RADINKA JOURNAL OF SCIENCE
AND SYSTEMATIC LITERATURE REVIEW

ISSN 2988-5825

https://www.rjupublisher.com/ojs/index.php/RJSLR

Advance Pumping Technologies for Sustainable Bio Energy Systems: A Review of Efficiency Metrics and Integration Strategies

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Abstract

The paper presents a systematic review of the pump technologies in industrial sectors by comparing the data on operational performance and case studies. Three types of pumps were considered, namely, positive displacement (rotary, reciprocating, linear), kinetic (axial flow, centrifugal, submersible), and special (vacuum, jet, peristaltic). The approach included literature review on technical specifications, evaluation of literature on the field performance of the pumps in industrial functions, and comparative evaluation of the pump selection criteria in the industries such as oil and gas, chemical processing, pharmaceuticals, mining, and bioenergy. It has been shown that positive displacement pumps are effective in high-viscosity flows more than 10,000 cP, and screw pumps are the most efficient with 80-95% efficiency covering the widest viscosity (1 to 10^{10} cP). The pressure capacity of reciprocating systems was excellent and plunger pumps were made to a pressure of up to 1,000 bar with low leakage rates of 0.1-0.5%. The most effective pumps were kinetic pumps that were suitable in high flow applications and in the case of axial flow systems that operated on a volume of up to 80,000 L/min. Positive displacement pumps were necessary in the bioenergy processes to transport biomass and digestate and centrifugal pumps to manage biogas condensate in the best way. This analysis results in the development of the evidence-based selection framework that allows operational cost savings of 15-30% due to the increase in the efficiency to the same extent and the achievement of completion of bioenergy process efficiency by 12%. These results give practical recommendations on how to maximize the choice of fluid transport systems in various industrial uses.

Keywords: Bio Energy, kinetic pumps, reciprocating pumps, digestate, sustainable industries

Acknowledgments: Thank you to all parties involved in this research.

For citation:
Perera, H., Hosan, S., Wijesekara, D., Vithanage, V., Abeysinghe, S., Koswattage, K**.** (2026). Advance Pumping Technologies for Sustainable Bio Energy Systems: A Review of Efficiency

Metrics and Integration Strategies. *Radinka Journal of Science and Systematic Literature Review*, *1*(1), 777-799.

Introduction

Pumps are essential mechanical devices employed to transfer fluids. Their overall intent was a combination of the kind of the Hydrodynamic Pumps and Positive Displacement Pumps. The working term and design pattern of these pumps may not be equal in all aspects, but the only similarity of the two has been in the transfer of fluid. The important aspect in selecting a given type of pump is the velocity of fluid and the nature of liquid. Different types of pumps serve different purposes. Dynamic pumps play an incredible role in the capability of producing flow by application of the kinetic energy and the positive type or kind, where fluid volume is must since the same is displaced out in each cycle of fluid flow. The classification is crucial to those engineers and industries, which require the determination of the correct form of the pump depending on characteristics of fluids. Dynamic pumps have found a lot of popularity in the sites where de Folks are required in huge amount and also in low viscosity fluids. Centrifugal pump is one of them which has been used in water supply systems as well as industries. Rotodynamic pump elevates the gyrating energy presented by a spinning endowment to the flow fulness and the position. They are also exceptionally effective regarding dewatering, irrigation, and sewage. Its capacity is 5000 LPH-7000 LPH; they are appropriate to use in domestic coke plant, whereas, they can do domestic coke plant requirement and appropriate coke plant requirement (Li & Chen, 2019). Nonetheless, positive displacement pumps pump a specific amount at a time. Their result is that they are preferable when high viscosity liquids are required and also in situations where one needs their specification when they require a specific flow rate.

Reciprocating pumps (i.e.piston and diaphragm pumps) and rotary pumps (i.e. gear and screw pumps) are included in this category as they also perform well for oil and fuel. Ezekiel Mills is created to provide continuous flow irrespective of the change in pressure. In both technological and economy point of view and also in ease of use in various working conditions the differences that exist between kinetic and positive displacement pumps are highly evident (Terutsuki et al., 2024). In discussing production of commodities or in reference to discussing ecological protection projects that are aimed at protecting other elements geared towards self sustenances it is of the essence that one knows the qualities that tend to be the type of some of the pumps so that the task that is going to be done is done efficiently. Although the pumps have a crucial role in all industrial sectors, the literature on systematic comparative frameworks to unify the operational performance, fluidity and industry related needs are scarce. The available literature has been mainly devoted to particular types of pumps or specific use of pumps in one specific industry, and they did not provide an in-depth cross-sector analysis allowing making evidence-based choices. Such a gap is especially conspicuous in developing industries such as bioenergy, where a wide variety of fluid characteristics such as high viscosity biomass slurry, corrosive digestates, and biogas condensates foment in need of purpose-built pumping technologies that strike the balance between efficiency, durability, and economic feasibility.

These gaps are addressed in the current study by giving systematic comparative analysis of pump technologies in various industrial applications. Although the use of separate pump technologies is long-established, the originality of the given work is seen in the creation of a unified selection system that allows to match the features of pump performance to the needs of a certain industry and, therefore, optimize the efficiency of operations and cost decrease. This model goes beyond the conventional one-parameter campaign of selection to the more intricate and interdependent fluid characteristics, service requirements and economic factors. The research aims will cover a number of dimensions which are interrelated. The first one is that the study will classify and compare the parameters of operational performance related to flow rate, pressure capacity, viscosity handling, and efficiency of positive displacement, kinetic, and specialized technologies of pumps in a systematic manner. Second, it compares criteria of pump selection and performance results in various industrial industries such as oil and gas, chemical processing, pharmaceuticals, mining, and bioenergy in order to determine sector-specific optimization measures. Third, the study determines the best pump-application matching strategies through the fluid characteristics and operational requirements with special focus to demanding applications of working with high-viscosity or corrosive fluids. Fourth, it formulates an evidence-based selection scheme that facilitates cost reduction in operation and efficiency enhancement with interest on the entire bioenergy sector that is expanding. Lastly, the study measures benefits to performance of proper selection of a pump in terms of operational cost savings and gains on a process basis, which are practical measures of making industrial decisions.Such a systematic tool gives engineers and decision-makers valuable actionable pump selection guidelines that take into consideration the complexities of the present day industrial fluid transport system. The framework allows making a sound selection choice and maximizing both the short-term and long-term sustainability goals by incorporating technical performance indicators and economic and operational aspects.

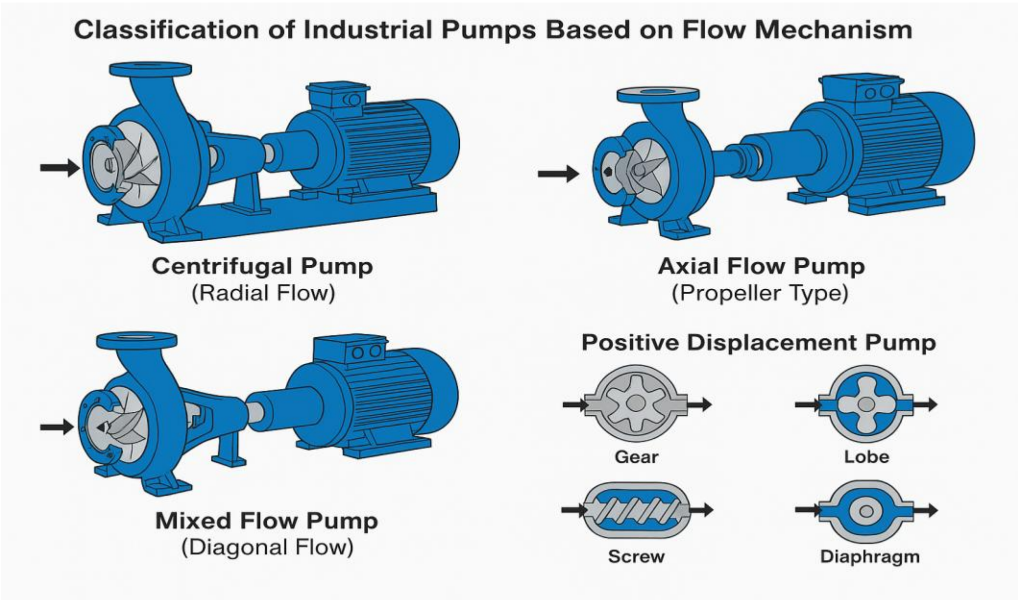


Figure 1. Pump Types

Categorization of Pumps

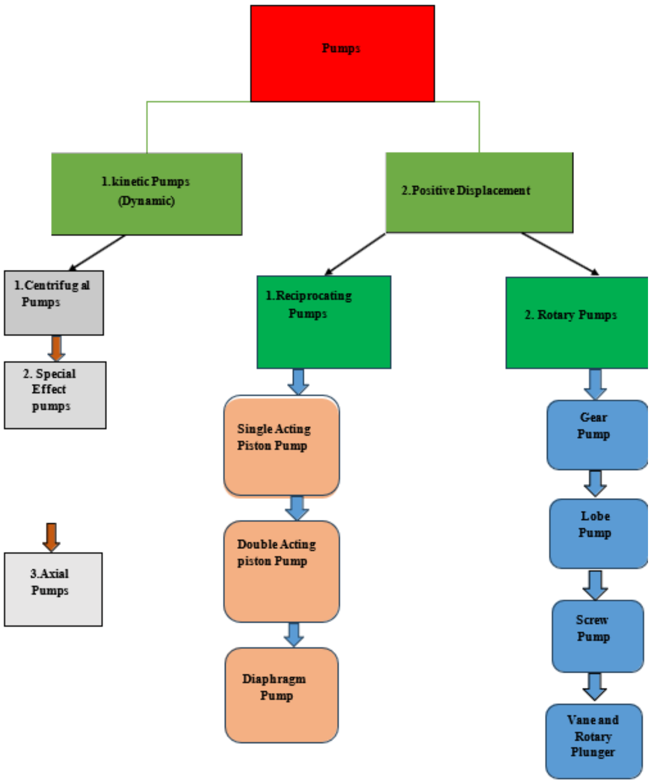


Figure 1. Categorization of pumps

Methodology

Positive Displacement Pumps

Though the PD pump or the positive displacement pump renders it with a quasi-constant flow rate in line with an ascertain constant speed, fluctuation in the counter force. The working principle of the pump is circular which could be driven by screws, pistons, rollers, gears, vanes or even diaphragm. The mechanism of positive displacement pump, in this pump, liquid can be entrapment in a hole so as to empty the specific amount of liquid (Yao et al., 2003). There are only a few very simple components that can be separated during the liquid displacement process namely piston, diaphragm and plunger.

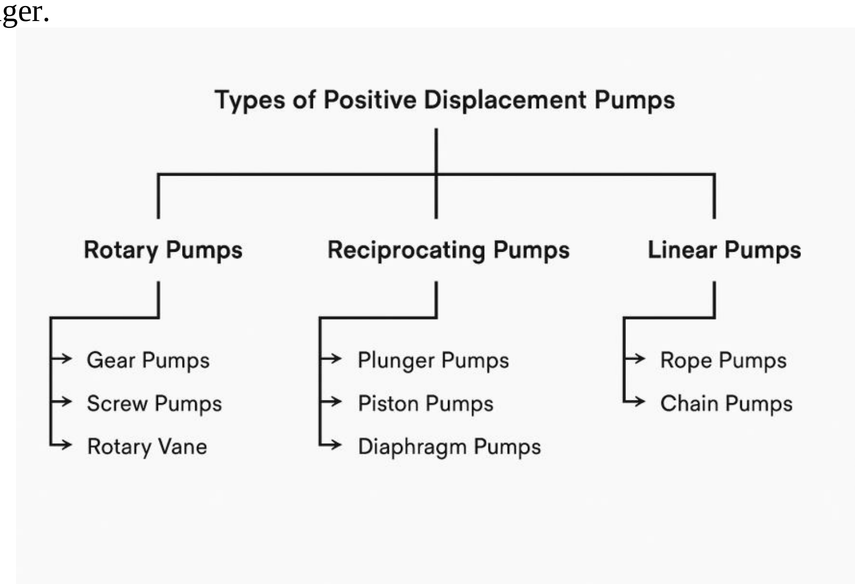


Figure 2. Positive displacement pumps

Rotary Pumps

The rotary pump is just a pump that has a rotary movement in delivering liquid and then it moves towards the discharge pipe and the lake. The common varieties of pumps are screw pump; internal gear, flexible impeller, sliding vane, helical twisted roots and circular pump. They fall into three major categories; gear pumps, screw pumps and rotary vane pumps. In gear pumps, there is geometry allowing the passage of fluid between the two rotating gears. Screw pumps have Two screw form rotor where they turn against each other. and one screws the two up and then it sucks the liquid on the inlet of the pump till the outlet of the pump (Bengtsson & Robinson, 2017). They have rotary vane pumps which resemble the scroll compressor but they contain cylindrical rotor and vanes are placed around it. It is covered within a cylindrical shaped housing. Having turned, the vane on the top of the rotor will trap the source between the rotor and the casing, and the liquid will come through the outlet.

Reciprocating Pump

In the reciprocating pump, the part of the reciprocating hydraulic part permits the flow of the liquid to the forward side in the reservoir. They have reciprocating parts, which are a plunger, piston or a diaphragm, and this type of pumps has some variants of valves, such as inlet valves, outlet valves, and others. In the mode when sucking liquids, the valve goes open and the outlet valve is closed. Therefore, in case of pressing the piston in any direction such that the cavity of the cavity expands then the liquid will get sucked in. (Kline et al., 2005). Types are grouped into three, that is, plunger pumps, piston pumps, and diaphragm pumps. Plunger pumps are chiefly used to move water. The piston pump has an internal piston, the pumping appliance, pumping the liquid. A diaphragm pump is basically a plunger pump except it has a flexible diaphragm to pump the liquid.

Linear Pump

Examples of linear pumps are rope pumps and chain pumps. Linear pumps can't be adjusted in operation. Such kinds of pumps may differ in their being location but their major limitation is the fact that they are volume-based. Such pumps may be very noisy when turned on due to the withdrawal of the piston within the cavity and consequently, they should be placed at a faraway distance to any home. These pumps are categorized to be of two kinds namely rope pump and chain pump. One example of the linear pump is the rope pump, in which a loose hanging rope will be placed in a well and raised using assistance of a long pipe, the ends will be the whole pipe-in-the-water. There are round disks that are in a rope and they will carry the water all the way to the outside. This type of pump is applied primarily to supply water to self and to people within the community (Altemose et al., 2017). The pumps may be fitted in boreholes or hand dug wells. An example of linear pump is the chain pump that consists of a chain carrying a series of circular discs. A portion of the chain is in the air dropped into the water, and the chain goes through a pipe, of slightly less diameter than that of the disc. When the chain is drawn up the pipe then the water becomes caught between the discs and shifts out at the top. Early Middle East China and Europe These pumps have been in use since centuries

Difference between Positive Displacement Pumps and Non-Positive Displacement Pumps

Most of the differences between positive displacement and non-positive displacement pump are pressure, efficiency, viscosity, performance.

Table 1. Difference between positive and non-positive displacement pumps

Parameters	Positive displacement pumps	Non-positive displacement pump

Pressure	These pumps can handle applications requiring high force, up to 800 bars.	These pumps may have a pressure of 18 to 20 bars and are utilized in low force applications.
Efficiency	Increases in pressure will inevitably result in higher efficiency.	At either higher or lower pressure, the efficiency will drop.
Viscosity	Because of the frictional losses in the pump, efficiency will rise as viscosity increases.	Because of the frictional losses in the pump, efficiency will drop as viscosity rises.
Performance	The flow will alter when the pressure changes.	When the pressure changes then the flow will constant

Source. comprehensive reference on pump types, characteristics, and performance

Types of Rotary Pumps, Gear Pumps

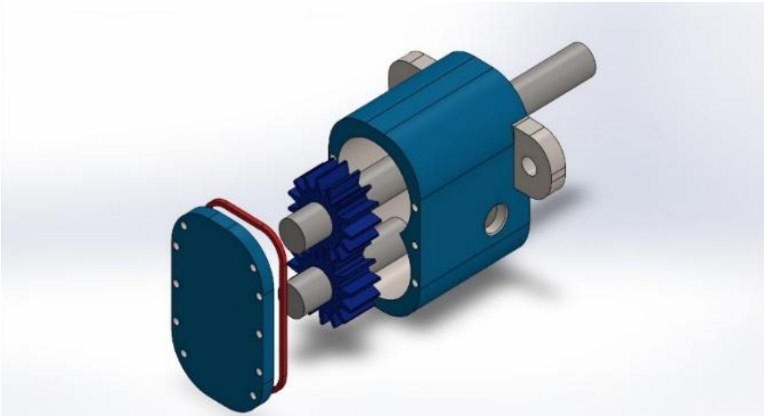


Figure 3. Gear pumps

Gear pumps are rotary positive displacement pumps, although you can also look at them as two rotational gears that spin in the chamber of the pump. These gears rotate in such a way, one pulling the liquid into the pump and then into the discharge line. The rotating gears catch the water lured inside their teeth and pass it further to the pump in the course of the turning. The liquid that has been trapped between gears gets carried along with the gears' rotation until it is ejected through the other side (Zang et al., 2024). In the design of gear pumps, there are of course two categories: the first category is external gear pumps and the second one is internal gear pumps. Pumps with external gears that rotary positive displacement consist of two sprockets, which are fixed on separate drive shafts which could be connected to drive the sprockets. The rotating gears are locked, making an identical fluid move between them from the inlet to the outlet, and thereby to the housing. The pump by internal gear works well with the bigger rotor gear and the smaller inner gear. The idler gear inside the antagonist ring is held by a shaft. In a few designs, both of them are powered, others only the rotor is propelled. Depending on the sense of gear rotation a gear pump may discharge the fluid in one or another direction (Dong et al., 2024). Universal Gear Pumps or internal and external gear pumps are mostly used in chemical factories, oil refineries, and automotive industries dealing with fuel, lubricants, and polymers. The external gear pump is designed in a simple and compact way and its smooth operation of high viscous fluids is a great benefit.

Screw Pumps

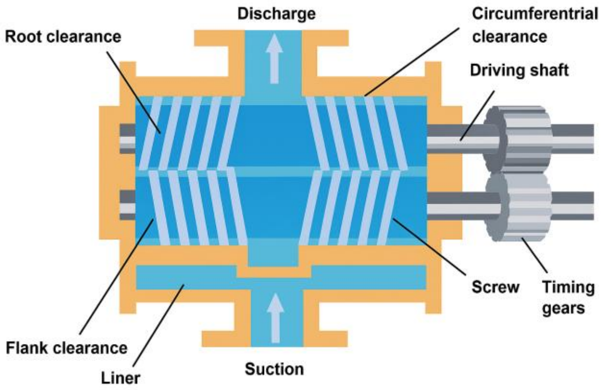


Figure 4. Screw pumps

It utilizes one or several screws that, when rotated, mate closely with a cylindrical cavity. The screws rotate and create cavities, moving the liquid from the inlet to the exit. It is used in applications where smooth, pulsation-free pumping action is useful such as fuel oil transport, hydraulics and in the chemical and food processing industries (Carpita & Sage, 2015). Very high flow rates, low noise output, and ability to handle both high and low viscosity liquids**.**

Lobe Pumps

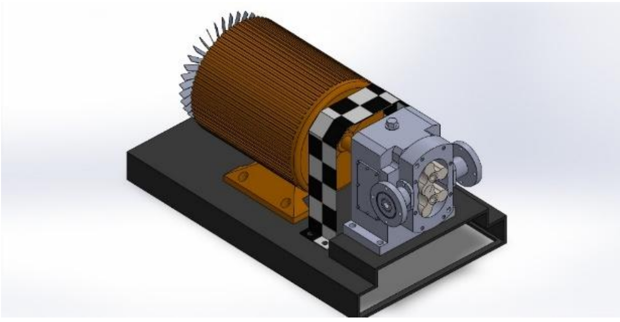


Figure 5. Lobe pumps

Lobe pumps work like gear pumps, but use lobed rotors that rotate against each other with only a small clearance, as opposed to gears. These are non-contacting, so they wear slower than rotary vane pumps. The lobes avoid touch, which reduces damage to pumped fluid and allows gentle handling (Cushman et al., 2015). Owing to their capability to handle larger solids as well as food pastes and pharmaceutical agents, they find use in the pharmaceutical, food and beverage industries. They are able to process solids gently, and are easy to maintain and clean, and can be used in sanitary products.

Vane Pumps

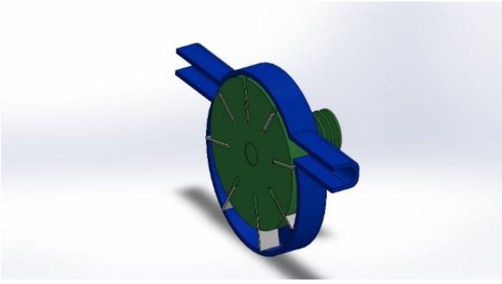


Figure 6. Vane Pumps

Vane pumps utilize several blades which are encased inside a larger cylindrical cavity. Fluid is transported into enclosed spaces as a result of the rotation of a shaft that houses cylindrical blades. In simpler terms, these blades compress fluid within the enclosed encasements and while this happens, the other area gets filled with fluid, and this process continues as the rotor turns. They are used when a steering or brake system automotive or fuel and solvent oiling are required fulfilling mid-pressure applications (Sage & Kubien, 2007). They are efficient under varying operating conditions and pressure even though they experience slight slippage or a general overhaul.

Table 2. The characterization of rotary pumps

Pump Type	Flow Rate (L/min)	Max Pressure (bar)	Viscosity Range (cP)	Efficiency (%)	Noise Level (dB)	Special Features	Applications
Gear Pump	1 – 1,500	5 – 210	10 – 100,000	75 – 90	65 – 80	Compact, good for high-viscosity fluids, bidirectional flow	Lubricants, fuels, polymers, oils (automotive, chemical)
External Gear	5 – 1,000	Up to 200	10 – 50,000	80 – 90	70 – 80	Simple, precise, high-pressure	Fuel injection, hydraulic systems
Internal Gear	1 – 1,200	Up to 150	100 – 100,000	75 – 85	65 – 75	Smooth flow, self-priming	Food-grade oils, viscous fluids
Screw Pump	50 – 4,000	10 – 150	1 – 1,000,000	80 – 95	50 – 65	Pulsation-free, quiet, wide viscosity range	Oil transport, chemical dosing, hydraulic and marine systems
Lobe Pump	10 – 3,000	5 – 80	10 – 1,000,000	70 – 85	55 – 75	Gentle on solids, CIP/SIP capable, hygienic	Pharmaceuticals, dairy, cosmetics, fruit pulps
Vane Pump	1 – 800	4 – 14	1 – 5,000	70 – 85	60 – 75	Variable displacement, mid-pressure, self-adjusting vanes	Automotive power steering, fuel transfer, solvent delivery

Source. Centrifugal and Rotary Pumps: Fundamentals with Applications

The different industrial demands on the various positive displacement pumps vary with the flow rate, pressure capacity, fluid viscosity, efficiency and noise that the pumps can bear(Simas-Rodrigues et al., 2015). Gear pumps operate within the flow range of 1 1,500 L/min and their pressure can go up to 210 bar, and they have the viscosity of 10 100,000 cP, and their well 75 - 90% and their noise is moderate 65-80%. External gear pumps have a flow rate of 5-1,000 L/min, efficiency of 8090 per cent, a viscosity of up to 50,000 cP and can achieve pressures up to 200 bar, are simple and can be highly precise in high pressures. Internal gear pumps handle 1-1,200L/min with up to 150 bars, intended when higher viscosity is needed and at much lower noise 65-75 dB. Screw pumps excel in quiet, pulsation-free delivery only 50–65 dB, with a wide flow capacity 50–4,000 L/min, pressure tolerance up to 150 bar, and handling viscosities up to 1,000,000 cP, delivering high efficiency (80–95%).Lobe pumps, used in hygienic areas, accommodate flows of 10-3,000 L/min, can reach on to 80 bar, and exhibit very high viscosities, above 100,000 centipoise, but with 70-85% efficiency and 55-75 dB noise (Yuan & Li, 2020). Vane pumps, often used in automotive systems, offer flow rates of 1–800 L/min, pressures of 4–14 bar, and viscosity handling between 1–5,000 cP, with efficiency of 70–85% and moderate noise (60–75 dB) (Tsogtbaatar et al., 2015).

Types of Reciprocating Pumps

A positive reciprocating pump operates by back-forward mechanism of pistons, plungers or diaphragms. This is called reciprocation. The first stroke creates a vacuum, which opens the outlet valve and shuts the inlet. The reverse stroke puts pressure on the fluid closing the inlet valve and opening the outlet. This lets the fluid leave the chamber.

a. Suction Phase: In this phase, the piston or plunger pulls back. This makes the cylinder bigger and lowers the pressure of the fluid inside a partial vacuum form. Because of this, fluid from the reservoir flows into the cylinder through the pump's inlet valve. The pressure from the atmosphere or upstream pushing on the fluid.
b. Discharge Phase: Next, the piston or plunger pushes forward. This shrinks the cylinder and ramps up the pressure. The high pressure then forces the fluid out through the discharge valve and into the delivery pipe.

Piston Pump

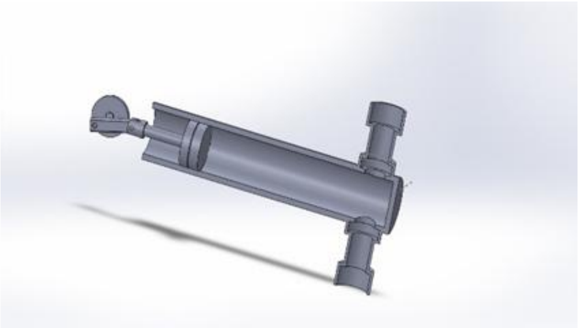


Figure 7: Piston pumps

A piston pump has a mechanical construction with pistons running in cylinders with valves for the inlet and outlet. When sucked up, the piston expands the pump chamber. Pressure will go down as you do this, and the cylinder hose of the piston pump opens up so fluid will flow through your intake. The piston pushes the fluid onto the cylinder and pushes the cylinder up when the pump is running (McCann & Carpita, 2015). Suction valves shut, then the release valve opens, pulling the water out. The piston pump is the usual one in agriculture, water treatment and industrial processes. A piston pump can be used with big volumes and fluid viscosity.

Plunger Pump

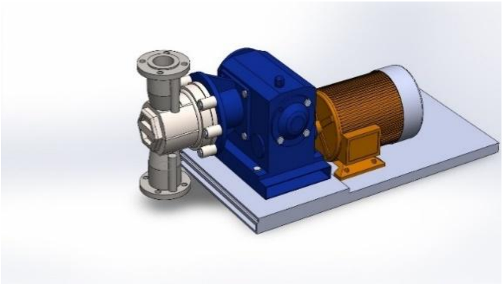
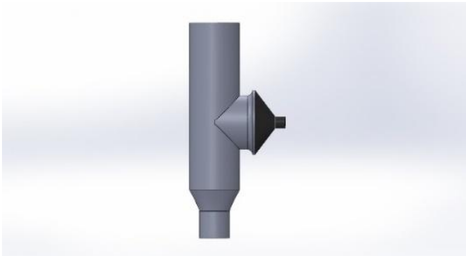


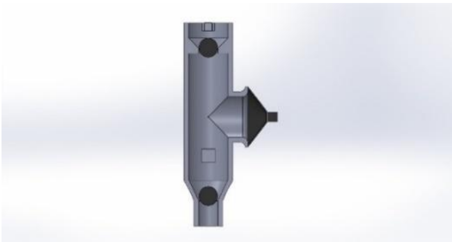
Figure 8. Plunger pump

A plunger pump is based on the same logic as piston pumps except in different forms. Plunger pumps work at high pressure and maximum flow because the plunger pump seal is very strong. These reciprocating pumps are used for all sorts of essential pumping functions, such as high- pressure water jetting and cleaning. The plunger pump is the earliest reciprocating pump currently on the market (Haberl et al., 2010). It is great for high pressure oil and gas production, pressure cleaning and dewatering. Advantages are pressure-rated, tough and effective without lealages.

Diaphragm pump



(a)



(b)

Figure 9. Diaphragm pumps

A diaphragm pump also known as membrane pump works on a principle of a flexible diaphragm that contracts and expands in order to change the volume of a chamber. This results in a vacuum that sucks the fluid into the pump through an inlet valve. When the diaphragm expands, it increases the chamber volume and reduces pressure thereby forcing the fluid out through the outlet valve. The diaphragm's cyclical movement, which is mechanically activated by a crank or motor or pneumatically activated by compressed air, makes sure that the fluid is moved constantly with every stroke(Krausmann et al., 2008). This is because the diaphragm and the pump body of diaphragm pumps can be made of materials that are not easily affected by chemicals hence suitable for handling chemical substances that are dangerous or that can cause corrosion. Furthermore, it is important to note that air operated diaphragm pumps are also capable of handling range a of wide fluid viscosity. Also, these pumps are preferred in applications where the pump environment is to be sealed to avoid mixing of fluids. This is because diaphragm pump is highly suitable in industries such as chemical industry, pharmaceuticals and water treatment. Diaphragm pumps are commonly utilized to transfer dangerous and aggressive fluids, thus isolating such fluids from the pumping elements. A Diaphragm pump is a positive displacement pump that offers zero leakage during operation, is capable of handling slurry and chemical fluids and is gentle on mixtures that are prone to separation (Mohammadi et al., 2017).

Table 3. The characterization of reciprocating pumps

Feature	Piston Pump	Plunger Pump	Diaphragm Pump
Pressure Handling	Medium	High	Low to medium
Seal Type	Moving with piston	Stationary (stronger)	Flexible diaphragm
Fluid Compatibility	Viscous fluids	Clean fluids (non-slurry)	Aggressive & slurry fluids
Leakage	Possible	Minimal	Zero
Application Examples	Irrigation, water use	Oil & gas, jet cleaning	Chemicals, pharma, slurry

Source. Fluid Power Engineering

Table 4. The mathematical characterization

Parameter	Piston Pump	Plunger Pump	Diaphragm Pump
Max Flow Rate (L/min)	50 – 500	10 – 1000	5 – 400
Max Discharge Pressure (bar)	20 – 100	100 – 1000	7 – 20
Suction Lift (m)	3 – 7	3 – 9	3 – 8
Viscosity Handling (cP)	Up to 10,000	Up to 500	Up to 50,000
Pump Efficiency (%)	80 – 90	85 – 95	60 – 85
Leakage Rate (%)	0.5 – 1.5	0.1 – 0.5	0 (fully sealed system)
Typical Stroke Rate (strokes/min)	30 – 100	20 – 80	20 – 300
Fluid Temperature Range (°C)	5 – 90	5 – 150	-10 – 120
Solids Handling Capacity (%)	≤ 2%	≤ 1%	≤ 10%
Material Compatibility	Moderate (stainless steel)	High (hardened steel, ceramics)	Very high (Teflon, EPDM, Viton)
Noise Level (dB)	70 – 80	75 – 85	60 – 75

Source. Fluid Power Engineering

Piston pumps, plunger pumps and diaphragm pumps have found appliances in metering, dosing and transfer applications with individually different performance properties. Piston pumps provide moderate flow rates (50–500 L/min) and discharge pressures up to 100 bar, with viscosity handling up to 10,000 cP, 80–90% efficiency, and leakage rates of 0.5–1.5% (Shrestha et al., 2024). They run 30 -100 stokes/minute, have a fluid temperature range of 5- 90 degrees and can handle solids up to 2 percent with moderate compatibility of materials generally constructed of stainless steel. Plunger pumps find use in high pressure where they can deliver up to 1,000 bars, at a flow rate range of 10 L/min and 1,000L/min, tolerating high viscosity up to 500 cP and are highly efficient between 85-95%with a low leakage rate 0.1-0.5%. They run at lower stroke frequencies 20-80 strokes/min and are able to operate at higher temperatures 5-150 C degrees and can process solids up to 1 percent and are constructed of very long-life materials namely hardened steel and ceramics. By contrast, diaphragm pumps have a completely closed system with no leakage and is suitable to pump highly viscous fluids to 50 000 cP and up to 10% solids with less pressure 720 bar and flow rates of 5400

L/min they are 60 85% efficient with quick strokes 20300 strokes/min and have high chemical compatibility due to materials such as Teflon, EPDM and Viton. with their smaller noise 60--75 dB complaint and their capability to take corrosive and abrasive fluids; they are preeminent in the transferring of slurry and chemical processing worlds (Patil et al., 2024). The different pump types have trade-offs between pressures, flow, leakage and chemical compatibility that reduce or determine their best use.

Table 5. Industrial Application Of Positive Displacement Pumps

Industry	Fluid Type	Viscosity (η)	Flow Rate (Q)	Pressure (P)	Special Consideration
Oil & Gas	Crude Oil	High (η_1)	Moderate (Q_1)	High (P_1)	Flow accuracy critical; handles high viscosity
Chemical Processing	Corrosive Chemicals	Medium–High (η_2)	Constant (Q_2)	Varying (P_2)	Corrosion resistance and leak-proof operation
Mining	Slurry / Ore Fluids	High (η_3)	High (Q_3)	High (P_3)	Harsh environment; durability is key
Pulp and paper	Pulp Slurry	Medium–High (η_4)	Precise (Q_4)	Moderate (P_4)	Flow consistency affects paper quality
Marine	Bilge Water / Fuel / Oil	Low–Medium (η_5)	Moderate (Q_5)	Moderate (P_5)	Operates in dynamic/unstable sea conditions
Automotive Manufacturing	Lubricants / Coolants	Low–Medium (η_6)	Precise (Q_6)	Low–Medium (P_6)	High precision needed in assembly lines
Textile	Dyes / Chemicals / Water	Low–Medium (η_7)	Variable (Q_7)	Moderate (P_7)	Dosing accuracy; minor fluctuations possible
Pharmaceuticals	API / Solvents / Fluids	Low (η_8)	Very Precise (Q_8)	Low (P_8)	Requires hygienic and sterile pumping
Wastewater Treatment	Sludge / Thick Fluids	Very High (η_9)	Moderate (Q_9)	Moderate–High(P_9)	Failure leads to environmental risk
Agriculture	Water / Agri-Chemicals	Low–Medium (η_{10})	High (Q_{10})	Low (P_{10})	Requires coverage over large areas

Source. Fluid Power with Applications

Results and Discussion

Kinetic Pumps

A dynamic pump delivers kinetic energy to the working fluid via the action of either axial or centrifugal forces. This process transforms that energy into an increase in pressure or flow rate. Dynamic pumps stand out especially due to the fact that their operation is premised on the principles of dynamism which is kinetic energy. One should however, know that these pumps mainly make use of centrifugal force to propel motion of the fluid. Although dynamic pumps work well, they work best in cases where there is a need to have a continuous flow rate and this makes them to be very useful in most of the industrial processes (Dincer & Acar, 2015). This is the difference between a dynamic pump and a positive displacement pump. In a dynamic pump, use of a rotating impeller to generate the cavity, while a positive displacement pump uses a reciprocating part to create the cavity.

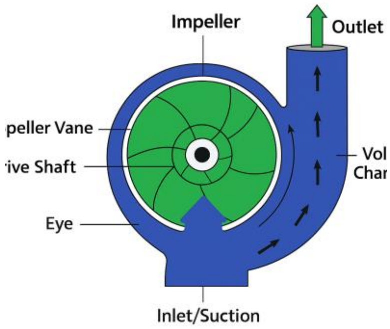


Figure 10**.** Kinetic pump

The number of rotatory parts is lower in dynamic pumps than positive displacement pumps. They weigh less than the PD pumps. Most common examples of dynamic pump are a centrifugal pump and a submersible pump. Dynamic pump is a category of pump where centrifugal force is used to lift a fluid from a particular area towards another area. The source for this centrifugal force is a rotating part. Due to the centrifugal pump impeller, a stream of high-velocity fluid is created (Mangoyana & Smith, 2011). This particular pure fluid then mechanically dilutes the fluids adjacent to the pump or casing while reacting with it. Following this process, when the outlet valve is opened, fluid can flow out to the required area.

Axial Flow Pump

Figure 11. Axial flow pump

An axial flow pump is categorized as a centrifugal pump where the inlet and outlet are in the same line as impeller shaft and this kind if pump does not have a suction that is perpendicular to the impeller. An axial flow pump does not change the direction of the fluid’s flow. It is equipped with an Impeller mounted in a cylinder. The impeller has three to four blades attached. The angle of all the blades mounted on the Impeller is like that the water comes out the pump axially along the rotation of the impeller and not out perpendicular to the rotation of the impeller (Yue et al., 2014). In many configurations, the flow and head can be varied by varying the pitch of the impeller blades. These are dynamic pumps capable of discharging high quantities of flows, sometimes reaching to the tens or even hundreds of thousands of gallons in the minute's figure. Sometimes it is known as a propeller pump because of the resemblance of the axial impeller to a ship's propeller Rather than axial pumps, it is the centrifugal ones that are used mostly in applications requiring low flow rates and high heads, including the nuclear industry. In projects demanding pumping large amounts of water or low-pressure increase, over eight times the number of axial pumps will be employed.

Centrifugal Pump

Centrifugal pumps use centrifugal force to move liquids. They are powered by electric motors or engines that provide mechanical energy. In effect, the centrifugal pump uses a centrifugal force to pump fluids, hence its name. There are many centrifugal pumps uses including being the hydraulic device that raises the pressure of liquids, blood, and air. They are widely adopted in many industries and even common pumps in households because they can be operated with low force. Centrifugal pumps, sump pumps, and positive displacement pumps are three common centrifugal pump types (Maraver et al., 2013). They have centrifugal force and centrifugal direction which allows effective pumping and flow of fluids. In steamships and submarines, similar pumps were also employed as part of onboard machinery. However, they were purposely built to lift mud. These pumps have a cost advantage compared to positive displacement pumps. It can transfer low viscous liquids and chemicals efficiently. Besides, it has a brilliant design and works on a simple mechanism making it an easy to operate and maintain pump. And the best part about them is that there is no heat transfer concerns or leakage. These pumps have no power loss.

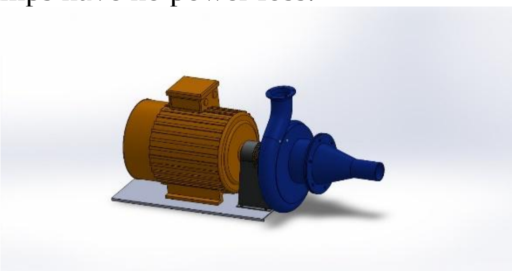


Figure 12. Centrifugal pump

Submersible Pump

A submersible pump is a mechanical device that works by pushing the water toward the surface instead of pulling it. It has a hermetically sealed motor connected to the pump body that helps in pushing the fluid toward the surface. These types of dynamic pumps are most usually used for slurry pumping, general industrial pumping, sewage pumping, septic tank pumping, and drainage (Zou & He, 2018).

Figure 13. submersible pump

Hydrant System

A hydrant system is a source of water that feeds into the building through a network of nozzles, pipes, and hydrants with enough pressure to deliver water for firefighting applications. This pump is installed with a series of pipes connected directly to the key water supply, supplying water at each hydrant outlet during emergencies. Each hydrant pump has several discharge valves that you can connect to a fire hose. It is a hydrant system assisting firefighters during the fire suppression process (Bartolozzi et al., 2017). The hydrant system enhances the ability of firefighters in controlling fires within the construction site it has been placed.

Figure 14. Hydrant system

Table 6. The characterization of kinetic pumps

Pump Type	Flow Rate (L/min)	Head (m)	Pressure (bar)	Efficiency (%)	Viscosity Range (cP)	Max Temperature (°C)	Typical Applications
Axial Flow Pump	5,000 – 80,000	1 – 15	0.1 – 1.5	60 – 75	< 100	60 – 90	Flood control, irrigation, cooling water circulation
Centrifugal Pump	20 – 30,000	5 – 150	0.5 – 15	70 – 90	< 500	40 – 120	Water supply, HVAC, chemical transfer
Vertical Centrifugal	100 – 15,000	10 – 150	1 – 15	70 – 88	< 400	60 – 150	Sump systems, boiler feed, high-temp water
Horizontal Centrifugal	50 – 25,000	5 – 120	0.8 – 12	75 – 90	< 400	40 – 100	Industrial fluid transfer, cooling systems
Submersible Pump	200 – 15,000	10 – 60	1 – 6	60 – 85	< 1500 (with slurry)	40 – 80	Drainage, sewage, slurry, borehole

							water pumping
Hydrant System Pump	900 – 3,000 (per outlet)	15 – 60	4 – 10	65 – 85	Water only	Ambient temperature	Fire protection and emergency water supply

Source. Fluid Machinery: Performance, Analysis, and Design

Various types of dynamic pumps find wide variety of industrial and utility applications depending on the nature of operation and hydraulic features. Axial flow pumps offer extremely high flow rates (5,000–80,000 L/min) at very low heads (1–15 m) and pressures (0.1–1.5 bar), with moderate efficiency (60–75%) and low viscosity handling (< 100 cP), making them ideal for flood control, irrigation, and cooling water circulation. The centrifugal pump is the most frequently used dynamic pump with a possible range of flow rates of 20-30,000L/min, heads as high as 150m and a pressure as much as 15 bar, a fluid efficiency of 70-90 % at fluids with a viscosity of below 500 cP and a heat content of 40-120 o C (Alqahtani et al., 2024). Vertical centrifugal pumps fall within this category and find application in sump system, boiler feed and able to handle high temperature water, a head of up to 150m and a temperature of up to 150 o C with a flow range of 100-15000 gallons per minute. Horizontal centrifugal pumps, with slightly better efficiency (75–90%), are preferred for industrial fluid transfer and cooling, with flow rates of 50–25,000 L/min and pressure capabilities up to 12 bar. submersible pumps are designed to handle dirty or slurry-laden fluids, supporting flow rates of 200–15,000 L/min, heads of 10–60 m, and viscosities up to 1,500 cP, functioning efficiently (60–85%) in submerged conditions at temperatures between 40–80°C. Lastly, hydrant system pumps are specialized for fire protection, delivering 900–3,000 L/min per outlet, pressures of 4–10 bar, and moderate efficiency (65–85%) for clean water at ambient temperature (Hashemian & Noorpoor, 2023). These pumps are chosen in regard to the head, flow rate required, temperature tolerance and so on, so that they are optimizable in regard to the intended use.

Other Type of Pumps, Vacuum Pump

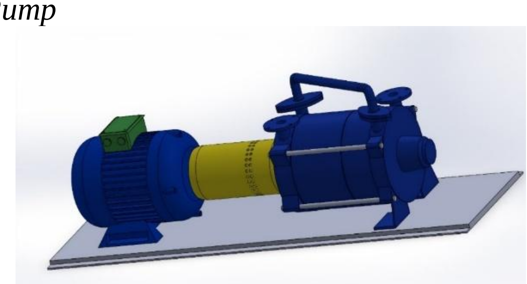


Figure 15. Vacuum Pumps

The basic principle of the vacuum pump is to take air and other gases out of the sealed area to create a vacuum. They use several modes of operation to include positive displacement, momentum transfer, and entrapment. One common type, the rotary vane pump, uses rotating vanes to create a partial vacuum by drawing in and expelling gas from a chamber. The vacuum created is of low pressure since the gas is being extracted. The applications of vacuum pumps vary from manufacturing, research, and medicine to aerodynamics. They are important in activities related to the manufacturing of semiconductors, distillation of chemicals and sterilization of medical equipment(Ivchenko et al., 2023). Vacuum pumps are used in research to conduct experiments in material science, chemistry and physics; in the space, the pump is used to recreate the conditions of outer space. Vacuum pumps are the unrecognized heroes, which have defined most industries and brought many discoveries that have transformed different fields. Their role towards keeping controlled conditions and generating vacuum conditions is priceless in the current context of science and technology. From laboratory to manufacturing plant and into space, vacuum pumps are the quiet powerhouses driving the art of innovation (Abidov et al., 2023).

Jet Pump

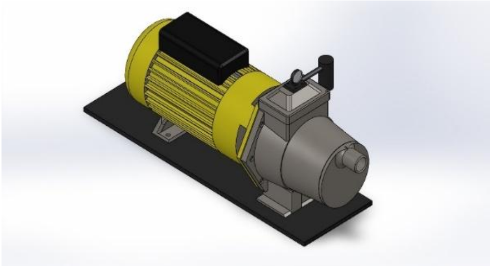


Figure 16**.** Jet pump

Jet pumps are designed based on a principle of fluid entrainment. They consist of a nozzle that forces a high-velocity jet of the fluid into a venturi tube. This high-speed jet creates a low- pressure zone within the venturi that in turn draws in a secondary fluid-usually the one to be pumped. The combined mixture of motive and secondary fluid is discharged next, allowing the secondary fluid to be conveyed to its destination Jet pumps can be utilized in various industries that range from agriculture, oil and gas, water supply, and wastewater treatment. They serve their purpose especially in lift applications of fluids from deep wells or in the movement of liquids that contain solids or of those having high viscosity. Jet pumps are also used in steam ejectors and aircraft fuel systems.

Peristaltic Pumps

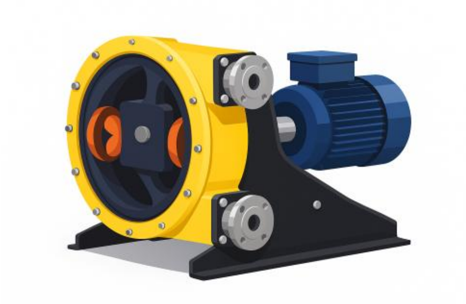


Figure 17. Peristaltic Pumps

Peristaltic pumps work on a very simple principle indeed. Inside the pump casing, there is a flexible tube, usually made of rubber or silicone. With rollers or shoes compressing and relaxing the tube in sequence, a series of "peristaltic" waves is created, pushing the fluid inside the tube forward. This has the effect of "milking" the fluid through the tube and provides a pulse-free and extremely accurate flow. Peristaltic pumps have quite a wide range of uses, from pharmaceutical to food/beverage to wastewater to laboratory applications, among others (Lavrič et al., 2024). They are especially valued when contamination may be problematic, as the fluid never actually leaves the confines of the tube and therefore does not come into contact with pump components.

Table 7. Various Industrial Pump Types Comparison

Pump Type	Flow Rate (L/min)	Vacuum / Pressure Range	Efficiency (%)	Fluid Viscosity (cP)	Typical Applications	Special Feature
Vacuum Pump	10 – 5,000	Vacuum: 10^{-1} to 10^{-6} mbar	50 – 80	Air/gas only	Semiconductor, medical sterilization, distillation, space research	Creates low to ultra-high vacuum
Jet Pump	50 – 3,000	Suction Head: Up to 60 m	30 – 60	Up to 5,000	Oil & gas, agriculture, deep well lifting, steam ejectors	No moving parts in contact with fluid
Peristaltic Pump	0.1 – 500	Discharge Pressure: 2 – 16 bar	50 – 90	Up to 100,000	Pharmaceuticals, food & beverage, lab dosing, wastewater	Zero contamina tion, ideal for sterile fluids

Source. Vacuum Technology and Applications

When applied to specialized fluid movement, there are different operating profiles of the vacuum, jet and peristaltic pumps. Vacuum pumps with a flow rate between 10 and 5,000 1/min and a vacuum level of 10 -1 to 10 -6 1/mbar have moderate efficiencies of 50 to 80 per cent. Their use is confined to air/gas media e.g. semiconductor production and space research. Jet pumps can produce a maximum of 60 m of suction, have a flow capacity of as low as 50 and as high as 3,000 L/min and will pump fluids as viscous as 5,000 c P. Their important benefit is that they have no moving parts that have to come into contact with the fluid and their range of efficiency is 30 to 60 percent, which is less, but they are ideal to induce deep well lifting and in erosive environments. In contrast, peristaltic pumps handle low to moderate flow rates (0.1–500 L/min) at discharge pressures of 2–16 bar, and can manage highly viscous fluids up to 100,000 cP (Lee & Lee, 2013). These pumps have a high performance of 50-90 percent and are particularly appreciated in the pharmaceutical and food-grade applications because of the fact that they have no contamination.

Application in Bioenergy Industry

The efficient use of fluids in forms of different pumping technologies is thus very important in bioenergy production. Their importance in transportation of biomass feedstocks, biogas and digestate at different stages of the production process cannot be overestimated, they help make the process productive and efficient. These pumps are also used in the bioenergy sector, and more particularly the anaerobic digestion systems, positive displacement. These pumps work by trapping a fixed amount liquid and forcing it through the discharge pipe. This mechanism has the advantage of dealing with high solid contents normally encountered in most feedstocks in biogas production. Hence, it is quite ideal for mixing and transferring thick slurry without loss of efficiency. Centrifugal pumps are among the common ones applied in the bioenergy industry, especially when handling low-viscosity fluids such as digested slurry or biogas condensate. These pumps. Utilize a rotating impeller to create a flow of fluid and can therefore be used very effectively to transfer liquids over long distances or high heads. Since it is able to handle variable flow rates, they have wide applications at different bioenergy production stages.

Biomass Transport

Pumps play very important roles in transferring feedstocks in most biomass conversion processes. Such as agricultural residues and algae to preprocessing facilities. Liquid–solid extraction methods often require the movement of slurries, where positive displacement pumps excel in conditions where flow rates need to be maintained irrespective of viscosity variation and solids content.

Biogas Production

Anaerobic digestion requires reliable pumping solutions for mixing organic materials to provide consistent digestion conditions throughout. High solid content in feedstock does introduce some challenges in fluid management, and therefore ups the ante for efficient mixing and pumping solutions. Besides, pumps are rather important in transferring the biogas, produced by decomposition of organic material, either into storage or for subsequent Processing into fuels such as Compressed Natural Gas and Liquefied Natural Gas (Petrochenkov et al., 2023).

Digestate Management

The digestate leftover after anaerobic digestion may be challenging to manage. Due to its high nutritional value and viscosity. Pumps are used to circulate this material for further treatment, application as fertilizers, or conversion to other useful products. Efficient pumping solutions support the optimal recovery of resources. from the digestate, hence increasing the general Smart pumps represent a disruptive movement in pump technology since the incorporation of sensors and IoT allows for real-time monitoring and analytics. These usually vain pumps use sensors that constantly monitor critical parameters such as pressure, temperature, flow rate, and vibration. The information not only optimizes performance but also yields maintenance that is predictive in nature, whereby operators can stay ahead and avoid failures. Thi is reduces downtime and operational costs. The possibility of monitoring and operating pumps remotely improves efficiency, especially for the bioenergy industry with complex processes that may also be geographically spread out. With the increasing drive for sustainability, the pump industry is aligning itself with environmental goals in terms of the development of energy-efficient designs. Modern pumps are also being manufactured as variable speed drives and energy optimized motors which consume minimum energy and maximize output. Such energy efficiency initiative is a major concern of the bioenergy sector whose operation cost and green effects should be reduced. Bioenergy production utilizes a range of specific pump requirements that have necessitated designing equipment to run at suboptimal levels. Such specialized pumps are important in providing performance in the application where standard pump failures could occur easily, being specially designed with strong materials and modern designing principles. The nature of their construction makes them resistant enough to manage the challenges resulting from the peculiarity presented by the bioproducts, different viscosities and corrosive materials. Case studies of advanced biofuel technologies in countries like Germany, Sweden, and Canada reveal considerable advances in developing and scaling up production technologies for advanced and emerging biofuels. These case studies provide insight into not just the successes of successful implementation but also those deficiencies and challenges faced during the commercial development of these technologies. The selected examples chosen were selected based on the expertise of the participating members and the maturity of the technologies with a minimum Technology Readiness Level - TRL 7 (Ruby, 2015). The economic viability of the use of pumps in bioenergy production is evidenced by the increasing investments in processes that mobilize and convert waste into usable energy. Policies of the European Union have been instrumental in driving the percentage of waste- derived biofuels, particularly in Nordic countries, which have enacted even more stringent requirements than those agreed on at the EU level Despite the progress, only a small fraction of the available waste resources is tapped; hence, there is great potential for further development Pilot projects on advanced biofuels are being very promising. However, scalability remains a major obstacle to adoption. Scalability in project development is crucial in an effort to make at least an impression on the overall energy market republic and private investment is also vital towards stirring innovation over financial restrictions.to commercialization. One also needs to consider sustainable practices that ensure biofuels production is in line with long-term environmental objectives.

Table 8. Pumps function in bioenergy production

Stage	Pump Type	Fluid	Viscosity (η)	Flow Rate (Q)	Head/ Pressure (H or P)	Primary Function	Special Features / Notes
Biomass Trans	Positive Displa cement	Slurries /Algae Agricultural \	High (η_1)	Controlled (Q_1)	Mode rate (P_1)	Transfer of high-solid biomassto prepro-cessing	Handles viscosity solids; maintains stability
Biogas Production	Positive Displacement	Organic slurry / solids	High (η_2)	Stable (Q_2)	High (P_2)	Mixing feedstock; transport tostorage processing	Ideal for feed; efficiency crucial for consistent digestion
Biogas Production	Centrifugal	Biogas condensate digestate	Low (η_3)	Variable (Q_3)	High (H_1)	Liquid Transfer over long distances	Suitable variable rates; distance transfer
Digestate Management	Positive Displacement	Digestate nutrient slurry)	High (η_4)	Moderate (Q_4)	Medium (P_4)	Circulation, transfer, resource recovery	Viscosity resistance; enhances sustaina bility
Monitoring Control	Smart IoT-e Pumps	All (monitored systems)	Variable (η)	Variable (Q)	Variable (P)	Real-time analytics, predictive maintenance	Sensors pressure, flow, vibration
Energy Efficiency	Variable Pumps	Any	Any	Adjustable (Q_5)	Adju stable (P_5)	Reduce energy consumptio during off-peak loads	Eco-aligned design; efficiency-tuned motors
Harsh Environments	Specialized Custom Pumps	Biogas Corrosive Liquids	Varies (η_6)	Applicatior -based	High (P_6)	Resistant design for corrosive and abrasive biofluids	TRL 7+ advanced biofuel (Germany, Sweden, Canada)

Source. Biogas production: Current state and perspectives.

Conclusion

The most important way to improve the technical, economic and environmental performance of bioenergy systems is to optimize pump selection. The positive displacement pumps superior high-viscosity materials, with solid-containing substrates, and are required to allow stable anaerobic digestion, and kinetic pumps can be used to transfer mass volumes at a less expensive quotient. New developments like IoT-based tracking, variable speed drive, and corrosion resistant material are converting pump systems into dynamic, low energy consuming parts that have the ability of working under harsh processing conditions. All these innovations are not only energy-saving and operation-stabilizing but also follow the principle of a circular economy by increasing equipment life and decreasing the environmental impact. The significance of the integrated policy, research and industrial endeavors of overcoming the impediments to deployment can be backed with the experience of technologically advanced states. Lastly, the prevalence of the pump technology is coupled with the process-based and sustainability-based needs, the accelerated gravitation towards the resilient and low-carbon bioenergy facilities.

Conflicts of Interest

No conflict of interest

Funding

This research received no external funding.

Author contribution

Hasith Perera and **Shen Hosan**: Conceptualization; Methodology; Software. **Dasith Wijesekara**: Data curation; Writing-Original draft preparation. **Vimukthi Vithanage** and **Shakya Abeysinghe**: Visualization; Investigation. **Kaveenga Koswattage**: Supervision. **Hasith Perera**: Software; Validation. **Kaveenga Koswattage**: Writing -Reviewing and Editing.

Declaration of generative AI in scientific writing

The author acknowledges having used the Generative AI tool Quillbplt-AI for grammar/language improvement. The author is solely responsible for all published content and has verified the accuracy and authenticity of the AI output.

References

Abidov, K. G., Zaripov, O. O., Khamudkhanova, N. B., Gafurova, M. O., & Zaripova, Sh. O. (2023). *Characteristics and parameters of pumping stations determining energy-saving modes*. 030023. https://doi.org/10.1063/5.0112385

Alqahtani, B., Yang, J., & Paul, M. C. (2024). Reliability and dispatchability improvement of a hybrid system consisting of PV, wind, and bio-energy connected to pumped hydropower energy storage. *Energy Conversion and Management*, *304,* 118212. https://doi.org/10.1016/j.enconman.2024.118212

Altemose, A., Sánchez-Farrán, M. A., Duan, W., Schulz, S., Borhan, A., Crespi, V. H., & Sen, A. (2017). Chemically Controlled Spatiotemporal Oscillations of Colloidal Assemblies. *Angewandte Chemie International Edition*, *56*(27), 7817–7821. https://doi.org/10.1002/anie.201703239

Bartolozzi, I., Rizzi, F., & Frey, M. (2017). Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy. *Renewable and Sustainable Energy Reviews*, *80*, 408–420. https://doi.org/10.1016/j.rser.2017.05.231

Bengtsson, K., & Robinson, N. D. (2017). A large-area, all-plastic, flexible electroosmotic pump. *Microfluidics and Nanofluidics*, *21*(12), 178. https://doi.org/10.1007/s10404-017-2017-1

Carpita, N. C., & Sage, R. F. (2015). Plants and bioenergy. *Journal of Experimental Botany*, *66*(14), 4093–4095. https://doi.org/10.1093/jxb/erv311

Cushman, J. C., Davis, S. C., Yang, X., & Borland, A. M. (2015). Development and use of bioenergy feedstocks for semi-arid and arid lands. *Journal of Experimental Botany*, *66*(14), 4177–4193. https://doi.org/10.1093/jxb/erv087

Dincer, I., & Acar, C. (2015). A review on clean energy solutions for better sustainability: A review on clean energy solutions for better sustainability. *International Journal of Energy Research*, *39*(5), 585–606. https://doi.org/10.1002/er.3329

Dong, Z., Qing, Z., Yu, Z., Haoran, L., Qifan, Y., Rui, Z., & Zhoujian, A. (2024). Performance response analysis and optimization for integrated renewable energy systems using biomass and heat pumps: A multi-objective approach. *Carbon Neutrality*, *3*(1), 33. https://doi.org/10.1007/s43979-024-00109-4

Haberl, H., Beringer, T., Bhattacharya, S. C., Erb, K.-H., & Hoogwijk, M. (2010). The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability*, *2*(5–6), 394–403. https://doi.org/10.1016/j.cosust.2010.10.007

Hashemian, N., & Noorpoor, A. (2023). Optimization and multi-aspect evaluation of a solar/biomass-powered multi-generation plant with an integrated thermoelectric generator unit. *Sustainable Energy Technologies and Assessments*, *56*, 102998. https://doi.org/10.1016/j.seta.2022.102998

Ivchenko, O., Andrusiak, V., Kondus, V., Pavlenko, I., Petrenko, S., Krupińska, A., Włodarczak, S., Matuszak, M., & Ochowiak, M. (2023). Energy Efficiency Indicator of Pumping Equipment Usage. *Energies*, *16*(15), 5820. https://doi.org/10.3390/en16155820

Kline, T. R., Paxton, W. F., Wang, Y., Velegol, D., Mallouk, T. E., & Sen, A. (2005). Catalytic Micropumps: Microscopic Convective Fluid Flow and Pattern Formation. *Journal of the American Chemical Society*, *127*(49), 17150–17151. https://doi.org/10.1021/ja056069u

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., & Haberl, H. (2008). Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*, *65*(3), 471–487. https://doi.org/10.1016/j.ecolecon.2007.07.012

Lavrič, H., Drobnič, K., & Fišer, R. (2024). Model-Based Assessment of Energy Efficiency in Industrial Pump Systems: A Case Study Approach. *Applied Sciences*, *14*(22), 10430. https://doi.org/10.3390/app142210430

Lee, K., & Lee, S. (2013). Patterns of technological innovation and evolution in the energy sector: A patent-based approach. *Energy Policy*, *59*, 415–432. https://doi.org/10.1016/j.enpol.2013.03.054

Mangoyana, R. B., & Smith, T. F. (2011). Decentralised bioenergy systems: A review of opportunities and threats. *Energy Policy*, *39*(3), 1286–1295. https://doi.org/10.1016/j.enpol.2010.11.057

Maraver, D., Sin, A., Royo, J., & Sebastián, F. (2013). Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. *Applied Energy*, *102*, 1303–1313. https://doi.org/10.1016/j.apenergy.2012.07.012

McCann, M. C., & Carpita, N. C. (2015). Biomass recalcitrance: A multi-scale, multi-factor, and conversion-specific property: Fig. 1. *Journal of Experimental Botany*, *66*(14), 4109–4118. https://doi.org/10.1093/jxb/erv267

Mohammadi, M., Noorollahi, Y., Mohammadi-ivatloo, B., & Yousefi, H. (2017). Energy hub: From a model to a concept – A review. *Renewable and Sustainable Energy Reviews*, *80*, 1512–1527. https://doi.org/10.1016/j.rser.2017.07.030

Patil, S. A., Khot, A. C., Chavan, V. D., Rabani, I., Kim, D., Jung, J., Im, H., & Shrestha, N. K. (2024). Electrostatically robust CoFeOF nanosheet against chloride for green-H2 production in alkaline seawater electrolysis. *Chemical Engineering Journal*, *480*, 146545. https://doi.org/10.1016/j.cej.2023.146545

Petrochenkov, A., Ilyushin, P., Mishurinskikh, S., & Kozlov, A. (2023). Development of a Method for Improving the Energy Efficiency of Oil Production with an Electrical Submersible Pump. *Inventions*, *8*(1), 29. https://doi.org/10.3390/inventions8010029

Ruby, T. M. (2015). Innovation-enabling policy and regime transformation towards increased energy efficiency: The case of the circulator pump industry in Europe. *Journal of Cleaner Production*, *103*, 574–585. https://doi.org/10.1016/j.jclepro.2015.02.017

Sage, R. F., & Kubien, D. S. (2007). The temperature response of C_3 and C_4 photosynthesis. *Plant, Cell & Environment*, *30*(9), 1086–1106. https://doi.org/10.1111/j.1365-3040.2007.01682.x

Shrestha, N. K., Inamdar, A. I., Im, H., & Cho, S. (2024). Boosting energy-efficient hydrogen evolution by electronically modulating Ni nodes in a framework for methanol oxidation in fresh and seawater. *Journal of Materials Chemistry A*, *12*(43), 29978–29988. https://doi.org/10.1039/D4TA05688D

Simas-Rodrigues, C., Villela, H. D. M., Martins, A. P., Marques, L. G., Colepicolo, P., & Tonon, A. P. (2015). Microalgae for economic applications: Advantages and perspectives for bioethanol. *Journal of Experimental Botany*, *66*(14), 4097–4108. https://doi.org/10.1093/jxb/erv130

Terutsuki, D., Miyazawa, S., Takagi, J., Yamada, A., Sun, Y., Abe, H., Wang, G., & Nishizawa, M. (2024). Spatiotemporally Controllable Chemical Delivery Utilizing Electroosmotic Flow Generated in Combination of Anionic and Cationic Hydrogels. *Advanced Functional Materials*, *34*(2), 2304946. https://doi.org/10.1002/adfm.202304946

Yao, S., Hertzog, D. E., Zeng, S., Mikkelsen, J. C., & Santiago, J. G. (2003). Porous glass electroosmotic pumps: Design and experiments. *Journal of Colloid and Interface Science*, *268*(1), 143–153. https://doi.org/10.1016/S0021-9797(03)00730-6

Yuan, L., & Li, R. (2020). Metabolic Engineering a Model Oilseed Camelina sativa for the Sustainable Production of High-Value Designed Oils. *Frontiers in Plant Science*, *11*, 11. https://doi.org/10.3389/fpls.2020.00011

Yue, D., You, F., & Snyder, S. W. (2014). Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. *Computers & Chemical Engineering*, *66*, 36–56. https://doi.org/10.1016/j.compchemeng.2013.11.016

Zang, Y., Zhang, B., Zhang, G., Hu, J., Shu, D., Han, J., Hu, M., Tu, M., Qiao, W., Liu, R., & Zang, Y. (2024). Effects of combined treatment with hydrogen-rich electrolyzed water and tea polyphenols on oxidative stress, intestinal injury and intestinal flora disruption in heat-stressed mice. *Journal of Thermal Biology*, *123*, 103921. https://doi.org/10.1016/j.jtherbio.2024.103921

Zou, S., & He, Z. (2018). Efficiently “pumping out” value-added resources from wastewater by bioelectrochemical systems: A review from energy perspectives. *Water Research*, *131*, 62–73. https://doi.org/10.1016/j.watres.2017.12.026