Solar-biomass hybrid renewable energy system for controlled environment agriculture in developing regions: a systematic review and research direction

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Abstract. In tropical underdeveloped countries, inadequate and unreliable electricity hinders the adoption of controlled environment agriculture (CEA) greenhouse farming, which could increase farm produce and reduce food insecurity. To meet the power supply challenge, countries with abundant renewable energy resources should embrace viable sustainable energy solution, such as a solar-biomass hybrid energy system. This study presents a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-guided review of fifteen peer-reviewed studies to show that the deployment of solar-biomass hybrid systems for CEA-greenhouse farming is scarce in tropical regions. Furthermore, the regular simulation-based and metaheuristic algorithms - such as genetic algorithms and particle swarm optimisation - commonly used to resolve hybrid renewable energy systems (HRES) do not account for the dynamic nature of greenhouse loads, integration of reliability factors, joint optimisation of system sizing and dispatch, solutions tailored for tropical conditions, and validation of optimisation outcomes. In view of these gaps, a five-layer framework comprising contextual resource modelling, component realism, joint optimisation, resilience engineering and prototype validation is proposed. This review charts a pathway from heavy simulation-based studies to resilient, site-specific applications for tropical greenhouse farming, explicitly linking methodological advances with practical deployment to strengthen energy access and sustainable food production goals.

1. Introduction

The power supply challenges faced by many developing countries directly limit their adoption of life-improving innovations such as controlled environment agriculture (CEA) greenhouse farming [1]. CEA is an innovative farming method that allows for year-round crop cultivation and would lead to increase in agricultural output, but it requires a steady, reliable power supply and other special provisions like greenhouses for its adoption [2]

For Sub-Saharan and South Asian countries with abundant renewable energy sources, hybrid renewable energy systems are a necessary pathway to solving their power supply challenges [3-5]. A review on the deployment of hybrid renewable energy systems (HRES) in developing countries shows that mini-grid solutions are technically feasible, but their widespread adoption is hindered by high initial capital costs, insufficient policy incentives, and limited local technical capacity. Therefore, a solar-biomass hybrid renewable energy system incorporating a battery bank is a viable means of power supply to meet the load profile of a CEA-based greenhouse for crop cultivation [5]. It is a system that makes use of solar irradiation and agricultural feedstock through renewable technology to generate dispatchable electricity required for maintaining the ambience within a greenhouse farm [6].

Many studies have shown that the adoption of HRES resolves the challenges associated with weak grids such as outages, voltage fluctuations, lack of or inadequate power supply to health centres and many rural communities that do not have grid supply [7, 8]. Nguyen et al. (2024) [9] carried out their study on solar-biogas-battery configuration for rural electrification and Olatomiwa et al. (2023) [8] worked on the deployment of HRES for healthcare facilities in Nigeria.

What is evident in this field of study is the rapid growth within it, moving from just feasibility studies to the use of advanced optimisation methods – mixed-integer linear programming (MILP) and metaheuristic algorithms - for determining various aspects and factors relevant to the workability of HRES before acquisition and deployment [10].

Some recent studies show that structural gaps still exist in the HRES born out of these advanced optimisation methods. The variable nature of greenhouse loads, and the swing in system voltage and frequency are not accounted for in the optimisation process as they are mostly considered to be stable or just fixed [11]. Another

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gap is the optimisation of sizing and dispatch separately or just sizing alone [1, 10], a situation that leads to oversizing of the system and underutilisation of flexibility of renewable resources like biomass. Furthermore, limited tropical region data are in use for tropical regions as opposed to the prevalent use of general global average data of solar irradiance, biomass availability and associated logistics [12]. Lastly, there is concern about the limited use of simulated outcomes for real-world CEA-based greenhouse prototypes; that is, prototype validations are rare [13].

This paper seeks to treat these gaps through preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. For this purpose, fifteen peer-reviewed journal articles on solar-biomass and other configuration of hybrid systems are examined with a view to charting a pathway consisting of a five-layered framework for the identified gaps. The proposed framework is integrated and emphasizes actual site resource modelling [14], component realism [9, 14], joint optimisation of sizing and dispatch [4, 15], prototype validation and resilience engineering [9] (survival of the designed system against extremities).

This proposed framework is such that it takes the solar-biomass hybrid system from just a simulation outcome to a real-world application that conveniently and sufficiently meets tropical greenhouse power supply needs for increased farming activities and crop yields. Beyond furthering the technical feasibility of renewable energy application, it strengthens the resilience of agricultural systems in developing regions.

2. Methodology

This systematic literature review (SLR) of solar-biomass hybrid renewable energy systems for CEA greenhouse farming in countries with weak grid power systems is done in line with PRISMA guidelines. The peer-reviewed journal articles that met the inclusion criteria were drawn from ScienceDirect and Google Scholar through the use of Boolean search strings, such as “solar-biomass hybrid”. Selected journal articles have varied combinations of optimisation tools – HOMER (Hybrid Optimisation of Multiple Energy Resources), MILP (Mixed-Integer Linear Programming), PSO (Particle Swarm Optimisation) and GA (Genetic Algorithm), and systems configurations.

Twenty-three journal articles were extracted; fifteen published between 2016 and 2026 were used. The selection process is illustrated in Fig. 1a, while the publication trend of the selected studies is shown in Fig. 1b. The database search was conducted in April 2026; studies published after this date are outside the scope of this review. The inclusion of literature that is not solely solar-biomass, covering rural electrification, healthcare HRES, and greenhouse systems in temperate regions in the PRISMA search, was deliberate to provide a comparative baseline.

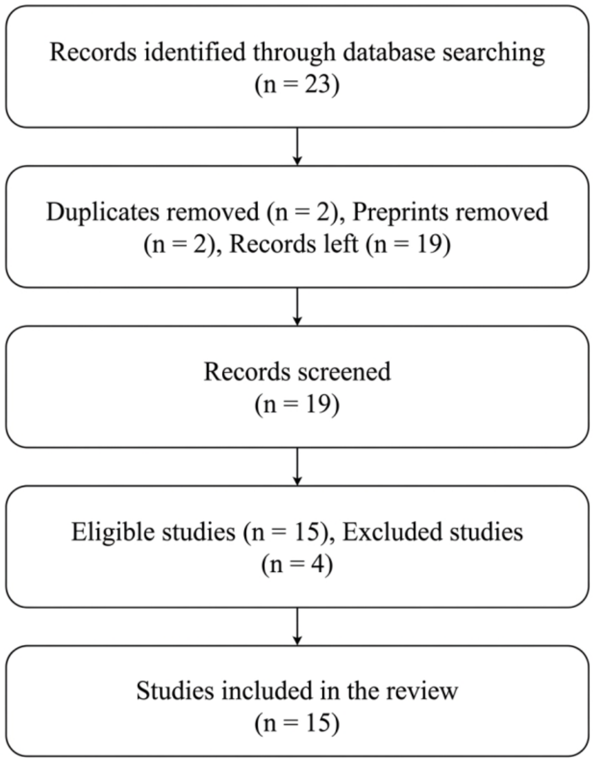

Fig. 1a. PRISMA flow diagram

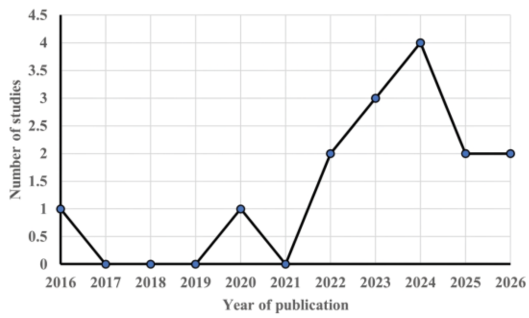

Fig. 1b. Publication trend of selected studies

This methodological choice was essential for demonstrating the central finding of this review: the scarcity of solar-biomass HRES research specifically for CEA greenhouses in developing regions. Therefore, to restrict this review only to greenhouse papers that cover only developing regions would eliminate the comparative evidence needed to situate and quantify the identified gap. This approach follows established systematic review practice, which supports transparent documentation of inclusion rationale in reviews that are tailored to establish gaps.

These fifteen journals cover system configurations, modelling approaches, optimisation methods, techno-economic metrics, areas of application and validation practices. In addition, the geographical spread of the studies - Nigeria, Ethiopia, Vietnam, Jordan, Egypt, Greece, Spain, and the United States – supports the framing of this paper. The methodological patterns seen in the dataset equally serve as the basis for developing this proposed framework.

Table 1. Comparative methodological dataset of all fifteen selected studies

Ref.	Configuration	Optimisation Method	Application Area	Techno-Economic Metrics	Type of validation / Identified Gap
[1]	PV+Wind+ESS (Battery)	Teaching and Learning Based Optimisation (TLBO)	Greenhouse agriculture in six zones of Nigeria	LCOE range: \$0.073/kWh (Kano) to \$0.172/kWh (Anambra); NPC range: \$373,371 (Ogun) to \$500,444 (Kano)	Comparative simulation using South Korea as reference. Gap: No biomass component included; used South Korean reference greenhouse data – not specific for Nigeria; no prototype validation.
[2]	Solar thermal adsorption cooling	Simulation model for custom adsorption cooling	Greenhouse climate control (hot-humid region)	Levelised annual cost of cooling: \$99.7/m^2 (Miami), \$83.6/m^2 (Houston); no LCOE/NPC for HRES	Simulation (case study). Gap: focus only on cooling; no electricity generation or dispatch optimisation; no biomass component; US-based climate data, not applicable to Sub-Saharan Africa or tropical developing regions; no prototype validation.
[3]	Hydro + PV + Wind + Diesel + Battery	HOMER Pro	Rural electrification in Ekwe, Imo State	NPC: \$1.01M; COE: \$0.106/kWh; RF: 77.4%; CO_2: 228,945 kg/yr	HOMER Pro; comparative analysis of seven configurations. Gap: No biomass in the optimal configuration; no greenhouse or CEA application; sizing only, no joint dispatch optimisation; no prototype validation.
[4]	Review (PV, Wind, Hydro, Biomass, and Fuel Cells)	Review of LP, GA, PSO, HOMER, and rule-based energy Management System (EMS)	General HRES – standalone and grid-connected (review)	No original techno-economic results; summarises cost and reliability outcomes of reviewed EMS techniques	It is a review paper on HRES. Gap: No site-specific results; no greenhouse or CEA application; no tropical developing-region context.
[5]	PV+ Biomass generator +Diesel +Battery	HOMER Pro	Rural electrification, Kajola, Ekiti State	COE: \$0.178/kWh; NPC: \$232,863; RF: 100%; average load: 52.75 kW; daily energy: 483.71kWh	Techno-economic feasibility analysis. Gap: Rural village load developed from on-site data; no greenhouse or CEA application; no weak-grid reliability metrics; no prototype validation; sizing without joint dispatch optimisation.
[6]	PV+Wind+Biogas	Multicriteria Decision Making (MCDM)	Agriculture (Farm facility in Nigeria)	LCOE: \$0.26/kWh; total cost of project: \$1,782,602 over 25 yrs; discounted payback: 7.22 yrs (simple payback: 5.84 yrs); CO_2: 16 kg/yrs	Case study (cost, emissions and payback analysis). Gap: Regular farm facility, not CEA greenhouse; sizing and dispatch not jointly optimised; no prototype validation.
[7]	PV + Biogas generator + Battery (grid-connected)	HOMER pro as a benchmark. Artificial Bee Colony (ABC), GA, PSO compared	Maizube dairy farm, Sabon Daga, Niger State.	LCOE: \$0.162/kWh, \$0.163/kWh, \$0.166/kWh (for PSO, GA and ABC); NPC: \$2.05M (PSO best); payback: 5yrs and 7 months; diesel usage reduced by 86%, and CO emission reduced by 96%	Benchmarked ABC, GA, and PSO algorithm against HOMER Pro used for validation. Gap: Dairy farm load, not a CEA greenhouse; dispatch treated separately from sizing; no dynamic greenhouse profiling; grid reliability modelled but not integrated into joint optimisation; no prototype validation.
[8]	PV+Wind+Diesel (grid connected)	HOMER Pro, load following dispatch	Rural health facilities, Nigeria (6 sites)	NPC range: \$32,167 (Kadassaka) to \$54,012 (Damare-polo) for optimal configurations; COE range: \$0.059 to \$0.115/kWh across 6 sites	Case study across six geopolitical zones in Nigeria. Gap: no biomass; no greenhouse or CEA application; sizing and dispatch handled separately; static healthcare load profile; no prototype validation.
[9]	PV+Biogas+Battery+Converter	HOMER Pro	Off-grid rural electrification, Vietnam	COE: \$0.48/kWh; NPC: \$25,730.89; RF: 100%; very low CO_2	Simulation, techno-economic metrics. Gap: Rural island electrification; no greenhouse or CEA application; static residential load; HOMER sizing only; no prototype validation.

[10]	PV+Wind+Batteries+Biomass generator	HOMER Pro	Microgrid for remote desert area	NPC: $3,483,519; COE: $0.118/kWh; GHG: 28,516 tonnes/yr	Sensitivity analysis, techno-economic simulation. Gap: No tropical or developing region applicability as arid climate data are not representative of tropical regions; biomass used as backup only, not as dispatch. No greenhouse or CEA application, no prototype validation, no joint dispatch optimisation.
[11]	PV + Wind + Battery + Fuel cell (generalized HRES)	Multi-objective GA	General HRES	The purchase of grid power reduced by 8.7-10.7% in single-objective against multi-objective strategies; no LCOE and NPC reported	Simulation-based validation (results compared across three multi-objective strategy cases – single, two and three objectives). Gap: No real-world case study; system parameters taken from literature; no site-specific or location data; no developing-region or tropical context; no biomass; no greenhouse or CEA application; sizing fixed from literature rather than optimised; no prototype validation.
[12]	PV + Wind + Battery + Biomass gasifier	Multi-objective GA (MOGA); three-time resolution compared	Electrification of Tilos Island, Greece	LCOE $0.21/kWh against diesel $0.46/kWh. RE coverage gets to 100% with hourly data but drops to 85.87-95.64% with minutes level setting as finer time resolution captures more gaps in renewable supply.	Multi-objective GA; three-time resolution compared (minute, 15-minute, and hourly). Gap: Used temperate mediterranean island context; no tropical or developing-region applicability; no greenhouse or CEA application; no dynamic agricultural load; no prototype validation.
[13]	Solar+Biomass +absorption chiller	TRNBuild simulation	Greenhouse for tomatoes	Biomass cost: 2.70 Eur/m^2/yr; Solar fraction: 54.92%; Coefficient of Performance (COP) of chiller 0.624. No LCOE& NPC reported.	Used monitored real-world greenhouse. Gap: Cover Mediterranean climate only. Thermal energy focus, no electrical HRES. No sizing or dispatch optimisation.
[14]	PV + Wind + Diesel + Battery	HOMER Pro	Rural electrification of Tulefa in Ethiopia	LCOE: $0.050/kWh; NPC: $68,363; RF: 98.8%; GHG emissions: 528 kg/yr (98.9% reduction against diesel-only)	Sensitivity analysis through HOMER Pro. Gap: Rural electrification focus; no biomass in the optimised configuration; no greenhouse or CEA application; no prototype validation; no joint dispatch optimisation.
[15]	PV+Diesel+ Hydrogen storage	Golden Jackal Optimisation (GJO) and PSO	Remote electrification in Jordan	Total NPC minimized; increased renewable penetration from 10% to 90%, raises total NPC by 39% with GJO outperforming PSO in convergence speed	Comparative results, reliability metrics. Gap: Electrification for general load; no biomass; no greenhouse or CEA application; hydrogen storage not viable for most developing region; sizing and dispatch treated separately; no prototype validation.

3. Result and Discussion

It is evident from the review of the fifteen selected journal articles that studies in solar-biomass hybrid energy systems have grown more during the 2020s. Among other factors, the growth in the studies can be attributed to the development and embrace of distributed energy systems aided by optimisation methods like MILP, metaheuristics (genetic algorithms, GA and particle swarm optimisation, PSO) and other advanced approaches. Earlier works were more on feasibility studies, and most renewable energy applications were directed at rural electrification and microgrids [3, 5], while their use for greenhouse farming remained scarce. Prieto et al. (2023) [13], in the Mediterranean, examined the use of solar-biomass for heating and cooling greenhouses, and Ahsan et al. (2026) [2] worked on solar-assisted adsorption cooling in tropical climates. However, there are methodological gaps such as static load assumptions and limited prototype validation which reduce the effectiveness and reliability of solar-biomass systems in practical applications, particularly in varying climatic conditions and diverse agricultural practices. Table 1 shows that HOMER Pro is the most commonly used simulation tool, while metaheuristic algorithms such as GA and PSO are gaining ground for optimisation. In the studies, the application area is clearly overtaken by rural electrification except for a few instances where studies are tailored for greenhouse farming. Furthermore, validation through prototype or real-world application is hardly the case, as most studies stopped at simulation and sensitivity analysis.

Another aspect seen in the reviewed studies lies in the configuration choices and the implication of such choices for greenhouse farming in tropical regions. Systems that combined solar PV and biomass tend to provide greater flexibility in terms of dispatch compared to PV and wind. The reason being that biomass can be stored and used when needed, thereby providing better control over voltage and frequency swings. The study carried out by Nguyen et al. (2024) [9] demonstrated that a solar-biogas-battery system would be reliable in rural Vietnam, while Prieto et al. (2023) [13] showed that the use of solar-biomass provided effective heating and cooling in the Mediterranean greenhouses. Combining solar and biomass equally becomes a means of managing livestock waste just as it underscores the inherent advantage of solar-biomass systems for harnessing sustainable development in developing regions. In contrast, PV-wind hybrids often underperform in tropical regions where wind speed is inconsistent, making solar-biomass systems more dependable for greenhouse energy needs.

Implementation of power supply solutions cannot be without economic consideration. Comparing techno-economic metrics across the reviewed studies, notable differences in results are seen. Where metrics are reported, the Levelised Cost of Energy (LCOE) ranges from about \$0.050/kWh to \$0.480/kWh depending on configuration, location, system sizing approach. Several studies do not report any techno-economic outcomes, creating a significant gap in the data. This situation is a particular challenge for deployment decisions in developing regions, where capital constraints are severe. The lack of data does not provide robust details that would-be adopters of CEA greenhouse farming methods would require to make an informed decision on investment choices and assess the feasibility of renewable energy projects in those areas.

Studies such as Emezirinwune et al. (2024) [6] highlight that hybrid systems can bring about a reduction in the levelised cost of electricity (LCOE) by 20 to 30% compared to systems that run on only diesel, with payback periods well within 5 to 10 years so long as a renewable energy source is available. Such cost and payback advantages give support to the economic viability of solar-biomass systems in agricultural applications, and are very relevant for subsistence farmers and people without financial muscle in Sub-Saharan Africa who would find it difficult to adopt renewable energy sources for farming engagement.

The case for hybrid systems in developing nations is made better because of the environmental benefits that come along with it. The use of biomass for energy generation reduces reliance on fossil fuels and promotes the conversion of agricultural and household waste into energy. This is in line with circular economic principles, turning waste into productive inputs as well as reducing the emission of greenhouse gases. This energy reliability and waste management potential positions solar-biomass hybrid systems as a sustainable means of agriculture in tropical regions. We see that without prototype validation; these benefits will remain largely theoretical. Pilot projects in tropical regions are very germane in confirming performance and would build confidence in practical application for human sustenance.

Therefore, the identified gaps need to be addressed for effective deployment of solar-biomass systems, an effort that will move beyond regular considerations like static loads, stable grids, separation of sizing and dispatch in optimisation processes. The implementation of real-world greenhouse farming avails proper validation of simulation results; this approach addresses the rarity of prototype greenhouse systems.

In the matter of identified gaps, the fifteen reviewed studies span four broad application areas, five addressed rural electrification – Oladigbolu et al. [3], Osalade et al. [5], Adetoro et al. [7], Nguyen et al. [9], and S. Yakubu et al. [14]; three examined greenhouse farming – Prieto et al. [13], Yakubu et al. [1], and Ahsan et al. [2]. While two more are the works of Olatomiwa et al. [4, 8], with one focused on healthcare facilities and the other on a general review of HRES with no site-specific application, the remaining five covered general or remote electrification contexts: Emezirinwune et al. [6], Torad et al. [10], Sharma et al. [11], Toudefallah and Stathopoulos [12], and Alsaqqar and Abuelrub [15]. That only three of the fifteen studies directly addressed CEA greenhouse farming – and none of them are located a developing tropical region – speaks to the very gap this review sets out to document.

4. Proposed Framework

This framework asserts that the design of a solar-biomass hybrid system for greenhouse farming should be tailored in line with the resources of a developing region. The modelling of solar, biomass, and climate data is to use actual data collected from the location of interest instead of adopting and using global averages that will give false outcomes. Similarly, the modelling of system components should be based on how they are meant to perform in the chosen region and location. For sizing and dispatch, joint optimisation of the twin will offer a system that has the capacity to meet daily power calls and accommodate the flexible use of biomass without having an oversized system. To achieve resilient HRES, the optimisation process should incorporate the fourth layer, which addresses weak-grid challenges like outages and fluctuations in voltage. Lastly, the results from the simulation should be used for real-life prototypes to confirm assumptions and ultimately build confidence in proposed design, as illustrated in Fig. 2.

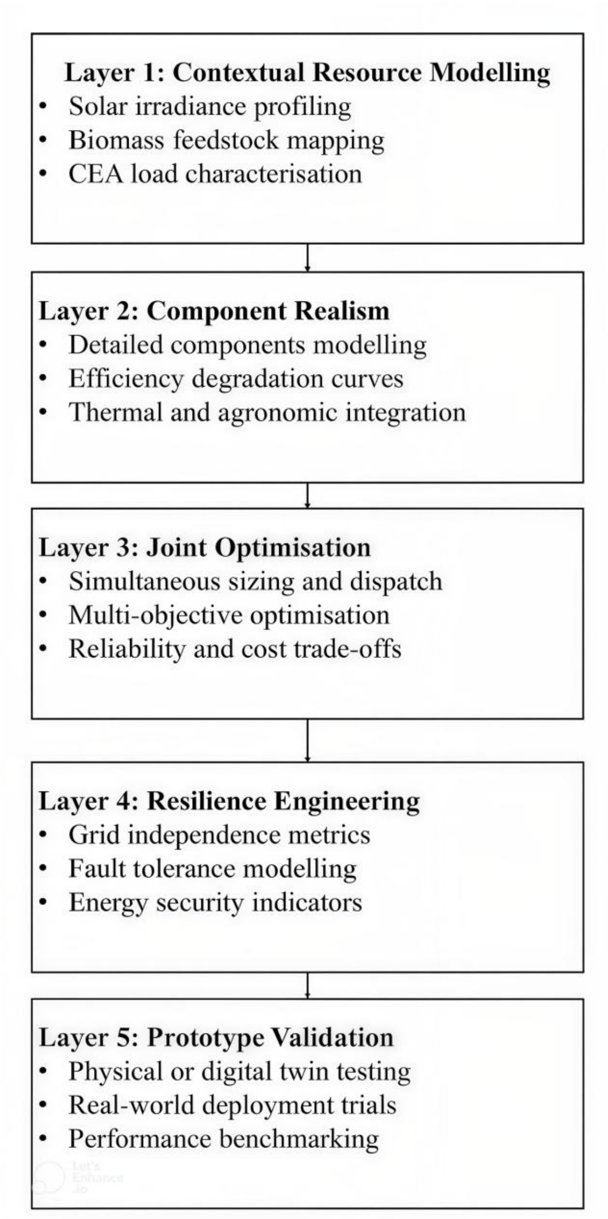

Fig. 2. Proposed five-layer framework for solar-biomass HRES in CEA

5. Conclusion

This review has attempted to show the progress and limitations of optimising solar-biomass hybrid renewable energy systems for CEA in developing regions. In addition, transitioning simulation results into real-life greenhouse farming purposes remains scarce in the tropical regions with weak power infrastructure, which hinders the effective implementation of these systems and limits their potential benefits for local farmers. Successful prototyping and deployment of HRES in agriculture will go a long way in solving food security concerns.

This proposed five-layered integrated framework offers a roadmap linking methodological advances with improved real-life greenhouse farming. Future work should focus on dynamic greenhouse load modelling, the integration of weak grid reliability, the expansion of tropical site-specific datasets, and the validation of the prototype. Addressing these priorities will move solar–biomass energy systems from being just theoretical models to applicable solutions, thereby strengthening energy access and agricultural productivity in tropical regions.

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