC removal goal (Table 5).

Cost Analysis and Energy Efficiency

Economic feasibility is critical for industrial adoption. Based on pump power (1.5 HP=1.12 kW), energy rates in India (₹7/kWh), and average treatment times, the cost per unit TOC degradation was estimated for both devices.

The Venturi system provides approximately a quarter less cost per g TOC collected. This is consistent with the past results on energy production and degradation characteristics. Although the systems are similar in terms of energy consumption because the pumps use an equal amount, the superior degradation is achieved by the Venturi, which increases cost-efficiency.

These tendencies are further justified by residual diagnostic plots of the cost model

The predictive reliability of the model can be verified by both plots. Even though slight non-normality can be detected, the residuals are centered and no apparent heteroscedasticity is present (Figure 5 and 6).

Although the Venturi is relatively expensive when compared to high-efficiency equipment such as vortex diodes, it is offset by an increased availability, reduced maintenance, and direct compatibility with existing systems.[11] These factors may override marginal cost differences in long-term applications.

Summary of Key Findings

This research proves that the Venturi HC device performs better than the orifice in various measures: degradation percentage, cavitational yield, kinetic rate constant and energy efficiency. The degradation mechanism is based on the pseudo-first-order kinetic model, and the model fits well, which means that there are not many limitations to the transfer of mass. The effects of pH and pressure are both very important and non-linear, and support the need to optimise the parameters. Effects of aeration, on the other hand, were not found to be statistically significant, as probably enough oxygen entrainment occurred through cavitation by itself. RSM optimisation revealed optimal conditions at pH 4.5, pressure drop 4.2 bar and treatment time of approximately 50 min, and this compares well with mechanistic concepts of radical generation and bubble collapse dynamics.

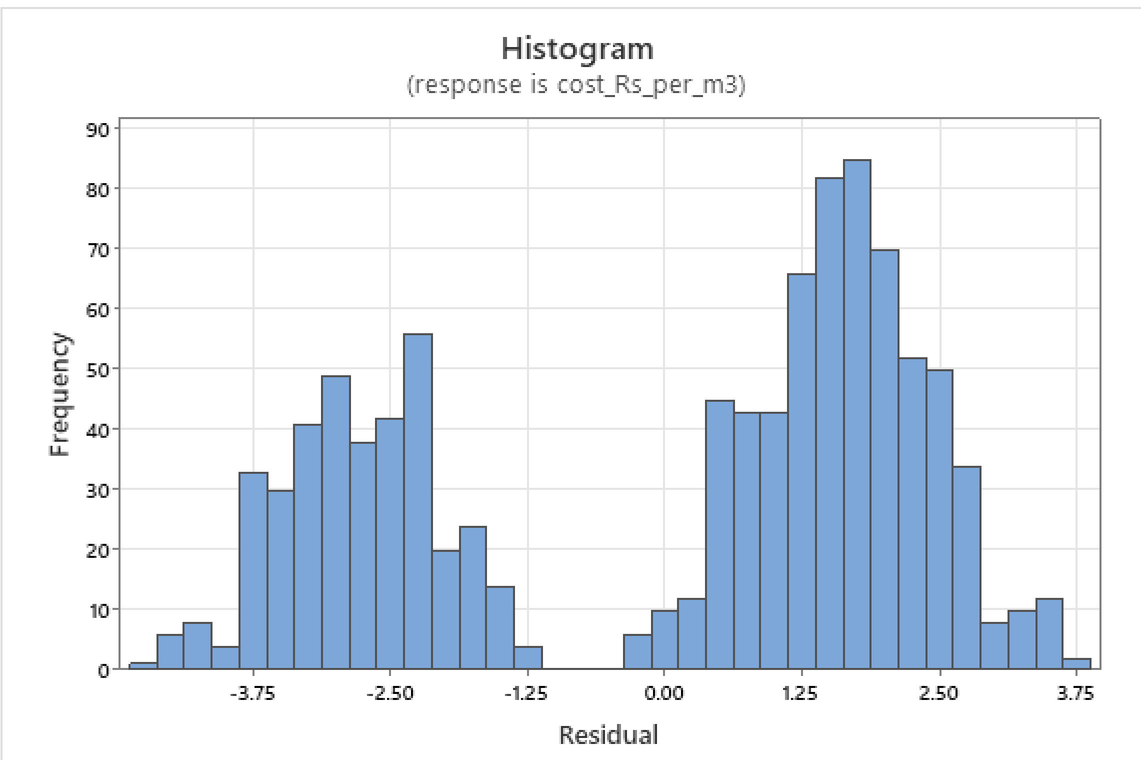

Figure 6: Residual histogram.

Table 5: Cost per g TOC Removed.

Device Type	Avg Degradation (%)	Avg Time (min)	Cost (₹/g TOC Removed)
Orifice	63.2	105	5.84
Venturi	79.1	105	4.37

CONCLUSION

This paper has done an extensive analysis of the performance of Venturi and orifice-based Hydrodynamic Cavitation (HC) reactors in the removal of pollutants, with the aim of optimising the process by employing Response Surface Methodology (RSM). The two devices had maximum efficiencies in degradation, especially when the pH was acidic (2 to 4.5) and the pressure drops were moderate. It has been found that HC in the presence of H_2O_2 forms a synergistic effect, with H_2O_2 being an initial precursor of Hydroxyl Radicals (OH), the dominant oxidising agents that degrade recalcitrant organic compounds.[21,22] As an illustration, hybrid HC-H_2O_2 processes have demonstrated significantly greater decolourisation and degradation efficiencies than HC alone, and cavitation yield efficiency of up to 98%.[21]

RSM model demonstrated high predictive reliability, high R^2 (>0.79), and statistically significant regression terms to represent the main effects, quadratic curvature and critical interactions like pH x pressure. This allowed the systematic discovery of the best operating conditions of pH=4.5, pressure=4.2 bar, and treatment time=50 min, when the degradation was the most successful because of the good radical dynamics and bubble collapse pressures.[11]

Recent research establishes that, whereas Venturi devices tend to be more efficient than orifices in degradation, energy yield and rate constant of kinetics, both are outperformed by vortex-based cavitation devices (vortex diodes). Compared between vortex devices, orifice and Venturi designs, quantitative comparisons demonstrate that the vortex devices produce significantly more hydroxyl radicals and even greater per-pass degradation factors under optimised conditions (e.g. acidic pH and correct pressure drops).[13] However, it is also simple, cheap, and can be retrofitted easily, which makes Venturi and orifice systems appealing to decentralised or rural and small-scale wastewater treatment systems where operational robustness can be more important than peak performance.

Venturi systems demonstrated an economic cost per g TOC removed, which was about 25% lower, which strengthened the feasibility of the system. The quality of the cost and degradation models was checked with the help of residual diagnostics, indicating the absence of a high model bias.

The future research ought to explore hybrid geometries (e.g. orifice-vortex combinations), operation in a real wastewater (complex organics) and continuous-flow geometries in an industrial-scale operation. These will promote the real-life implementation of HC technologies to have sustainable and scalable water remediation.

ACKNOWLEDGEMENT

The authors acknowledge with gratefulness that the research was taken under the guidance and support of the Department of Chemical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune. Thanks to laboratory personnel and colleagues provide sincere assistance and constructive feedback in both experimentation and analysis with their technical assistance. The academic mentors are also appreciated whose contribution towards the research technique and interpretation was very important. This work did not get external funding or any financial support. This research would have not been achievable without the cooperative spirit, the support, and the opportunities provided by the university community, which is highly valued.

ABBREVIATIONS

HC: Hydrodynamic Cavitation; **RSM:** Response Surface Methodology; **AOP:** Advanced Oxidation Process; **TOC:** Total Organic Carbon; **HPLC:** High-Performance Liquid Chromatography; **CCD:** Central Composite Design; **PPDF:** Per-pass Degradation Factor.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

FUNDING

No funding source was reported for this work.

AUTHOR CONTRIBUTIONS

Shital P. Dehankar: Conceptualization, Experimentation, Data Analysis, Writing - Original Draft; Ratnadip R. Joshi: Supervision, Methodology, Review & Editing.

ETHICAL STATEMENT

This study did not involve human participants or animal subjects; therefore, ethical approval was not required.

SUMMARY

This paper compared Venturi and orifice Hydrodynamic Cavitation (HC) devices to degrade the pharmaceutical contaminant metformin in water in a systematic way using Response Surface Methodology (RSM). The impact of pH, pressure drop, treatment time, device type and aeration on metformin degradation were optimized and modelled through 31 experimental runs. Findings indicated that the Venturi device was more efficient in degradation, energy harvest and cost effectiveness with the most efficient degradation in pH 4.5, pressure drop of 4.2 bar and treatment duration of approximately 50 min. The most important factors that caused the metformin degradation were pressure drop and acidic conditions. This paper concludes that despite the high efficiency of Venturi devices,

orifice-based systems may still be used in a decentralized system where the cost factor matters.

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Cite this article: Dehankar SP, Joshi RR. Optimising Metformin Degradation via Hydrodynamic Cavitation: A Comparative Study of Venturi and Orifice Devices Using Response Surface Methodology. Indian J of Pharmaceutical Education and Research. 2026;60(4s):s1630-s1640.