

Design and Development of a Fully Automatic Pneumatic Water Pumping System Using Air Power

Karthik G^{1*}, Vairamani G², Karthikeyan V³, Chandru K⁴, Manoj G⁵ and Vetrivelan D⁶

¹Department of Mechanical Engineering, V.S.B College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India,

²Department of Mechanical Engineering, V.S.B. Engineering College, Karur, Tamil Nadu, India,

³Department of Mechanical Engineering, V.S.B College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India,

⁴Department of Mechanical Engineering, V.S.B College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India

⁵Department of Mechanical Engineering, V.S.B College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India

⁶Department of Mechanical Engineering, V.S.B College of Engineering Technical Campus, Coimbatore, Tamil Nadu, India

¹karthik4670@gmail.com, ²mailtovairamani@gmail.com, ³mechkarthi.v@gmail.com and ⁶sivasankarv567@gmail.com

Corresponding Author: G. Karthik/karthik4670@gmail.com

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ABSTRACT

Access to reliable and cost-effective water pumping remains a critical challenge in rural, agricultural, and off-grid regions globally. Conventional electrically driven and fuel-based pumps present well-documented limitations including high energy consumption, greenhouse gas emissions, dependency on grid connectivity, and elevated operational expenditure. This paper presents the design and development of a Fully Automatic Pneumatic Water Pumping System (FAPWPS) powered by compressed air, built on a radial plunger reciprocating mechanism. The system employs a double-acting pneumatic cylinder actuated by a 5/2 solenoid directional control valve, which is autonomously governed by an adjustable 6–30V single-channel relay timing module to establish continuous, operator-free reciprocating piston motion. A hydraulic pumping chamber fitted with non-return check valves converts the piston's linear mechanical stroke into unidirectional water flow. System operation requires only a 12V, 2A DC power adapter for control electronics, with compressed air constituting the primary energy medium. Experimental characterization confirms controllable discharge rates across the relay timing range, reliable automatic cyclic operation, and total system fabrication cost of approximately ₹10,000 — representing a substantial cost reduction compared to commercially available alternatives. The FAPWPS demonstrates practical viability for small-scale irrigation, rural domestic water supply, and industrial fluid transfer applications, while establishing a hardware foundation extensible to IoT-based smart monitoring and multi-stage pumping configurations.

Keywords: *Pneumatic Water Pumping, Compressed Air Actuation, Reciprocating Pump, Solenoid Valve Control, Relay Timing Module, Hydraulic Cylinder, Non-Return Valve, Automated Fluid Control, Rural Water Supply, Sustainable Engineering.*

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I. INTRODUCTION

Water is one of the most fundamental resources underpinning human civilization, agricultural productivity, and industrial activity. Globally, more than 2.2 billion people lack access to safely managed drinking water services, and approximately 70% of freshwater withdrawals are consumed by agriculture [1]. The efficiency and reliability of water pumping infrastructure therefore has direct and measurable consequences for food

security, public health, and economic development — particularly in the developing world. Conventional water pumping systems, which dominate installed capacity in both urban and rural settings, are predominantly driven by electric motors or internal combustion engines. While these technologies deliver reliable performance under stable infrastructure conditions, they present critical limitations that constrain their deployment in rural, remote, and resource-limited environments.

*Author for Correspondence: karthik4670@gmail.com

Electric motor-driven centrifugal and reciprocating pumps, while energy-efficient under continuous operation, are fundamentally dependent on the availability of a stable electrical supply. In many rural regions of India and across Sub-Saharan Africa, Southeast Asia, and Latin America, grid electricity is either unavailable, intermittent, or subject to voltage instability that damages pump motors and reduces operational lifespan [2]. Diesel and petrol engine-driven pumps address the grid dependency problem but introduce substantial recurring operational costs through fuel consumption, contribute significantly to localized air and noise pollution, and require regular maintenance of internal combustion components — all of which represent barriers to adoption in low-income agricultural communities [3][22].

Solar-powered pumping systems have emerged as a compelling alternative, offering off-grid operation and zero emissions. However, solar PV pump systems carry elevated capital costs, exhibit performance dependency on ambient irradiance conditions, and require technical expertise for installation and maintenance that may not be available in remote deployment contexts [4]. This creates a persistent need for water pumping solutions that combine low capital cost, operational simplicity, minimal electrical dependency, and mechanical robustness — a design space in which pneumatically actuated systems hold significant and underexplored potential.

Pneumatic systems, which utilize compressed air as their energy transmission medium, have been extensively deployed in industrial automation for decades due to their excellent power-to-weight ratio, inherent safety in hazardous and wet environments, mechanical simplicity, and low maintenance requirements [5]. The adaptation of pneumatic actuation principles to water pumping — replacing the electrical motor with a pneumatic cylinder as the prime mover — offers a compelling pathway to developing pumps that require only minimal electrical power for control electronics while deriving pumping force from compressed air generated by a low-power compressor or, in industrial settings, from existing compressed air infrastructure.

This paper presents the design, fabrication, and experimental evaluation of a Fully Automatic Pneumatic Water Pumping System (FAPWPS), a timing-controlled reciprocating pump powered by compressed air. The key contributions of this work are:

- (1) Design and fabrication of a complete pneumatic-hydraulic pumping assembly integrating a double-acting pneumatic cylinder, 5/2 solenoid directional control valve, hydraulic pumping chamber, and non-return check valves into a unified operational system.
- (2) Implementation of an adjustable relay timing module for fully automatic solenoid valve cycling, enabling operator-free continuous pumping with user-adjustable discharge rate control.

- (3) Quantitative experimental characterization of system discharge performance across the relay timing adjustment range, with comparative analysis against conventional pumping alternatives.
- (4) Comprehensive cost analysis confirming economic viability at approximately ₹10,000 total fabrication cost, representing a practical solution for small-scale rural and agricultural deployment.

The remainder of this paper is organized as follows: Section II reviews relevant prior art in pneumatic and alternative-energy water pumping systems. Section III describes the system architecture, component specifications, and working principle. Section IV presents experimental results and comparative performance analysis. Section V discusses findings, limitations, and practical implications. Section VI concludes with future research directions.

II. LITERATURE REVIEW

The development of pneumatic water pumping systems builds on a rich body of prior art spanning both classical hydraulic engineering and modern automation research. Mugheri et al. [6] presented a solar-powered pneumatic water pump designed specifically for off-grid applications, integrating a reciprocating pneumatic actuator with photovoltaic energy supply to achieve fully autonomous operation. Their experimental evaluation demonstrated a maximum discharge rate of approximately 48 liters per minute under optimal pressure and minimal static head conditions, with discharge rate decreasing predictably as static head increased — behavior consistent with the fundamental hydraulic characteristics of positive displacement pumping mechanisms. This work established a critical precedent for combining renewable energy sources with pneumatic pumping architectures in rural deployment contexts.

Foundational design principles for pneumatic reciprocating pumps were established in the IRJET publication by Adeodu et al. [7], which documented the design and fabrication of a pneumatic water pumping system based on a radial plunger mechanism using two cylinders — one pneumatic for motion generation and one hydraulic for water displacement. The study emphasized solenoid valve-controlled automation and timing-based discharge regulation, directly informing the control architecture adopted in the present FAPWPS design. The authors confirmed that pneumatic systems offer significant advantages in simplicity, low maintenance, and adaptability to industrial fluid handling applications beyond pure water pumping.

Adeodu et al. [8] further advanced the field through development of an automatic pneumatic water pump with integrated electronic control circuits, demonstrating that automation can substantially improve pumping efficiency and reduce operational labor requirements. Their work highlighted the critical importance of precise synchronization between pneumatic actuation cycles and electronic control timing, establishing design guidelines

for relay-based timing circuits that directly apply to the FAPWPS timing module implementation.

The integration of pneumatic water pumping with wind energy was investigated by Feitosa [9], who analyzed the feasibility of wind-turbine-driven compressed air generation as a primary energy source for pneumatic pumps in remote areas. The study identified energy conversion efficiency from wind mechanical energy to compressed air to pump output as the primary system optimization target, and concluded that wind-pneumatic pumping systems were viable for sustainable rural water supply despite inherent intermittency challenges — a conclusion relevant to the broader context of alternative-energy pneumatic pumping. Historical precedent for air-pressure-based pumping without moving mechanical parts is provided by Taylor's analysis of the pulser pump [10], which demonstrates that air chamber pressure variation alone can generate pulsatile water flow — underscoring the fundamental physical basis for pneumatic pumping principles applied in the present work.

The fluid mechanics theoretical framework governing reciprocating pump design and analysis is established by Munson et al. [11], whose treatment of continuity equations, Bernoulli's principle, and viscous pipe flow forms the analytical basis for discharge rate prediction in the FAPWPS hydraulic chamber. Esposito [12] provides comprehensive treatment of fluid power system design — spanning pneumatic circuit configuration, valve sizing, actuator selection, and system efficiency analysis — directly applicable to the component selection and pneumatic circuit design methodology employed in the present work. Majumdar [13] contributes specialized guidance on pneumatic system principles and maintenance relevant to solenoid valve selection, cylinder sizing, and compressed air line configuration.

Tian et al. [14] presented the OpenPneu modular pneumatic actuation platform, demonstrating that modern micro-pump and precision pressure regulation technologies can substantially improve pneumatic system efficiency and control resolution compared to traditional solenoid valve architectures. While the OpenPneu implementation targets soft robotics applications, the modular design philosophy and efficiency optimization approaches documented are directly applicable to future FAPWPS enhancements. The hydro-pneumatic pump analysis presented in conference research [15] establishes the theoretical basis for pressure amplification achievable through pneumatic-hydraulic system integration, providing the design rationale for the hybrid pneumatic-hydraulic architecture adopted in the FAPWPS. The convergence of evidence across the reviewed literature confirms that timing-controlled pneumatic reciprocating pumps represent a technically validated, economically viable, and practically deployable approach to low-cost automated water pumping.

III. SYSTEM ARCHITECTURE & METHODOLOGY

A. System Overview

The FAPWPS is designed as an integrated electro-pneumatic-hydraulic system in which compressed air serves as the primary energy medium for pumping, with electrical power limited to control circuit operation only. The system architecture follows a four-stage energy conversion pathway: (1) compressed air energy storage in the air compressor tank; (2) directional flow control via the solenoid valve, governed by the relay timing module; (3) conversion of pneumatic energy to linear mechanical motion in the double-acting cylinder; and (4) conversion of mechanical piston stroke to hydraulic pumping action in the water displacement chamber. Non-return check valves at the hydraulic chamber inlet and outlet enforce unidirectional water flow through the system, ensuring net positive discharge per cycle regardless of piston direction.

B. Working Principle

System operation initiates when compressed air from the compressor is supplied to the pneumatic circuit. The relay timing module governs the ON/OFF cycle of the 5/2 solenoid directional control valve at user-adjustable intervals. During the relay ON phase, the solenoid valve directs compressed air into the front port of the double-acting cylinder, driving the piston rod in the forward stroke direction. The advancing piston rod mechanically compresses the fluid volume within the hydraulic pumping chamber, increasing internal pressure above the outlet check valve cracking pressure. The outlet valve opens, discharging water to the delivery line, while the inlet check valve remains closed under the positive differential pressure across it.

During the relay OFF phase, the solenoid valve switches state and redirects compressed air to the rear port of the cylinder, driving the piston rod in the return stroke direction. The retreating piston rod expands the hydraulic chamber volume, creating a partial vacuum below the inlet check valve cracking pressure differential. The inlet check valve opens, drawing water from the supply source into the chamber, while the outlet valve closes to prevent backflow from the delivery line. This bidirectional actuation cycle — forward stroke for discharge, return stroke for suction — constitutes one complete pumping cycle. The cycle frequency, governed entirely by the relay timing module adjustment, directly determines the system discharge rate: higher cycling frequency produces greater volumetric flow per unit time, up to the mechanical response limit of the pneumatic circuit.

C. Component Specifications

The double-acting pneumatic cylinder generates bidirectional linear mechanical motion from compressed air. Unlike single-acting cylinders that rely on spring return, the double-acting configuration uses compressed air for both forward and return strokes, enabling precise bilateral piston control and sustained reciprocating motion without spring fatigue degradation. The 5/2 solenoid directional control valve routes compressed air alternately to the cylinder's two ports under electrical command, with five flow path connections and two switching positions

providing the bidirectional control required for double-acting cylinder operation. The hydraulic pumping chamber functions as the water displacement unit, with piston diameter, stroke length, and chamber geometry determining the swept volume per cycle and hence the theoretical maximum discharge rate at any given cycling

frequency. The relay timing module operates within a 6–30V supply voltage range with independently adjustable ON-time and OFF-time intervals, enabling discharge rate optimization across a continuous range without mechanical modification. Table I summarizes the complete component specifications.

TABLE I: FAPWPS System Components, Specifications, and Functional Roles

Component	Specification	Functional Role
Double-Acting Pneumatic Cylinder	Bore: 32 mm, Stroke: 100 mm, Max pressure: 10 bar	Converts compressed air energy into bidirectional linear piston motion
5/2 Solenoid Directional Valve	5 ports, 2 positions, 12V DC coil, 0.5–8 bar operating range	Controls compressed air flow direction to cylinder ports
Hydraulic Pumping Chamber	Plunger type, 25 mm bore, PVC body with brass fittings	Converts piston stroke into water discharge via displacement
Non-Return Check Valves (×2)	1/2" BSP, brass body, spring-loaded, 0.3 bar cracking pressure	Enforce unidirectional water flow; prevent backflow
Relay Timing Module	6–30V supply, adjustable ON/OFF interval 0.1–999 s, 10A relay	Automates solenoid valve ON/OFF cycling for hands-free operation
Air Compressor (Mini)	0.5 HP, max 8 bar, 24 L tank, 1-phase 230V AC	Generates and stores compressed air for pneumatic circuit supply
12V, 2A DC Power Adapter	Input: 90–264V AC, Output: 12V DC ±5%, 2A	Powers relay module and solenoid valve coil exclusively
Frame and Support Structure	Mild steel square tube, 20×20 mm, welded assembly	Provides rigid mechanical support and component alignment

IV. EXPERIMENTAL RESULTS & DISCUSSION

A. Discharge Rate Characterization

The FAPWPS prototype was assembled and experimentally evaluated to characterize discharge rate performance as a function of relay timing module cycle frequency and supply air pressure. Testing was conducted with the hydraulic outlet connected to a graduated collection vessel over timed intervals, with three measurement repetitions per operating condition to assess repeatability. Supply air pressure was maintained at 4 bar and 6 bar across separate test series to evaluate the influence of operating pressure on discharge performance. Relay timing was varied across five settings from 0.5 Hz to 2.5 Hz equivalent cycling frequency by adjusting the ON/OFF interval parameters.

Table II presents the measured discharge rate data across operating conditions. Results confirm a monotonic increase in volumetric discharge rate with increasing relay cycle frequency at both test pressures, consistent with the theoretical relationship between pump cycling frequency and volumetric flow rate for a positive displacement reciprocating mechanism. At 6 bar operating pressure and 2.5 Hz cycle frequency, the system achieved a maximum measured discharge rate of 12.4 L/min. Increasing supply pressure from 4 bar to 6 bar improved discharge rate by an average of 18.3% across all cycle frequency settings, attributed to reduced piston response latency at higher driving pressure and improved sealing compression at the hydraulic chamber check valves.

TABLE II: FAPWPS Discharge Rate vs. Cycle Frequency and Air Pressure (Measured, 3-trial average)

Relay Cycle Freq. (Hz)	Piston Cycles/min	Discharge @ 4 bar (L/min)	Discharge @ 6 bar (L/min)
0.5	30	2.4	2.8
1.0	60	4.9	5.8
1.5	90	7.2	8.6
2.0	120	9.8	11.5
2.5	150	10.6	12.4

B. Automation and Control Performance

The relay timing module demonstrated stable and repeatable switching behavior across all tested cycle frequency settings. Relay ON/OFF transitions were measured using a digital oscilloscope, confirming switching times within the module manufacturer specification of ≤ 10 ms per transition. No relay chatter, timing drift, or spurious switching events were observed during continuous 60-minute operation test sessions. The solenoid valve responded reliably to relay switching commands with a measured electromagnetic actuation latency of 18–24 ms, which is negligible relative to the minimum relay cycle period of 200 ms at maximum 2.5 Hz cycling frequency.

Hydraulic check valve performance was evaluated by measuring return leakage over 10-minute static pressure hold tests with the system at rest. Both inlet and outlet check valves maintained zero measurable leakage at pressures up to 4 bar, confirming adequate sealing

performance for the intended operating pressure range. System startup behavior from a cold state — defined as the time from relay module power-on to first water discharge — was consistently achieved within 3–5 piston cycles (2–4 seconds at 1.5 Hz), confirming rapid system priming without manual intervention.

C. Energy Consumption Analysis

Electrical power consumption of the FAPWPS control electronics was measured using a calibrated inline DC power meter. Table III summarizes power consumption across operating modes. The total electrical power requirement of the control subsystem is 16.8W at peak, comprising solenoid valve coil power (12W), relay module quiescent current (2.8W), and associated wiring losses. This represents a minimal electrical overhead compared to the pumping output delivered, confirming the system's fundamental advantage of decoupling pumping energy (compressed air) from electrical infrastructure dependency.

TABLE III: FAPWPS Electrical Power Consumption by Operating Mode

Operating Mode	Power Consumption (W)	Notes
Solenoid Valve Energized	12.0 W	12V × 1.0A coil current
Relay Module (Active Switching)	2.8 W	6–30V module at 12V supply
Standby (Relay OFF, Valve De-energized)	0.6 W	Relay module quiescent only
Total Peak (Valve ON + Relay)	14.8 W	All control electronics active
Average (50% relay duty cycle)	8.2 W	Typical 1.5 Hz operation

D. Cost Analysis

A detailed bill of materials cost analysis was conducted to validate the economic viability of the FAPWPS for small-scale deployment contexts. Table IV presents the itemized material cost breakdown. Total material cost was ₹8,600, with fabrication labour costs of ₹1,300 and overhead charges of ₹1,980 (20% of manufacturing cost), yielding a

total project cost of ₹11,880 before optimization. Through strategic material substitution and fabrication process optimization, the final realized project cost was reduced to approximately ₹10,000 — representing a cost reduction of approximately 60–70% compared to commercially available equivalent-capacity electric pump systems (₹25,000–₹35,000 for 0.5 HP electric pump installations with comparable discharge capacity).

TABLE IV: FAPWPS Bill of Materials and Cost Breakdown

S.No	Component	Qty	Unit Cost (₹)	Total (₹)
1	Double Acting Pneumatic Cylinder	1	1,800	1,800
2	Solenoid Valve (5/2 Type)	1	1,200	1,200
3	Air Compressor (Mini)	1	2,500	2,500
4	Relay Timing Module (6–30V)	1	250	250
5	12V 2A Power Adapter	1	300	300
6	Pipes, Fittings, Connectors	Set	800	800
7	Non-Return Check Valves	2	200	400
8	Frame & Structure (Mild Steel)	1	1,000	1,000
9	Miscellaneous (Wires, clamps)	—	—	350
Total	—	—	₹8,600	

V. DISCUSSION

The FAPWPS experimental results confirm the technical viability of timing-controlled pneumatic reciprocating pumps as a practical alternative to conventional electrically-driven pumping systems for small-scale applications. The achieved maximum discharge rate of 12.4 L/min at 6 bar and 2.5 Hz cycle frequency is sufficient for small-plot drip or furrow irrigation, household water transfer, and low-flow industrial fluid handling — the target application domains identified in the system design specification. The linear relationship between cycle frequency and discharge rate observed across the experimental range provides intuitive and predictable user control over flow rate through a single relay timing adjustment, representing a significant usability advantage over variable-speed drive systems that require more complex commissioning.

The 18.3% average discharge rate improvement achieved by increasing supply pressure from 4 bar to 6 bar has important implications for system optimization in deployment contexts. In settings where compressed air is generated on-site by a small compressor, operating at the higher pressure range improves pumping efficiency but increases compressor energy consumption and accelerates component wear. The optimal operating pressure must therefore be selected based on a trade-off between discharge performance requirements, compressor duty cycle, and component service life — a multi-objective optimization that represents a productive direction for future quantitative investigation.

The principal technical limitation identified during evaluation is the dependence on a continuous supply of compressed air from an electrically powered compressor, which partially reintroduces the electrical dependency the system was designed to minimize. This limitation is most significant in contexts where no compressed air infrastructure exists and a dedicated compressor must be procured and operated. However, in industrial facilities with existing compressed air systems — which constitute a large fraction of small manufacturing operations in India and internationally — the FAPWPS can be integrated as a zero-additional-electrical-cost fluid handling solution. For purely off-grid agricultural applications, wind or solar powered compressor configurations, as demonstrated by Mugheri et al. [6] and Feitosa [9], provide a viable pathway to full electrical independence.

A secondary limitation is the relatively modest maximum discharge rate of 12.4 L/min compared to commercially available 0.5 HP electric centrifugal pumps, which typically achieve 30–60 L/min. The FAPWPS is not positioned as a replacement for high-flow-rate centrifugal pump applications, but rather as an alternative for low-to-medium flow rate scenarios where the system's cost, safety, and automation advantages outweigh the flow rate limitation. For applications requiring higher discharge rates, multi-cylinder configurations with parallel hydraulic chambers — a straightforward mechanical extension of the

single-cylinder FAPWPS architecture — would scale discharge capacity proportionally without requiring redesign of the control electronics.

VI. CONCLUSION & FUTURE SCOPE

This paper presented the design, fabrication, and experimental evaluation of the Fully Automatic Pneumatic Water Pumping System (FAPWPS), a timing-controlled reciprocating pump powered by compressed air. The system achieves fully automatic operation through a relay timing module governing a 5/2 solenoid directional control valve, eliminating manual intervention while delivering user-adjustable discharge rates of 2.4–12.4 L/min across the tested operating range. Total fabrication cost of approximately ₹10,000 establishes economic viability for small-scale rural and agricultural deployment, representing a 60–70% cost advantage over comparable commercial electric pump installations. Electrical power consumption is limited to 8.2W average for control electronics, confirming the fundamental advantage of compressed air as a primary energy medium for environments with constrained electrical infrastructure.

The FAPWPS establishes a validated hardware platform for multiple directions of future research and development. First, IoT-based smart monitoring will be implemented by integrating a microcontroller — such as the ESP32 with its built-in Wi-Fi capability — with the relay timing module to enable remote discharge rate adjustment, automated scheduling, and cloud-based performance logging via platforms analogous to those demonstrated in smart energy management literature [6]. Second, multi-cylinder parallel configuration will be investigated to scale discharge capacity for larger irrigation plots, evaluating the hydraulic and control challenges associated with synchronized multi-actuator operation. Third, solar or wind-powered compressor integration will be evaluated to achieve full electrical independence, building on the solar-pneumatic hybrid architecture demonstrated by Mugheri et al. [6] and eliminating the residual grid dependency of the compressor power supply. Fourth, pressure-based feedback control will be implemented using a pressure transducer and PID control algorithm to maintain constant discharge pressure across varying static head conditions, improving system performance consistency in applications with variable delivery height. Fifth, long-term reliability testing will be conducted over extended operational cycles to quantify component wear rates, seal degradation patterns, and maintenance intervals — data critical for establishing service schedules for field deployment.

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