Experimental Evaluation of Automated Intermittent Pneumatic Mixing in Moisture-Controlled Anaerobic Digestion

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Abstract: Stable anaerobic digestion depends on both substrate preparation and reproducible mixing conditions inside the bioreactor. This paper presents an experimental evaluation of automated intermittent pneumatic mixing combined with moisture-controlled substrate preparation for anaerobic digestion systems. Moisture content and dry matter fraction of a prepared corn silage substrate were determined by thermogravimetric analysis and used to calculate the required water addition for target moisture levels before reactor loading using a wet-basis mass-balance approach. The main experimental comparison was performed between manual pneumatic mixing and automated intermittent pneumatic mixing controlled by a time relay and solenoid valve. The automated mode provides repeatable gas injection into the distribution chamber, reduces operator-dependent variability, and improves the reproducibility of the mixing regime. Experimental results showed that automated intermittent mixing increased total biogas production from 99.35 m³ to 125.63 m³, corresponding to an absolute increase of 26.28 m³ and a relative improvement of 26.45% compared with manual operation. In addition, intermittent operation reduced compressor duty cycle compared with hypothetical continuous mixing, indicating potential energy savings during long-term operation. The study introduces operational performance indicators for comparing mixing modes and applies a practical moisture-standardization procedure for substrate preparation. Unlike previous studies focused separately on substrate preparation or mixing automation, the proposed approach integrates moisture-controlled substrate standardization, automated pneumatic mixing, and operational performance evaluation within a single experimental workflow. The proposed method can be applied to small and medium-scale biogas plants where simple, low-cost automation is preferable to complex control systems while improving process stability and biogas productivity.

1 INTRODUCTION

Anaerobic digestion is widely used for the conversion of organic waste into biogas and stabilized digestate and is considered one of the key technologies for renewable energy production and sustainable waste management [1], [7]. The efficiency and stability of anaerobic digestion depend on a combination of biological, thermal, hydraulic, and mechanical factors inside the bioreactor. In addition to temperature control and microbial activity, substrate preparation and mixing conditions strongly influence mass transfer, gas release, and the uniformity of the digestion process [2], [6]. Insufficient or irregular mixing may lead to the formation of floating crusts, sediment accumulation, local temperature gradients, and stagnant zones with limited substrate circulation, which negatively affects biogas productivity and process repeatability [2], [7].

For small and medium-scale biogas plants, pneumatic bubbling is an attractive alternative to conventional mechanical mixing because it reduces the number of moving mechanical components inside the reactor and simplifies maintenance requirements. Pneumatic agitation can be implemented using relatively simple compressors, gas receivers, and bubbling pipelines, which makes this approach suitable for decentralized agricultural and rural biogas installations. However, in many practical systems the pneumatic mixing process is activated manually by the operator. As a result, the duration and frequency of agitation depend on operator attention and routine practice, introducing variability into reactor operation. Under such conditions, the same biogas plant may operate under different mixing regimes from one production cycle to another.

Automated intermittent pneumatic mixing offers a practical solution to this limitation. By integrating a solenoid valve and a time relay into the gas-distribution system, pneumatic bubbling can be activated according to a predefined schedule without continuous operator intervention. Such automation improves the repeatability of the mixing regime and stabilizes substrate agitation conditions inside the reactor. In addition, intermittent operation reduces compressor duty cycle compared with continuous mixing and therefore may decrease operational energy demand during long-term plant operation.

Substrate preparation is also an important factor influencing anaerobic digestion performance. The moisture content of biomass affects substrate rheology, pumpability, microbial accessibility, and the tendency of heterogeneous feedstock to form dense layers or local accumulations [5], [6]. In practical operation, the same nominal feedstock composition may exhibit different actual moisture levels because of seasonal variation, storage conditions, or raw-material heterogeneity. Consequently, uncontrolled moisture variation may influence biogas yield independently of the selected mixing mode. For this reason, moisture determination and water-addition calculation should be considered as part of a substrate-standardization procedure prior to evaluating mixing performance.

This paper presents an experimental and calculation-based evaluation of automated intermittent pneumatic mixing combined with moisture-controlled substrate preparation for anaerobic digestion systems. The study integrates:

1) thermogravimetric determination of substrate moisture content and dry matter fraction;
2) wet-basis mass-balance calculation of required water addition before loading;
3) experimental comparison of manual and automated intermittent pneumatic mixing modes;
4) operational performance indicators for evaluating biogas-yield improvement, repeatability, and potential energy reduction.

Experimental results demonstrated that automated intermittent pneumatic mixing increased total biogas production from 99.35 m^3 to 125.63 m^3, corresponding to an absolute increase of 26.28 m^3 and a relative improvement of 26.45% compared with manual operation. The automated mode also provided more reproducible mixing conditions and reduced operator-dependent variability.

Unlike previous studies focused either on substrate preparation or on mixing-system automation separately, the proposed approach integrates moisture-controlled substrate standardization, automated intermittent pneumatic mixing, and operational performance evaluation within a single practical workflow for anaerobic digestion systems. The proposed method is intended primarily for small and medium-scale biogas plants where low-cost and operationally simple automation solutions are preferable to complex industrial control systems.

The remainder of the paper is organized as follows. Section 2 describes the experimental system, substrate preparation procedure, moisture calculations, and the compared mixing modes. Section 3 presents the experimental results and discusses the influence of automated intermittent pneumatic mixing on biogas production, process repeatability, and operational performance. Section 4 summarizes the main findings and outlines directions for future research.

2 MATERIALS AND METHODS

This section describes the experimental system and calculation procedures used to evaluate automated intermittent pneumatic mixing in moisture-controlled anaerobic digestion. The methodology includes: (i) a description of the biogas plant and pneumatic bubbling system; (ii) the comparison of manual and automated mixing modes; (iii) substrate moisture determination and water-addition calculation prior to loading; and (iv) performance indicators used to assess biogas-yield improvement and operational repeatability. Moisture content was determined by thermogravimetric analysis with time–mass recording, while the required water addition was calculated using a wet-basis mass balance [5], [6]. The automated mixing mode was implemented using a solenoid valve and a time relay, enabling repeatable gas injection into the distribution chamber according to a predefined schedule [4].

2.1 Experimental Biogas Plant and Pneumatic Mixing System

The experimental system was based on a biogas plant equipped with a pneumatic bubbling system for substrate mixing. The system included a biochemical reactor, gas holder, water seal, compressor, receiver, distribution chamber, solenoid valve, and a set of perforated bubbling pipes installed in the lower part of the reactor. During operation, biogas accumulated in the upper part of the reactor was compressed and supplied through the distribution chamber into the bubbling pipes. The gas jets passed through the substrate layer and provided mixing by pneumatic agitation. This configuration reduces the need for mechanical moving elements inside the reactor and is suitable for small and medium-scale biogas installations.

The automated control unit consisted of a solenoid valve connected to a time relay. In the automated mode, the relay opened and closed the solenoid valve according to a predefined schedule, allowing gas injection into the distribution chamber without manual operator intervention. In the experimental configuration, intermittent mixing was applied every 4 h 30 min for 30 s, which was selected as the operating schedule for automated pneumatic agitation.

2.2 Mixing Modes Compared

Two pneumatic mixing modes were considered in this study: manual pneumatic mixing and automated intermittent pneumatic mixing. In the manual mode, gas supply to the distribution chamber was activated by the operator through a valve. Therefore, the timing and duration of mixing depended on operator attention and routine practice. This mode represents the conventional operation of simple pneumatic mixing systems used in small and medium-scale biogas plants.

In the automated intermittent mode, gas supply was controlled by a solenoid valve connected to a time relay. The valve was opened and closed according to a predefined schedule, which provided repeatable activation of pneumatic bubbling and reduced operator-dependent variability. In the experimental configuration, the mixing system was activated every 4 h 30 min for 30 s. This mode was selected to provide regular substrate agitation while avoiding continuous energy demand.

For methodological comparison, continuous mixing was also considered as a reference concept. Unlike intermittent mixing, continuous operation provides permanent agitation but may increase energy consumption and may not be necessary for small-scale systems where periodic substrate agitation is sufficient. Therefore, the main experimental comparison in this paper focuses on manual and automated intermittent pneumatic mixing, while continuous operation is used as an energy-related reference scenario. The considered mixing modes are summarized in Table 1 for clarity of comparison.

The following subsection describes the substrate preparation and moisture-control procedure used to standardize the feedstock before comparing mixing performance.

2.3 Substrate Preparation and Moisture Determination

A prepared corn silage substrate was used as the test material for moisture determination. Because heterogeneous biomass can exhibit local moisture variation, the bulk substrate was manually mixed before sampling to improve representativeness and reduce sampling bias [5], [6]. A test portion was then taken from the mixed substrate and immediately placed on the analyzer pan to minimize unintended moisture change during handling.

Moisture measurements were performed using a laboratory moisture analyzer Kern MLB 50-3N. The instrument operates by thermogravimetric moisture determination: the sample is weighed, heated under a controlled program, and the mass loss is recorded until the measurement endpoint is reached. This procedure is consistent with standard gravimetric approaches for moisture and solids determination widely used in biomass and wastewater analysis [3]. The analyzer provides moisture readings with a resolution of 0.01% and mass readings with a resolution of 0.001 g, with a maximum load of 50 g [8].

Table 1: Mixing modes considered in the study.

Mixing mode	Control principle	Mixing activation	Main limitation / feature
Manual pneumatic mixing	Operator-controlled	Manual opening of gas supply valve	Human factor; irregular timing
Automated intermittent pneumatic mixing	Time relay + solenoid valve	Every 4 h 30 min for 30 s	Repeatable operation; reduced operator dependence
Continuous mixing	Constant operation	Continuous or near-continuous agitation	Higher energy demand

The determination procedure included the following steps. First, the analyzer was prepared and tared with the empty pan. Second, the test portion was placed on the pan and evenly distributed as a thin layer to promote uniform heating and drying. Third, the drying program was started, and the analyzer recorded sample mass as a function of time. The run was completed when the endpoint criterion of the analyzer was reached, corresponding to stabilization of the measured mass. For the demonstrated run, the total measurement duration was 18 min 30 s.

The recorded time–mass data were subsequently used to calculate wet-basis moisture content, dry matter fraction, and the initial moisture value required for the water-addition calculation.

The next subsection presents the mass-balance equations used to calculate moisture content, dry matter fraction, and the amount of water required to reach target substrate moisture before loading.

2.4 Moisture and Water-Addition Calculations

To standardize the initial substrate condition before comparing mixing modes, moisture content and dry matter fraction were determined for the prepared substrate portion. Moisture content was determined by a gravimetric approach based on the initial (wet) sample mass and the final (dry) mass after completion of the drying program [5], [6]. The following quantities were used:

Initial mass: m_0;

Final (dry) mass: m_d;

Using m_0 and m_d, the moisture content on a wet basis, W (%), was calculated according to (1), where ($m_0 - m_d$) represents the mass of water removed during drying:

$$W = \frac{m_0 - m_d}{m_0} * 100\%. \tag{1}$$

The dry matter fraction, DM (%), was then determined as the complement of moisture on a wet basis according to (2):

$$DM = 100\% - W. \tag{2}$$

For reporting purposes, the water mass contained in the analyzed portion was calculated according to (3):

$$m_w = m_0 - m_d. \tag{3}$$

To estimate the amount of mixing water required to reach a target wet-basis moisture, W_t (%), for a given substrate mass, M, a wet-basis mass balance was applied [2], [6]. Let W_0 (%) denote the measured initial moisture content of the substrate (wet basis). Assuming that added water affects only the water fraction while the dry matter mass remains constant, the required added water mass, M_{add}, was calculated according to (4):

$$M_{add} = M * \frac{W_t - W_0}{100 - W_t}, \tag{4}$$

where mw is the water mass in the analyzed portion; M and M_{add} are expressed in the same mass units (e.g., kg); and W_0 and W_t are expressed in percent.

In this study, the moisture-control calculation was used as a substrate-standardization step, ensuring that differences observed between manual and automated pneumatic mixing modes were not primarily caused by uncontrolled variation in initial substrate moisture. For operational use, the water-addition calculation can be implemented as a simple spreadsheet or summarized as guideline values per 100 kg of substrate for typical target moisture levels.

In Section 3, the recorded time–mass data are first used to compute W, DM, and practical guideline values of M_{add} per 100 kg of substrate. These standardized substrate-preparation parameters are then linked to the comparison of manual and automated pneumatic mixing modes.

2.5 Performance Indicators for Comparing Mixing Modes

To evaluate the influence of pneumatic mixing mode on anaerobic digestion performance, a set of operational and energy-related indicators was introduced. The indicators were selected to characterize biogas productivity, process repeatability, and potential reduction in energy consumption under automated intermittent operation.

The primary performance metric was the total biogas production obtained under each operating mode. The absolute increase in biogas production was calculated according to (5):

$$\Delta V = V_{auto} - V_{manual}, \tag{5}$$

where V_{auto} is the total biogas volume obtained under automated intermittent pneumatic mixing, and V_{manual} is the total biogas volume obtained under manual pneumatic mixing.

To compare the efficiency of the two operating modes, the relative biogas-yield improvement was determined according to (6):

$$I_{BG} = ((V_{auto} - V_{manual}) / V_{manual}) \times 100\%, \tag{6}$$

where I_{BG} represents the percentage increase in biogas production relative to the manual mode.

In addition to gas yield, process stability and operational repeatability were considered. In manual operation, the activation of pneumatic bubbling depends on the operator and may vary in duration and timing between cycles. In contrast, the automated intermittent mode provides repeatable activation intervals through the use of a time relay and solenoid valve. Therefore, repeatability of mixing activation was used as a qualitative indicator of process stability.

To evaluate operational efficiency, the energy demand associated with pneumatic mixing was estimated. The energy consumption of the mixing system during operation was calculated according to (7):

$$E_{mix} = P \times t_{on}\,, \tag{7}$$

where P is the power of the compressor or gas-supply equipment, and ton is the total operating time during the considered period.

For comparative analysis, continuous mixing was considered as a reference operating scenario. The potential energy saving achieved by intermittent mixing relative to continuous operation was estimated according to (8):

$$SE = (1 - E_{int} / E_{cont}) \times 100\%, \tag{8}$$

where E_{int} is the energy consumption under intermittent operation and E_{cont} is the estimated energy consumption for continuous mixing over the same period..

Under the experimental schedule used in this study, pneumatic mixing was activated every 4 h 30 min for 30 s. Such intermittent operation substantially reduces the cumulative compressor operating time compared to continuous agitation while maintaining regular substrate mixing. Consequently, the automated intermittent mode combines improved operational repeatability with lower expected energy demand.

The proposed indicators provide a practical framework for comparing pneumatic mixing modes in terms of biogas productivity, process stability, and operational efficiency. The following section presents the experimental results obtained from substrate moisture measurements and from the comparison of manual and automated intermittent mixing modes.

3 RESULTS AND DISCUSSION

3.1 Substrate Moisture and Water-Addition Results

Following the procedure described in Section 2.3, a time–mass record was obtained during thermogravimetric drying of the prepared corn silage substrate. Table 2 reports the measured sample mass as a function of time. The sample mass decreased monotonically from 2.000 g to 0.475 g due to moisture removal and approached a quasi-stable value toward the end of the run, which is consistent with the analyzer endpoint criterion based on mass stabilization [5]. The total duration of the demonstrated measurement was 18 min 30 s.

Table 2: Time–mass data recorded during moisture determination of the substrate.

Time, t (min)	Measured mass,m (t) (g)
0	2.000
1	1.800
2	1.710
3	1.560
4	1.410
5	1.280
6	1.167
7	1.060
8	1.000
9	0.930
10	0.833
11	0.750
12	0.690
13	0.674
14	0.630
15	0.600
16	0.570
17	0.520
18	0.480
18.5	0.475

Using the final stabilized mass as m_d, the next subsection calculates the wet-basis moisture W, dry matter fraction DM, and the corresponding mixing-water requirement for typical target moisture levels. These values are used to standardize substrate preparation before comparing manual and automated pneumatic mixing modes.

3.2 Moisture Content and Dry Matter Fraction

Using the initial wet mass m_0 and the final dry mass md obtained at the analyzer endpoint, the substrate moisture content on a wet basis and the dry matter fraction were calculated according to (1)–(3). The initial wet mass was 2.000 g, while the final dry mass after thermogravimetric drying was 0.475 g. Therefore, the water mass removed during drying was 1.525 g.

The resulting values of W, DM, and mw for the tested substrate portion are summarized in Table 3. These parameters quantify the initial condition of the substrate batch and can be used as input data for standardized substrate preparation. In the context of this study, they help reduce the influence of uncontrolled feedstock-moisture variation when comparing manual and automated pneumatic mixing modes.

Table 3: Moisture content and dry matter fraction for the tested substrate portion.

Parameter	Symbol	Value
Initial wet mass (g)	m_0	2.000
Final dry mass at endpoint (g)	m_d	0.475
Water mass in portion (g)	m_w	1.525
Moisture content, wet basis (%)	W	76.25
Dry matter fraction (%)	DM	23.75

The measured initial moisture W_0 = 76.25% was then used to calculate the amount of mixing water required for typical target moisture levels before evaluating the influence of mixing mode on biogas production.

3.3 Visual Observation of the Sample Before and After Drying

A visual comparison of the tested substrate portion before and after the thermogravimetric moisture-determination run is presented in Fig. 1. After drying, the sample exhibited the expected reduction in apparent wetness and a more compact structure, which is consistent with the measured mass decrease from 2.000 g to 0.475 g [5]. Although visual assessment was not used for quantitative evaluation, the image provides additional documentation of the tested material and supports the traceability of the laboratory procedure [6].

The measured initial moisture W_0 = 76.25% is used in the next subsection to estimate the required amount of added water for target moisture levels before comparing the effect of mixing mode on biogas production.

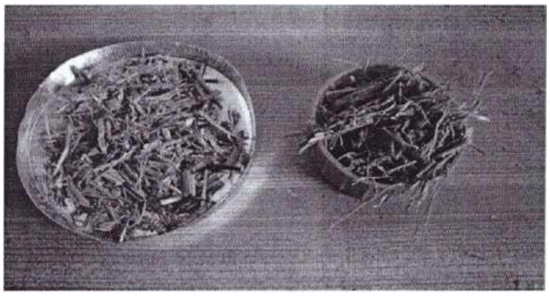

Figure 1: Tested substrate portion before and after thermogravimetric drying (moisture determination run).

3.4 Practical Estimation of Mixing Water or Target Moisture Levels

For operational use, the measured initial moisture W_0 = 76.25% can be applied to estimate the amount of added water required to reach a target moisture level before loading. For a substrate batch of mass M with initial wet-basis moisture W_0 and target wet-basis moisture W_t, the required added water mass Madd was estimated using the wet-basis mass balance defined in (4). The calculation assumes that the added water contains no dry matter and that the dry matter mass of the substrate remains constant during dilution [2], [6].

For routine operation, (4) was evaluated for a reference batch mass of M = 100 kg to obtain practical guideline values. Table 4 summarizes the corresponding added water mass M_{add} required to reach typical target moisture levels.

Table 4: Example guideline values of added water per 100 kg of substrate for typical target moisture levels.

Target moisture, W_t (%)	Added water per 100 kg, M_{add} (kg)
85	58.33
92	196.88

The values in Table 4 were calculated directly from the measured initial moisture W_0 = 76.25% using the wet-basis mass balance in (4). Therefore, they represent exact calculation values for the tested substrate portion and may differ from rounded operational guideline values based on tabulated initial-moisture categories.

The estimate applies when $W_t > W_0$, that is, when substrate moisture is increased by adding water.

If $W_t \leq W_0$, water addition is not required; achieving a lower moisture level would require dewatering or mixing with a drier co-substrate. These values provide standardized substrate-preparation parameters and reduce the risk that differences in biogas production are caused by uncontrolled variation in initial moisture.

The next subsection presents the main experimental comparison of manual and automated pneumatic mixing modes using biogas-production data.

3.5 Biogas Production Comparison Under Manual and Automated Mixing Modes

The main experimental comparison was performed between manual pneumatic mixing and automated intermittent pneumatic mixing [9]. In the manual mode, gas supply to the pneumatic bubbling system was activated by the operator. In the automated mode, gas injection was controlled by a time relay and solenoid valve, providing repeatable intermittent mixing according to a predefined schedule.

The experimental results demonstrated that automated intermittent pneumatic mixing increased the total biogas production from 99.35 m^3 in the manual mode to 125.63 m^3 in the automated mode. The absolute increase in biogas production was 26.28 m^3, corresponding to a relative improvement of 26.45% compared to manual operation.

Table 5 summarizes the comparative biogas-production results for the investigated mixing modes.

Table 5: Comparison of biogas production under manual and automated pneumatic mixing modes.

Mixing mode	Total biogas production, V (m^3)	Absolute increase, ΔV (m^3)	Relative increase, IBG (%)
Manual pneumatic mixing	99.35	—	—
Automated intermittent pneumatic mixing	125.63	26.28	26.45

The obtained results indicate that automated intermittent pneumatic mixing improves both biogas productivity and operational repeatability. The predefined activation schedule ensured more stable and reproducible substrate agitation compared with manual operation, where the mixing regime depends on operator intervention. More regular pneumatic bubbling likely contributed to improved substrate homogenization and reduction of stagnant zones inside the reactor, which positively influenced the anaerobic digestion process.

The results additionally suggest that intermittent automated mixing may provide operational advantages over continuous agitation by reducing unnecessary operating time of the pneumatic system while maintaining stable reactor performance. Further analysis of operational stability and energy-related aspects is presented in Section 3.6.

3.6 Operational Stability and Energy Considerations

In addition to the increase in total biogas production, the automated intermittent pneumatic mixing mode demonstrated improved operational stability and reduced dependence on manual operator intervention. In the manual mode, the activation time and duration of pneumatic bubbling depended on routine operational practice and therefore could vary between operating cycles [10]. Such variability may lead to irregular substrate agitation, uneven gas distribution, and the formation of stagnant zones inside the reactor.

In contrast, the automated intermittent mode ensured repeatable activation of pneumatic bubbling through the use of a time relay and solenoid valve. The predefined operating schedule (30 s activation every 4 h 30 min) maintained regular substrate agitation throughout the digestion process while minimizing unnecessary compressor operation. As a result, the automated mode provided a more reproducible mixing regime and reduced the influence of human-factor-related variability.

From an operational perspective, intermittent pneumatic mixing also decreases the cumulative operating time of the gas-supply equipment compared with continuous agitation. Assuming a continuous operating mode as a reference scenario, the intermittent schedule used in this study corresponds to a substantially lower duty cycle and therefore lower expected electrical energy consumption of the compressor system. Although direct electrical measurements were not performed in the present work, the reduction in operating time indicates the potential for energy savings during long-term reactor operation.

The combination of increased biogas yield, improved repeatability of mixing activation, and reduced expected operating time of the pneumatic system demonstrates the practical suitability of automated intermittent mixing for small and medium-scale anaerobic digestion systems. These results support the use of simple automation elements as an effective approach for improving both process stability and operational efficiency in biogas plants.

4 CONCLUSIONS

This paper presented an experimental and calculation-based evaluation of automated intermittent pneumatic mixing combined with moisture-controlled substrate preparation for anaerobic digestion. The substrate preparation stage included thermogravimetric determination of moisture content and dry matter fraction in a prepared corn silage substrate. The measured initial wet mass was 2.000 g, and the final dry mass at the endpoint was 0.475 g, corresponding to a wet-basis moisture content of 76.25% and a dry matter fraction of 23.75%. These values were used to calculate the required water addition for target substrate moisture levels before loading.

The main experimental comparison demonstrated that automated intermittent pneumatic mixing increased total biogas production from 99.35 m³ in the manual mode to 125.63 m³ in the automated mode. The absolute increase was 26.28 m³, while the relative improvement compared to the manual mode reached 26.45%. The automated mode provided repeatable gas injection through a time relay and solenoid valve, reducing operator-dependent variability and improving the stability and reproducibility of the mixing regime.

The study additionally introduced operational indicators for evaluating mixing performance, including biogas-yield improvement, process repeatability, and estimated energy efficiency. Although direct electrical measurements were not performed, the intermittent operating schedule substantially reduced compressor operating time compared with continuous mixing, indicating the potential for lower energy consumption during long-term operation.

The novelty of the proposed approach lies in combining substrate moisture standardization, automated intermittent pneumatic mixing, and operational performance assessment within a single practical workflow for anaerobic digestion systems. The proposed method is particularly suitable for small and medium-scale biogas plants where low-cost automation and stable operating conditions are important.

Further research should include direct monitoring of compressor energy consumption, long-term evaluation of daily biogas productivity, investigation of different intermittent mixing schedules, and validation of the proposed approach under varying substrate compositions and reactor loading conditions.

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