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Low-cost real-time monitoring and automated control system for a bench-scale portable downdraft gasifier

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ABSTRACT

This research work focuses on the development of a real-time monitoring and automated control system with remote access, as well as integrated data collection and storage, for a portable biomass gasification prototype to generate electricity from agricultural waste. The prototype consists of an air-blown downdraft fixed-bed gasifier and a producer gas conditioning unit, which operate together in a remotely controlled ensemble. The proposed system stands out for its compact size, transportability, and low-cost design, making it suitable for implementation in small agricultural facilities, especially in areas where conventional electrification is limited or non-existent. Two preliminary tests were conducted to evaluate the performance of the monitoring system. In the first test, the system achieved a target temperature of 600 °C in less than 20 min and maintained it within a variation range of ±25 °C. After holding this temperature for an hour, the setpoint was raised to 800 °C, with the system achieving the new target in less than 10 min. In the second test, a setpoint of 800 °C was reached in 16 min, with an additional 3 min required for stabilization. Both tests, lasting approximately 4 h, consumed a total of 13.43 kg of biomass. The results demonstrate the system's ability to reach target temperatures in less than 25 min while maintaining stable temperature oscillations. The system's graphical interface enables intuitive, real-time, and remote monitoring and management of temperatures in several zones along the gasifier's height. Additionally, the interface allows manual or algorithmic control of the system's actuators, with the ability to modify the control algorithms through over-the-air updates.

Introduction

The agrifood industry is a significant contributor to global waste production, with large amounts of biomass generated during agricultural and food processing activities. If properly managed, agroindustrial waste holds significant potential to become a valuable resource for energy recovery, especially in remote locations with abundant biomass resources. One promising management approach is gasification, which allows agroindustrial waste to be used for decentralized renewable electricity generation [1]. This decentralized approach is particularly well-suited to the dispersed population and economic activities of rural regions, providing a practical alternative to reduce reliance on fossil fuel sources for electrification and increase energy security [2]. Moreover, gasification of agroindustrial waste reduces the need for open burning, thereby mitigating fire risks and decreasing greenhouse gas emissions. Local energy production can also boost economic development, create jobs, and improve living standards in rural communities. Furthermore, scalability and adaptability of gasification systems make them versatile, allowing them to be tailored to the varying energy needs and capacities of different rural areas.

Gasification is a thermochemical conversion process that involves subjecting a solid carbonaceous feedstock to partial oxidation with a gasifying agent, typically air, oxygen, steam, or combinations thereof [3,4]. For small-scale gasification systems designed for electricity generation, air is usually the preferred option due to its economic advantages [5–7]. The air-blown gasification process allows organic carbon materials, such as agroindustrial biomass waste, to be converted into a lean fuel gas, known as producer gas, which is suitable for power generation [8,9].

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Nomenclature

A/D	Analog to digital
ANFIS	Adaptive neuro-fuzzy inference system
FIS	Fuzzy inference system
FLC	Fuzzy logic controller
GUI	Graphical user interface
I2C	Inter-integrated circuit
ICE	Internal combustion engine
MIMO	Multi-input multi-output
OTA	Over the air
PCB	Printed circuit board
PID	Proportional integral derivative
PSO	Particle swarm optimization
PTC	Positive temperature coefficient
PWM	Pulse width modulation
RTC	Real-time clock
RTOS	Real-time operating system
SPI	Serial peripheral interface

Gasifiers are broadly classified as fixed bed, fluidized bed, and entrained flow [3]. Fixed-bed gasifiers are in turn subcategorized into updraft, downdraft, and crossdraft types. Downdraft gasifiers are characterized by a parallel downward flow of both the solid feedstock and the gasifying agent. In this design, the gasifying agent (i.e., air) is introduced below the upper area and the producer gas is extracted through the lower part of the reactor. Downdraft gasifiers are the preferred option for small-scale distributed power generation due to their simple construction, reliable operation, short startup time (20–30 min), adaptability to various biomass feedstocks, and high carbon conversion efficiency [3,7,10,11]. As a result of these advantages, downdraft gasifiers currently dominate the market, especially in power generation applications, accounting for roughly three-fourths of all gasifiers marketed commercially [12]. Additionally, they produce less tar because the oxidation zone immediately follows the pyrolysis zone, where these compounds are formed [3]. This characteristic makes downdraft gasifiers particularly suitable for small-scale electricity production with internal combustion engines (ICEs) [4], especially for applications requiring up to 1 MW of thermal power [3]. However, the producer gas must be cooled before use as a result of the high reactor outlet temperature [13]. Small-scale downdraft gasifiers provide the added advantage of being containerizable for convenient transportation and can even be designed as mobile power generation units [11]. These features make them particularly attractive for electrifying isolated communities in rural areas [2,14], as they can be operated in off-grid mode or integrated into microgrids without the need for prior electrical infrastructure. As main drawbacks, downdraft gasifiers generally exhibit lower thermal performance compared to other technologies and may face challenges when processing biomass feedstocks with high ash and moisture content. Downdraft gasifiers can be subclassified into two major design variants: throated (also known as constricted) and throatless (also known as topless, open top, or open core). Constriction in the combustion stage favors the thermal cracking of most of the tar by forcing all pyrolysis products to pass through a narrow section, thus improving the quality of the producer gas [3,15,16].

The gasification process can be divided into four main stages: drying or dehydration, pyrolysis or volatilization, combustion or oxidation, and gasification or reduction [3,17,18]. In fixed-bed gasifiers, these reactions occur in specific areas, whereas, in fluidized-bed gasifiers, the reactions can occur simultaneously throughout the reactor. However, during the actual operation, the four reaction zones commonly overlap with no clear or discrete separation between them [17]. In the drying stage, the solid fuel reaches temperatures up to 200–250 °C, losing most of its moisture and reducing its content to around 5% [4,19]. Pyrolysis follows, where biomass chemical bonds break (thermolysis) at temperatures in the range of 150 to 700 °C, leading to pyrolytic products (including both light and heavy hydrocarbons, the latter commonly known as tars) [3,4,18,20]. Drying and volatilization occur simultaneously, producing gaseous, liquid, and solid fractions. Non-condensable gases make up 70% to 90% by weight of the products [20]. In the combustion zone, temperatures reach between 500 and 1500 °C due to exothermic oxidation of pyrolysis products in oxygen's presence [4,21,22]. Oxidation must occur with limited oxygen to avoid complete fuel combustion [20]. Heat from combustion drives drying, pyrolysis, and gasification. Using air as a gasifying agent introduces inert gases like nitrogen (N_2) and argon (Ar) into the product gas [20]. Finally, in the gasification zone, hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) are formed through reduction reactions of oxidized carbonaceous solids with downstream gases. This endothermic process occurs at temperatures in the range of 600 to 1100 °C [3,20,21]. As temperature changes affect gas composition and tar concentration, strict control over the process temperature is essential. Higher temperatures increase carbon conversion and reduce tar formation, but also lead to an increased risk of ash sintering and a decline in the calorific value of the product gas [20].

Automation and control systems for biomass gasifiers have advanced significantly in recent years. Early automation systems relied on basic functionalities such as temperature monitoring or implementing proportional–integral–derivative (PID) controllers for specific process variables, which proved inadequate for dynamic biomass conditions. Sagüés et al. [23] introduced a fuzzy inference system (FIS) to control gasifiers, encoding expert knowledge into if-then rules. This approach allowed the system to dynamically adjust process parameters like air flow and grate frequency based on biomass type and moisture content, enhancing adaptability and process efficiency. Gandhi et al. [24] developed a fuzzy logic controller (FLC) for downdraft gasifiers, utilizing a multi-input multi-output (MIMO) system to regulate temperature and CO/CO_2 ratio. Their approach significantly improved stability and response time compared to conventional PID controllers, demonstrating the effectiveness of FLC in handling the nonlinear dynamics of biomass gasification. Gøbel et al. [25] advanced the field with a dynamic one-dimensional mathematical model that incorporated conservation laws and reaction kinetics to optimize stationary performance and identify efficient control strategies for handling load changes. Striūgas et al. [26] further demonstrated practical advancements in automation by integrating staged air supplies, moving grates, and pressure-based char discharge systems into multi-fuel downdraft gasifiers. Their work highlighted the importance of controlling parameters such as bed pressure and temperature to enable effective gasification of diverse biomass feedstocks. More recently, Daniel and Gandhi [27] focused on improving PID controller performance for downdraft gasifiers by utilizing particle swarm optimization (PSO) and adaptive neuro-fuzzy inference system (ANFIS) techniques. Their work demonstrated that PSO and ANFIS-based PID tuning outperformed traditional Ziegler–Nichols methods in temperature control, providing better transient response and reduced overshoot.

Despite the aforementioned improvements in the control and optimization of biomass gasifiers, there are still numerous opportunities for further research. A remarkable gap in the relevant scientific literature is the development of more intuitive, low-maintenance monitoring and automated control systems that are suitable for portable biomass gasifiers in remote locations. Many existing systems tend to be complex and require skilled personnel for maintenance, which limits their applicability in off-grid settings or underserved areas, where simplicity and reliability are paramount. Moreover, attracting and retaining skilled operators for gasification systems remains a significant challenge, particularly in rural and often remote areas [28]. Nonetheless, overcoming these challenges could unlock the full potential of waste-to-energy solutions for the electrification of isolated communities.

This paper presents an intuitive, low-maintenance monitoring system for a compact, portable biomass gasifier intended for electric power generation in remote locations. Unlike traditional systems, which are often complex and require skilled operators, the proposed system is specifically designed for transportability, as well as ease of operation and maintenance. Additionally, the compact control unit (housed in a 250 × 250 × 100 mm waterproof enclosure) enhances portability, enabling quick installation and flexible deployment in diverse environments. The proposed system not only collects and stores operational data, but also provides real-time monitoring and remote control capabilities, enabling adjustments to working temperatures to adapt to different biomass types. These features make the system highly intuitive and user-friendly, addressing a gap in the market for portable, easy-to-operate biomass gasifiers that can drive electrification in remote or underserved areas.

Methodology

This section outlines the rationale behind the selected design, focusing on simplicity, cost-effectiveness, and ease of use. The monitoring and automated control system features compact, high-precision hardware utilizing low-cost commercial sensors and actuators. Additionally, an intuitive graphical interface allows for straightforward remote management, enhancing both usability and operational efficiency from physical and software perspectives.

Biomass feedstock characterization and choice of gasifying agent

Biomass gasification processes are inherently complex due to their multivariable, nonlinear behavior, as well as the variability of biomass properties such as chemical composition, moisture content, and particle size. In the experiments presented in this paper, olive pomace pellets were used as feedstock, the physicochemical properties of which can be consulted in a previous work of some of the authors [7]. Air was used as gasifying agent, due to its availability and low cost [6,7]. As mentioned above, the resulting gaseous product from air-blown gasification is a lean fuel gas with a high content of inert gases known as producer gas. Despite its relatively low calorific value, it is still suitable for power generation using ICEs [9,29].

Design of the biomass gasifier

Among the various available alternatives, a downdraft fixed-bed reactor was selected in this study. The height of the reactor is 1.4 m, making it easily transportable. This reactor uses gravity as the driving force to move the fuel from the feed hopper (upper section) to the combustion zone (lower section), where the highest temperatures are reached [3]. In this study, a downdraft reactor with a constriction in the combustion zone was used. The inclusion of a constriction zone forces the products from pyrolysis to pass through a narrow passage, where they undergo combustion in a process known as flaming pyrolysis, thereby reducing the formation of tar [3,18]. Furthermore, temperatures above 800 °C are reached, promoting thermal cracking reactions, which significantly reduce the tar content in the producer gas [30]. This reduction in tar content is critical, not only for improving the quality of the producer gas but also for lowering the operation and maintenance costs, as tar deposits can lead to clogging and damage to equipment.

The gasification process produces a lean fuel gas known as producer gas, which can be used to power a generator set for electricity generation [9]. However, some impurities contained in the hot producer gas, such as fly ash, tar, and moisture, can condense in the low-temperature sections and adhere to the internal surfaces of the system, leading to severe fouling and corrosion issues [7]. For this reason, the system incorporates gas conditioning and filtration elements downstream of the reactor, ensuring continuous operation without frequent maintenance interruptions [4]. Another design consideration is the elevated temperature at which the producer gas is generated, which can be detrimental to the engine–generator set. To mitigate this issue, a heat exchanger is used to reduce the outlet temperature. All these components, including the sensors, actuators, gas filtration equipment, and adaptation components, are schematically illustrated in Fig. 1.

During operation, the gasification temperature is carefully adjusted by regulating the airflow rate to strike a balance between the calorific value and yield of producer gas. These temperature settings can be adjusted to adapt to variations in biomass composition, including moisture content, ash content, and energy density, which significantly influence the performance of the gasification process. The system's programmable graphical interface allows users to manually or automatically modify the temperature set points and heating rates by manipulating the operation of the different motors, thereby providing real-time control over the gasification process.

Biomass decomposition under substoichiometric operating conditions generates a dense mist composed of water vapor and tar that adheres to the system walls and is carried downstream by the continuous flow of gas. The producer gas leaves the gasification reactor at around 400 °C [7], and contains particulates, condensates, tar, and water vapor [18]. This hot producer gas must be cooled and cleaned, ensuring it is virtually free from tar, water vapor, and particulates, and at near ambient temperature if it is to be utilized in an internal combustion engine [18]. In this study, a compact producer gas conditioning system is included to support extended operation with reduced maintenance (see Fig. 1). This system consists of a gas-air countercurrent-flow heat exchanger that lowers exhaust gas temperature from 400 °C to about 50 °C, suitable for the engine–generator set; a cyclone that redirects part of the inlet airflow to the heat exchanger outlet to avoid particle buildup in the condenser; a condenser that traps contaminants at the bottom of a container to prevent them from circulating through the piping; and an ash collection box with a removable door for easy withdrawal of accumulated residues after several hours of operation.

Operating procedure

The first step is to load the reactor with the biomass feedstock and securely seal it against air leakage [31]. Proper sealing is essential to maintain control over the reactor's internal conditions, as the centrifugal blower is the sole component responsible for injecting a regulated amount of air into the reactor. To ensure that the product gas is usable for power generation applications and contains a minimal number of contaminants, the goal is to achieve a chemical decomposition reaction of organic matter under substoichiometric conditions [3]. Gasification reactions occur at elevated temperatures in an oxygen-lean atmosphere, which reflects the paramount importance of an air-tight sealing [32–34].

After sealing against leakage, combustion must be initiated manually, a process that lasts for approximately 20 min depending on the moisture content of the feedstock [7]. During this stage, a blowtorch provides heat, and the blower injects as much air as possible, thereby promoting heat distribution and the formation of the first layer of charred particles in the combustion chamber. Once the process has become self-sustaining, the user can switch to automatic mode. In this mode, the system automatically regulates the air intake to the reactor by adjusting the airflow rate based on feedback from the temperature sensors integrated into the reactor. The aim of the electronic system is to maintain operation within established temperature ranges, facilitating the gravity-driven movement of the feedstock through the different sections of the reactor, while simultaneously eliminating ash deposits from the walls through vibrations generated by two motors placed at the bottom of the reactor.

During the biomass gasification process, it is essential to maintain the temperature in the combustion zone at around 800 °C to provide the required heat supply for the endothermic pyrolysis and reduction reactions, as well as for minimizing tar production [5,35,36]. Tar is

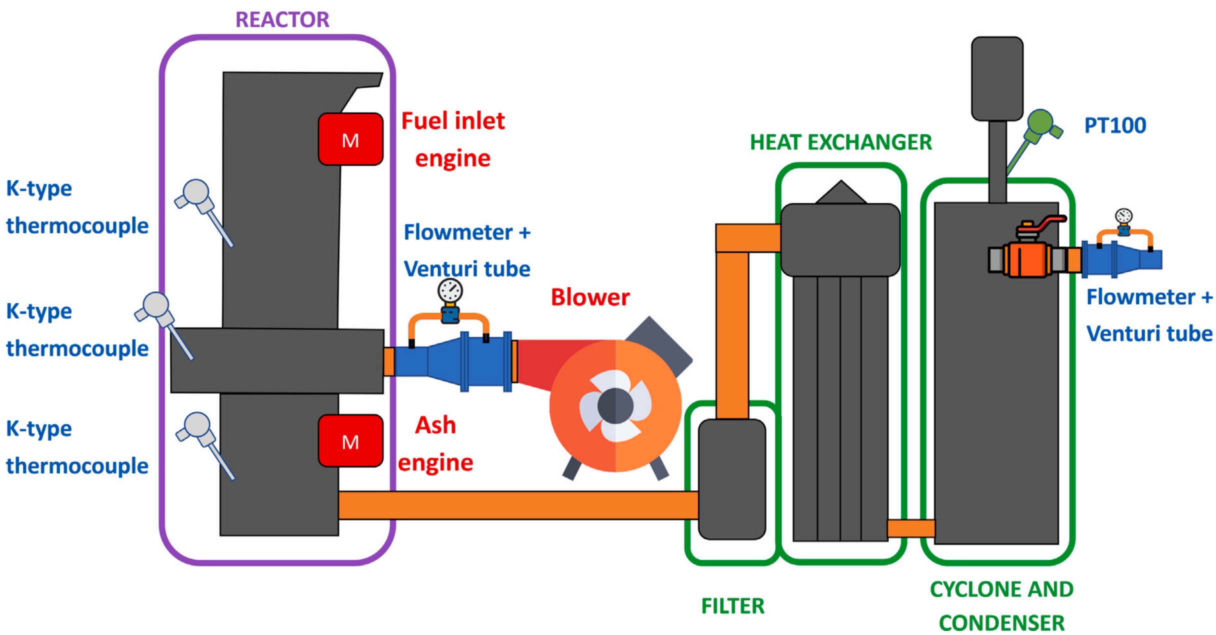


Fig. 1. Overview of the prototype assembly, highlighting its main components.

detrimental to both the environment and the power generation unit, thereby reducing its lifespan [30]. The producer gas from the reactor is at elevated temperatures and may contain impurities, necessitating pretreatment before it can be used in an engine. Filtration removes impurities such as dust, tar, and moisture, which may clog the intake manifold of the engine and increase maintenance requirements. The heat exchanger reduces the gas temperature from approximately 400 °C at the reactor outlet to around 50 °C, making it suitable for engine operation. After the conditioning stage, the system is equipped with a T-valve that allows the producer gas to be routed either to the flare stack or to the generator set. An effective approach to determine whether the producer gas has an adequate calorific value is to ignite it. A blue flame indicates the gas is appropriate for use as fuel [7], thereby avoiding the need for an expensive gas analyzer.

Hardware design

Temperature and airflow sensors were strategically placed to evaluate the performance of the prototype and determine whether they satisfy the design specifications. These sensors provide real-time data on the state of the system, enabling the implementation of necessary actions to stabilize the pyrolysis reaction. The key parameter for maintaining this reaction is the combustion temperature. The reactor, in conjunction with the control unit, must sustain the temperature at approximately 800 °C, with a narrow allowable range (±25 °C). Temperature stability depends on the volume of air introduced as an oxidizer. The control unit adjusts the control signal using pulse width modulation (PWM) of the blower based on the data provided by the temperature sensors. Unlike all-or-nothing control, where the system operates only in states of maximum or no power, PWM allows continuous adjustment of energy without incurring the significant thermal losses associated with linear regulation. This is because the switching devices used in PWM operate in saturation or cut-off modes, minimizing power dissipation [37]. In addition, PWM offers a more efficient response in terms of stability and speed control, reducing sudden fluctuations in flow pressure and allowing better adaptation to the dynamic conditions of the system. This feature is essential in applications that require precise flow regulation without introducing additional disturbances to the flow measurement [38].

Sensors

Industrial-grade sensors were selected to characterize the biomass gasifier prototype. These sensors feature specially designed and sealed enclosures to operate in environments with contaminants, such as dust and splashes. They also incorporate 4–20-mA industrial standard transducers, which are known for their immunity to the electromagnetic noise generated by motors [39,40]. In the prototype, potential sources of electromagnetic noise that could negatively impact the instrumentation include the motors responsible for dislodging ash from the reactor walls, facilitating fuel descent into the combustion chamber, as well as the blower motor.

K-type thermocouples, with a temperature range of 0–1200 °C, were placed at different sections along the vertical axis of the reactor [41]. Additionally, a PT100 sensor, with a temperature range of 0–100 °C, was chosen to monitor the performance of the heat exchanger, ensuring that the temperature is reduced to approximately 50 °C. The PT100 sensor provides a higher resolution within its operating range than the thermocouples, justifying the change in sensor type. Differential pressure sensors coupled with properly sized Venturi tubes were used to measure the airflow at the inlet and outlet of the prototype. This setup generates a pressure variation (ΔP) proportional to the airflow rate (Q), as indicated in Eq. (1).

$$\Delta P = P_1 - P_2 = \frac{Q^2 \rho \left(A_1^2 - A_2^2\right)}{2 A_1^2 A_2^2} \tag{1}$$

where A denotes the internal cross-sectional area of the tube and ρ represents the gas density. Subscripts 1 and 2 correspond to the converging conical section and the throat section of the Venturi flow meter, respectively.

This combination is preferred in industrial settings for fluids prone to contamination, where other measurement devices such as rotameters are inoperative.

Actuators

To ensure efficient gasifier operation, several physical components were integrated to enhance system performance and control. The blower adjusts combustion temperature by regulating the airflow rate injected into the reactor, increasing the oxidizing agent and allowing higher combustion temperatures. Agitator motors prevent the buildup of plant-based fuel on the reactor walls, promoting its movement

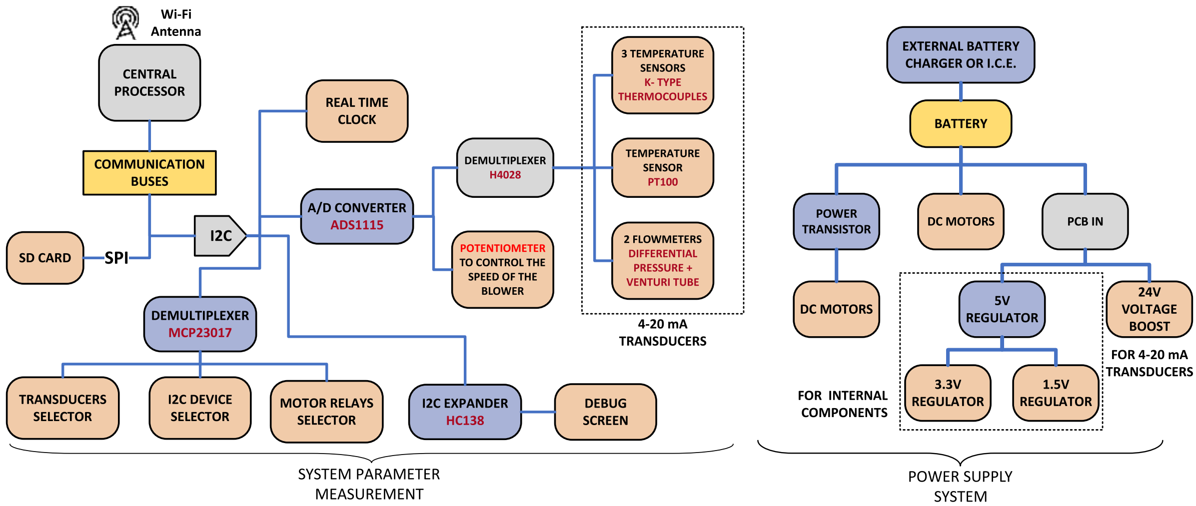


Fig. 2. Schematic diagram of the main hardware elements.

to the combustion zone by gravity and avoiding ash accumulation. Additionally, a T-valve connected to a chimney redirects the producer gas either for incineration in a flare stack or to the engine intake manifold based on a test of the flame's color. The flame should turn blue to confirm that the gas is sufficiently clean and tar-free. This configuration enables real-time verification that the target reaction temperature, approximately 800 °C, has been reached.

Wireless control system

Data collection was performed wirelessly, allowing the operators to interact with the system in real time, even in manual mode, without the need to open the sealed control unit enclosure. Despite the wireless nature of data transmission, it is crucial to maintain secure communication between the system and the computer without data loss. A web interface was developed to help visualize the data and control the various system components. Through this interface, users can access historical measurement records, calibrate sensors, adjust control parameters, and set target temperatures.

The system was designed to monitor and control the prototype autonomously, although manual ignition is required during the initial phase. All the measurements and actuator inputs were stored locally on a microSD card, complete with timestamps. With each new data collection, these measurements were updated and displayed on the user's graphical web interface, enabling the detection of irregularities and monitoring of the system's overall performance.

The control system comprised a control unit, real-time clock (RTC), microSD card slot, connectors for the 4–20-mA sensors, power supply system, and power-consuming elements. These elements included relays for motor actuation (without regulation) and a power stage for precise control of the blower motor. A schematic diagram of the control system is illustrated in Fig. 2.

The principal component of the control unit is an ESP32 microcontroller (Espressif Systems, China). This system-on-chip integrates two ultralow-power processors, offering robust computational capabilities while minimizing energy consumption. ESP32 can implement multiple communication protocols, including SPI and I2C, which are essential for interfacing various sensors and actuators within a system [42, 43]. Furthermore, ESP32 supports wireless connectivity in the 2.4-GHz band, incorporating both Bluetooth and Wi-Fi transceivers, which facilitate seamless data transmission and remote monitoring.

The printed circuit board (PCB) is complemented by additional key components, as shown in Fig. 3. These elements enhance the functionality and reliability of the control unit, thereby ensuring the efficient operation of the gasification system. The PCB integrates power

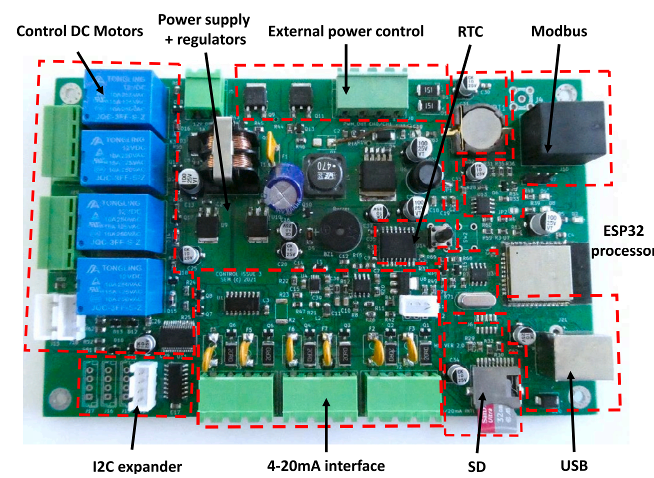


Fig. 3. Prototype control unit hardware.

management circuits to stabilize the supply voltage, signal conditioning modules for accurate sensor data acquisition, and communication interfaces to ensure reliable data exchange between the microcontroller and the peripheral devices.

Incorporating an ESP32 microcontroller into the control unit design provides a versatile platform capable of managing complex control tasks and real-time data processing. Its wireless communication capabilities also enable remote monitoring and control, which are critical for optimizing the performance and safety of the gasification process. The integration of these features into a compact, energy-efficient design underscores the suitability of ESP32 for industrial applications such as biomass gasification.

Measurements of temperature and gas flow rate

To measure the gas temperature and flow, the instrumentation system employs industrial sensors that incorporate standard 4–20-mA transceivers. These transceivers require a supply voltage of 24 V, which is provided by a voltage booster integrated into the system. Sensors consume minimal energy; therefore, a high current supply is unnecessary.

Temperature was measured inside the reactor using three K-type thermocouples located at different zones such as drying–pyrolysis, oxidation, and reduction [26,27]. A PT100 sensor was used at the gas outlet of the system to ensure that the heat exchanger operated correctly and that the producer gas could be safely introduced into the ICE without causing damage. Differential pressure sensors coupled with Venturi tubes were used to measure the inlet airflow rate and the producer gas flow rate at the outlet. The resulting pressure difference ($\Delta P = P_1 - P_2$) allows for direct calculation of the fluid flow rate (Q), as follows:

$$Q = A_1 A_2 \sqrt{\frac{2\left(P_1 - P_2\right)}{\rho\left(A_1^2 - A_2^2\right)}} \tag{2}$$

To optimize the design and reduce the size of the measurement hardware, the instrumentation system employed a single ADS1115 analogue-to-digital (A/D) converter, necessitating the use of a demultiplexer for all 4–20-mA analogue inputs.

The transceivers are not designed for immediate operation; they require a stabilization time of approximately 6 s after being powered, totaling approximately 36 s for the six sensors. To bypass this delay, a resistor connected to the negative pole of each transceiver was used to continuously power it. When a data sample is required, the transistor redirects the current from each input to the A/D converter without disrupting operation. This approach enables the instant measurement of all parameters.

To verify the behavior and linearity of the system in response to changes in the flow rate and temperature, each sensor was calibrated in the laboratory. This process included setting up different valves that redirected the airflow toward either the reactor or the exhaust. The reduction in the cross section of the air hoses was considered in the calculations because it imposes a limitation on the maximum flow rate that can be supplied by the blower.

For temperature calibration, a calibrated PT100 sensor and a type-K thermocouple (RS Amidata) were used. The differential pressure gauges were calibrated with a high-power blower, exceeding the power of the blower eventually installed in the prototype, along with a pressure meter capable of measuring up to 200 slm (12 m^3/h).

Power supply system

The system is powered by a gel battery designed for photovoltaic systems, which provides a voltage of 12 V and can supply a high current. Once electricity is generated, the battery can be charged using a photovoltaic panel or by the system itself. During the experiments, the battery was charged in the laboratory using a mobile battery charger.

The system operates at five different voltages on the printed circuit board:

- 12 V: Supplied by the battery, from which the remaining voltages in the system arise. Through a series of protective fuses, it also provides a high current to components, such as the agitator motors responsible for ash removal and the movement of solid fuel inside the reactor, as well as feeds the transistor that regulates the blower.
- 24 V: Generated by an embedded converter (XL6009) capable of supplying up to 1 A, this voltage powers the 4–20-mA transceivers. Each device is equipped with a PolyFuse (PTC-based resettable fuse) thermistor to prevent control unit issues in the event of an external short circuit, opening the circuit until the issue is resolved.
- 5, 3, and 1.5 V: These voltages are provided by AMS1117-XX linear low-dropout regulators and are used to power various integrated circuits within the system.

Power consuming elements

Both the motors that vibrate the reactor and the blower that drives air for combustion are powered by a 12-V battery. The motors operate using a simple on/off control mechanism implemented through relays. By contrast, the blower utilizes a PID control system that modulates the power supply using PWM and an external power transistor.

Firmware and software

This section describes the software and firmware that make up the control system, including task management, interaction with the web interface, and flexible programming for process automation and real-time monitoring.

Firmware

To provide robustness against failures during operation and allow the parallelization of different tasks to be performed by the control unit, the FreeRTOS operating system was implemented. RTOS allows the programmer to define tasks and set execution priorities, thereby ensuring that the system works as planned. To prevent data loss, data are stored locally on a microSD card, which also supports remote access.

If the system must stop immediately, the monitoring will continue without corrupting the data as long as the power is not cut or the user stops it; therefore, turning off the system and removing the microSD card could allow access to the information provided by the different sensors and the system to be able to locate and correct malfunctions.

The process of data acquisition and system control is composed of seven main tasks, which are illustrated in the simplified workflow diagram in Fig. 4. These tasks include Wi-Fi TCP/IP communication, firmware update, web server request processor, web socket data interchange, sensor data capture, automatic mode interpreter, and the PID power control loop.

Upon startup, all tasks are initialized and stored in static memory, remaining in a standby state until an event allows them to continue. Initially, the system attempts to establish a wireless connection with a known Wi-Fi network. If no connection is achieved after several attempts, the system creates a new network (access point mode) such that the user can access the control and monitoring interface provided by the internal web server. Web server pages are stored in the internal memory of the microcontroller; therefore, if the SD card is removed or damaged, the server will continue to work. In addition, the web server allows for the review and configuration of the sensor calibration values.

By default, the system starts in manual mode, allowing the user to control the motors and inlet airflow through a remote web user interface. This manual control allows for ignition and reactor initiation. The user can also control the data acquisition. Once the gasification process inside the reactor is started, the system can be switched to automatic mode. In this mode, the control unit is responsible for maintaining the desired temperature by adjusting the inlet airflow to regulate combustion.

Software

The control unit utilizes a programming language that allows users to define the operating time intervals for each motor. System behavior is configured using a sequential instruction-based language, such as BASIC. Users can start, stop, or modify a program interactively and remotely via a command-line interface. This customizable approach offers significant system flexibility, enabling future automation of processes such as system startup or generator control by incorporating the necessary instructions.

By default, the system operates in automatic mode, requiring no user interaction. In the event of communication loss, the system continues functioning independently. The graphical user interface (GUI) provides real-time visualization of variable trends, temperature setpoint adjustment, sensor calibration, OTA updates, and remote data retrieval from the memory card. In manual mode, users can also adjust blower power as desired.

Due to the system's high thermal inertia, constant interaction with the blower's flow control is unnecessary. To save resources, measurements can be recorded every 30 s. However, to obtain more precise monitoring curves, measurements should be updated every second.

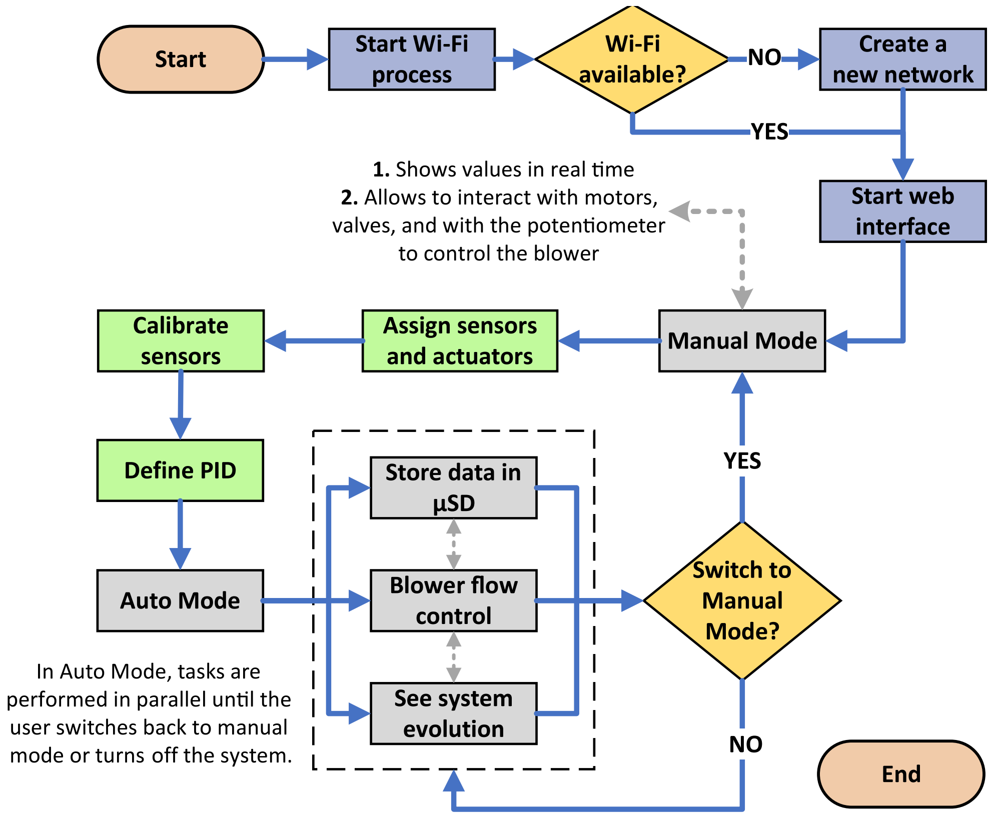


Fig. 4. Schematic workflow diagram of the firmware operation.

Results and discussion

To validate the system's functionality and its responsiveness to user demands, two field tests were conducted. The aim of both tests was to investigate the temperature behavior inside the gasifier, as well as the ability of the automated control system to maintain the target temperature. The system was fully loaded to its maximum capacity with 26.62 kg of olive pomace pellets and then started from ambient conditions (approx. 25 °C).

The first test aimed to evaluate the system's response to changes in predefined working conditions. According to the scientific literature [27], airflow rate and biomass type are the among the most important factors affecting the temperature in biomass gasifiers. Temperature control is relatively straightforward and depends directly upon the supplied amount of air [26]. Initially, a temperature setpoint of 600 °C was established. After the system stabilized at this temperature, the setpoint was raised to 800 °C. The transition to the higher temperature took approximately 10 min, during which the system maintained stability at the new temperature.

The second test focused on achieving 800 °C, starting again from ambient conditions. This temperature aligns with the typical operating conditions for temperature control in downdraft gasifiers, as documented in the scientific literature [26,27]. Once both tests were completed, the system was opened for cleaning, and the remaining charred feedstock was weighed. Overall, 13.43 kg of biomass feedstock was consumed during the tests. The experimental setup used for the field tests is shown in Fig. 5.

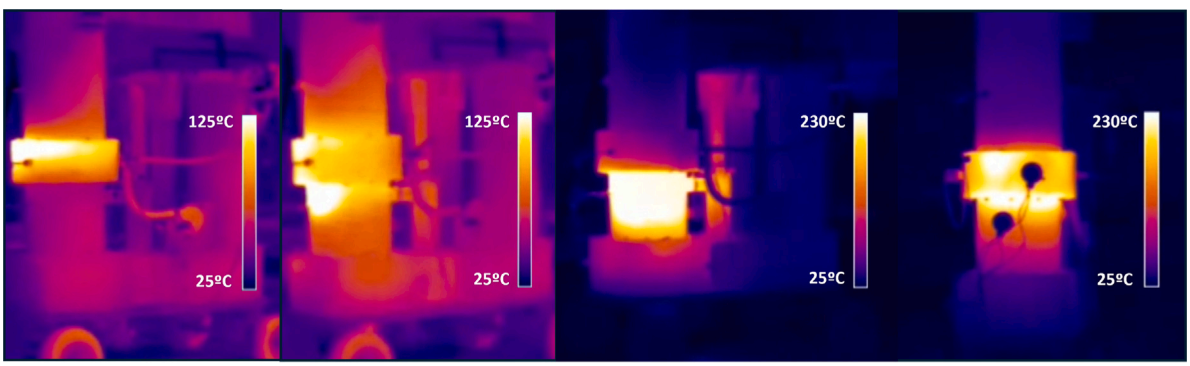
During the first test, a thermal imaging camera (SATIR D600, Ireland) was used to monitor the system's performance throughout the transitional phase. Fig. 6 shows four thermal images captured at different intervals, illustrating the temperature distribution across the reactor's external surface. The process began with heat generation in the combustion zone, which then propagated to the adjacent pyrolysis and gasification zones. The surface temperature peaked at 125 °C during the external heat supply via a blowtorch and stabilized around 230 °C during steady-state operation. The significant temperature gradient observed between the interior (800 °C) and the exterior (230 °C) of the gasification reactor reflects the system's high insulation efficiency.

System performance during the first startup phase

The initial startup was conducted on May 27, 2024, to evaluate whether the control system could maintain a stable temperature in the reactor's central zone. During this test, the temperature was initially set at approximately 600 °C, with a tolerance of ±25 °C, before being raised to a final target of 800 °C. The behavior observed in this test is illustrated in Fig. 7 (a), where significant variations in temperature readings are observed across different zones of the reactor along with the inlet air and outlet producer gas flow rates. Specifically, temperatures in the lower, middle, and upper zones varied considerably, considering that these sensors are only 30 cm apart. This variation can be attributed to the natural thermal gradients that occur in biomass gasification reactors, where the combustion zone is typically much hotter than the reduction and pyrolysis zones. The temperature distribution across the reactor is influenced by the composition and downward movement of the fuel, the airflow rate, and the heat transfer processes. The producer gas outlet temperature remained consistently stable at approximately 40 °C due to the effective operation of the heat exchanger, ensuring its suitability for use in internal combustion engines [7].

Flow measurement exhibits significant noise due to the inherent nature of the flow sensing system, which is subject to constant small pressure fluctuations. These variations arise from the blower blade position, which may either have just passed or be actively pushing

Fig. 5. Images of the reactor prototype, including a close-up view of the control system.



a) b) c) d)

Fig. 6. *(a)* Combustion zone during startup *(b)* Temperature distribution in the reactor within approximately 30 min from startup *(c)* Temperature distribution in the reactor around one hour after startup *(d)* Temperature distribution in the reactor during steady-state operation showing the placement of thermocouples.

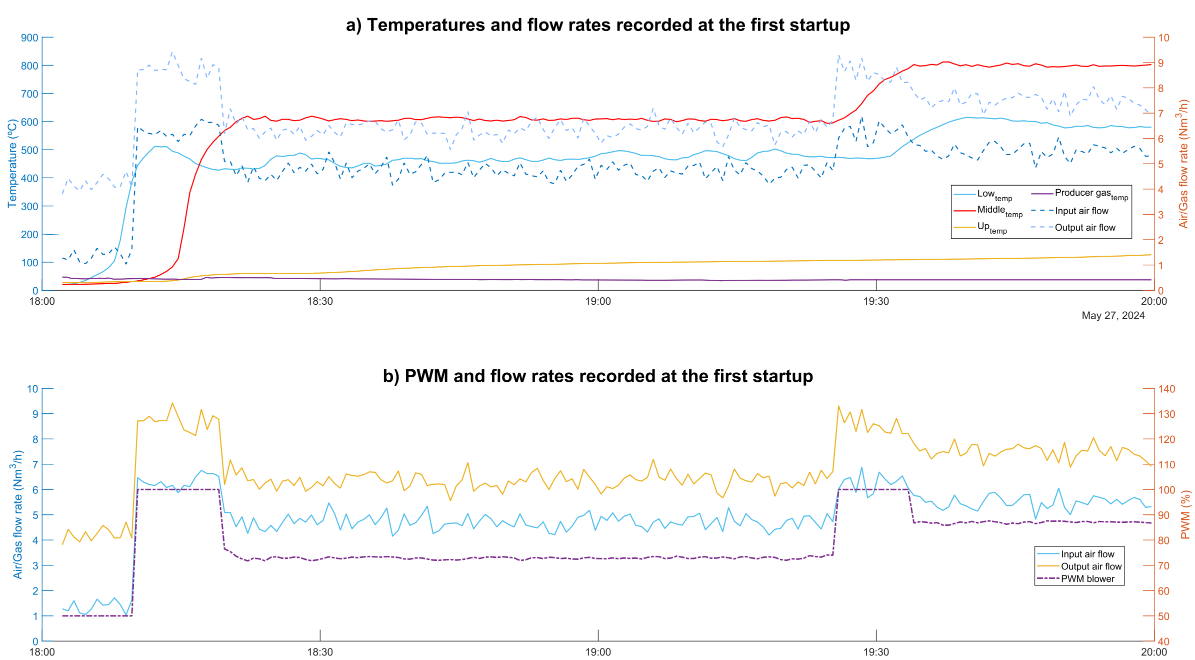


Fig. 7. Temperatures, air and producer gas flow rates, and PWM recorded during the first startup.

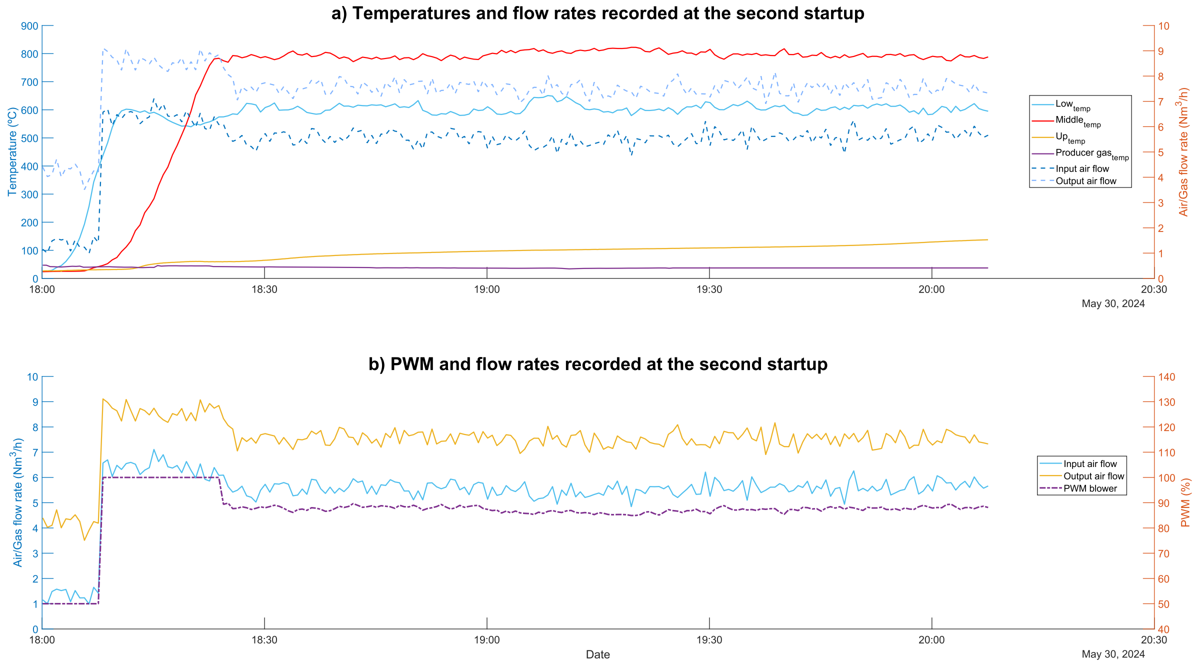


Fig. 8. Temperatures, air and producer gas flow rates, and PWM recorded during the second startup.

air at each measurement point. Fig. 7 (b) illustrates the behavior of the control signal, which regulates the power supplied to the blower, compared to the instantaneous flow rates measured with flow meters.

In Fig. 7 (a), it can be observed that after seven and a half minutes, a temperature of around 400 °C was reached in the reduction zone at the reactor's lower section, at which point the automatic mode could be activated. In automatic mode, the system first aims to reach the target temperature by increasing air intake to promote combustion, as reflected by the initial sharp increase in the airflow rate, as can be observed in Fig. 7 (a) and (b). Once the target temperature is reached, the system regulates the incoming airflow to maintain the setpoint temperature until deactivation, shutdown, or the establishment of a new operating temperature. As evidenced, the control strategy, based on PWM, allows for precise adjustment of the blower power, enabling fine-tuned control over the reactor temperature. Any temperature deviations are addressed promptly through this feedback mechanism, which adjusts the blower's operation. The rapid response of the system ensures that the desired temperature is achieved within minutes, maintaining the stability and efficiency of the gasification process.

System performance during the second startup phase

The second startup aimed to replicate a more realistic operating condition by directly targeting a set-point temperature of 800 ±25 °C in the combustion zone. Automatic mode was activated after an 8 min startup phase. The system reached the target temperature within 16 min and stabilized it in approximately 3 additional minutes, maintaining a uniform temperature for the entire two-hour test duration. The temperature behavior throughout the process is presented in Fig. 8 (a), displaying the temperatures in the lower, middle, and upper zones of the reactor, along with the producer gas temperature at the reactor outlet. The blower-induced airflow and the producer gas flow rate at the outlet are also shown in Fig. 8 (a).

Similar to the first test, Fig. 8 (b) reveals some instability in airflow measurements caused by minor pressure fluctuations inherent to the blower's operation, which did not significantly affect system performance. Despite this slight instability induced by the blower, the control signal analysis in Fig. 8 (b) indicates minimal variation between input and output temperatures and flow rates, demonstrating an overall stable and reliable system performance.

Conclusions and future outlook

The biomass gasification technology presents substantial potential for the utilization of agricultural waste. As demonstrated in this study, monitoring and automated control systems facilitate the widespread use of portable gasification systems to support electrification in off-grid areas, such as remote or isolated regions (including rural areas), due to their low cost, compact size, ease of handling and maintenance, and adaptability to various biomass sources. Moreover, these versatile systems constitute a valuable research tool for testing the gasification performance with diverse biomass types, thus facilitating the determination of key parameters in the design of larger-scale gasification plants.

The ESP32-based control system with FreeRTOS not only efficiently manages the gasification process, but also possesses computational capacity beyond immediate needs. This means that while the system awaits key events, its processor has ample resources to handle additional tasks without compromising performance. Thanks to these features, it is possible to integrate additional sensors (such as two 4–20 mA sensors), expand communication with I2C devices, and even coordinate various gasifiers simultaneously via wireless connectivity or the Modbus protocol, which is widely used in industry. Beyond energy management optimization, this capability also enables the implementation of a parallel redundant system, ensuring continuous operation in case of failures or maintenance. All of this can be achieved without major modifications to the current design, reinforcing the flexibility and scalability of the solution. Furthermore, remote access through an intuitive mobile interface not only simplifies system operation but also bridges the gap between technology and its users.

Even though the current system represents a significant advancement in portable biomass gasification, there are several opportunities for future development. One key area for improvement is the integration of modern optimization techniques, such as model predictive control or particle swarm optimization, which could enhance the performance of the system by dynamically adjusting parameters like air flow rate and temperature setpoints. Implementing such optimization strategies could further improve system efficiency, adaptability to different biomass types, and overall stability under varying operational conditions.

Future studies could focus on exploring the use of different biomass types to assess their impact on system performance. Additionally, efforts could be made to improve the startup process, making it fully automated, as well as to develop an automatic biomass feeding system. Moreover, exploring the use and control of the engine–generator set through the same control board would simplify the system architecture. Another promising direction for improvement involves expanding the system's capabilities by integrating additional sensors, optimizing communication protocols for large-scale deployments, and further enhancing the user experience through even more intuitive control interfaces. These advancements would facilitate the wider adoption of biomass gasification systems for sustainable energy production in remote and off-grid regions.

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Antonio Rodríguez Orta: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel Sánchez Raya:** Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Roque Aguado Molina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Juan Antonio Gómez Galán:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **David Vera Candeas:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Diego A. López García:** Validation, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.seta.2025.104344.

Data availability

No data was used for the research described in the article.

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