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A sustainable future: the impact of real-time feedback systems on water conservation efforts

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Lack of fresh water and population explosion are major sustainability challenges globally. Water management is closely linked to sustainable development goals (SDGs), as water is fundamental to sustainable development and plays a role in achieving all SDG targets, either directly or indirectly. This article explores the potential of sensor-based real-time feedback systems as a tool for promoting water conservation and addressing the global challenges of water scarcity. This approach aims to mitigate existing water issues by changing the behavior of people, encouraging the uptake of water conservation measures, and changing the patterns of utilization for long-term sustainability. It incorporates principles from behavioral science to modify user behavior by using information processing theory that exposes users to water scarcity messages. As a theoretical concept, the applications of the theory of planned behavior and nudge theory are explored to guide individuals' choices toward water-saving behaviors through feedback that subtly influences decision-making. Concerns such as cost, data privacy, and the sustainability of behavior change are discussed. The effectiveness of real-time feedback mechanisms has been demonstrated in other domains, such as energy conservation, yet remains underexplored in the context of water management. This article highlights the feasibility of such systems, examines their potential impact on water conservation efforts, and discusses key challenges such as cost, data privacy, and behavioral adaptability. By integrating sensor technology with water fixtures and providing instant feedback, individuals can be nudged toward sustainable consumption patterns, ultimately reducing the burden on water treatment facilities and ensuring long-term water security.

Sustainability spotlight

Water is the foundation of life, yet its scarcity threatens billions worldwide. A sustainable future demands proactive solutions, and real-time feedback systems for water conservation present a transformative opportunity. Integrating sensor-based technology with behavioral insights can empower individuals and communities to make informed choices by reducing water waste and alleviating pressure on treatment facilities. This innovation not only conserves a critical resource but also fosters economic resilience, environmental sustainability, and public well-being. Small actions, amplified at scale, have the power to secure water equity for future generations because sustainability is not just a goal; it is a responsibility.

Water: a pressing issue for our planet

Water is essential for human and environmental sustainability, yet pollution and scarcity pose severe challenges. Governments worldwide are increasingly recognizing the urgent need for water security. Despite advancements in water treatment technologies, pollution loads continue to overwhelm treatment facilities. Thus, conservation must complement treatment to ensure long-term sustainability.

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Challenges in water treatment

Modern water treatment technologies address an expanding range of pollutants, including microplastics and emerging contaminants such as PFAS (per- and polyfluoroalkyl substances). Even at low levels, these pollutants pose risks to human health, prompting scientists to develop more efficient and cost-effective removal methods. However, treatment alone cannot address the increasing stress on water resources. High water consumption exacerbates pollution, strains treatment capacities, and raises operational costs. Hence, reducing water use is critical for minimizing environmental and economic burdens.

The role of behavioral science in water conservation

A crucial aspect of sustainable water management is conservation. Simply put, reducing water consumption lessens the treatment burden and lowers the risk of pollution. To achieve this, we need to understand human behavior and people's responses to the calls for conservation. However, mass communication through conventional programs such as conferences, news articles or appeals made to the public are normally ineffective. Traditional awareness campaigns often fail to translate into sustained behavioral change. Despite expressing willingness, individuals struggle to adopt conservation habits due to a lack of immediate feedback. Behavioral science suggests that real-time information can significantly influence decision-making. Two key behavioral theories, the Theory of Planned Behavior and Nudge Theory, provide strong frameworks for guiding effective water conservation interventions. The Theory of Planned Behavior, as proposed by Ajzen,[1] posits that individual behavior is driven by intention, which is influenced by attitudes, subjective norms, and perceived behavioral control. In the context of water conservation, this theory can be applied to understand how people's intentions to conserve water are shaped. For instance, if individuals believe that saving water positively impacts the environment, and they perceive that they have control over their water usage, they are more likely to adopt water-saving behaviors. The theory also suggests that social aspects, such as observing others conserve water, can further enhance the likelihood of behavioral adoption. Nudge theory, as proposed by Thaler & Sunstein,[2] offers an alternative approach to subtly influence behavior without direct coercion. Unlike traditional behavior-change methods that require deliberate decisions, this theory focuses on structuring choices in a way that naturally leads individuals toward more sustainable decisions. By providing real-time feedback about water usage and its environmental impacts, individuals can be nudged toward conservation behaviors. For example, presenting users with messages comparing their water consumption to that of others or to social aspects can subtly influence them to adjust their behavior toward water conservation. These approaches are powerful tools for modifying human behavior regarding water utility through real-time feedback systems, guiding people towards better choices. Both theories emphasize the importance of feedback in influencing behavior. While the theory of planned behavior stresses the role of intention and perceived control, Nudge theory utilizes immediate, subtle cues to shape decisions without requiring overt cognitive effort from the user. By integrating sensor-based feedback systems, water conservation efforts can become more effective and engaging.

Sensor-based feedback systems for water conservation

A smart sensor-based system at water fixtures can provide real-time feedback, displaying usage data alongside conservation messages. Smart sensor-based systems differ from conventional flow meters by integrating real-time data analytics, user feedback interfaces, and connectivity (*e.g.*, Internet of Things (IoT)), enabling dynamic feedback and adaptive messaging, rather than simply recording aggregate water flow. For instance, users could see their water consumption compared to the daily limit for a drought-affected region. The system can also highlight how seemingly minor actions, like handwashing, contribute to overall water usage. This approach leverages psychological principles such as repetition and visual reinforcement to foster long-term behavioral change. Daily water consumption varies significantly depending on lifestyle and infrastructure, with estimates indicating that generally, for a 5-minute shower, around 70–90 liters of water are consumed, while for a 10- to 15-minute shower water usage increases to 160 to 240 liters respectively.[3] According to the IS 1172:1993 report,[4] the domestic water demand for low-income group colonies includes 5 liters for cooking, 5 liters for drinking, 55 liters for bathing, 40 liters for washing clothes, utensils, and house, and 30 liters for flushing water closets. Furthermore, this domestic water demand for urban communities under ordinary conditions can be increased to 200 liters per household per day. The estimated usage of water in airports is around 25–35 liters per passenger, for office buildings around 30–50 liters per person per day, for hotels 500 to 1500 liters per room per day, for shopping malls approximately 10–30 liters per person, and for restaurants, the usage is around 25–100 liters per meal served. Instances such as personal swimming pools, overuse of coolers, washing machines, dishwashers, and bidets; forgetting to turn off showers and taps; leaks in toilets, HVAC (heating, ventilation, and air conditioning) systems and washing vehicles frequently can lead to significant overconsumption of water than manageable requirement. This misuse of water not only increases stress on available water sources but also leads to wastage that could otherwise be allocated to more critical needs in other economically weaker communities.

This article proposes a novel approach to encourage water conservation by leveraging behavioral science and technology. The concept involves implementing sensor-based information systems at points of water use, such as faucets. These systems would provide real-time feedback on water usage. After using water, users would see the amount they consumed displayed along with a message correlating their use to global water scarcity. For example, it could show how their 20 liters used for a shower are compared to the daily water allowance for someone in a drought-stricken region. Additionally, the system could highlight the importance of even small amounts of water, like the 500 ml used for handwashing. With the power of repetition encountering this type of information, users are more likely to retain it and make conscious efforts to conserve water in the future. Integrating a proposed sensor-based feedback system with the water fixtures, as illustrated in Fig. 1, can help us in monitoring the water usage, instilling a feeling of responsibility and empowerment in individuals whenever it displays a comment. This activity has the potential to help build positive behavioral habits as individuals view their dashboard, and to encourage others to adopt it as both a personal and societal responsibility, thereby promoting water stewardship

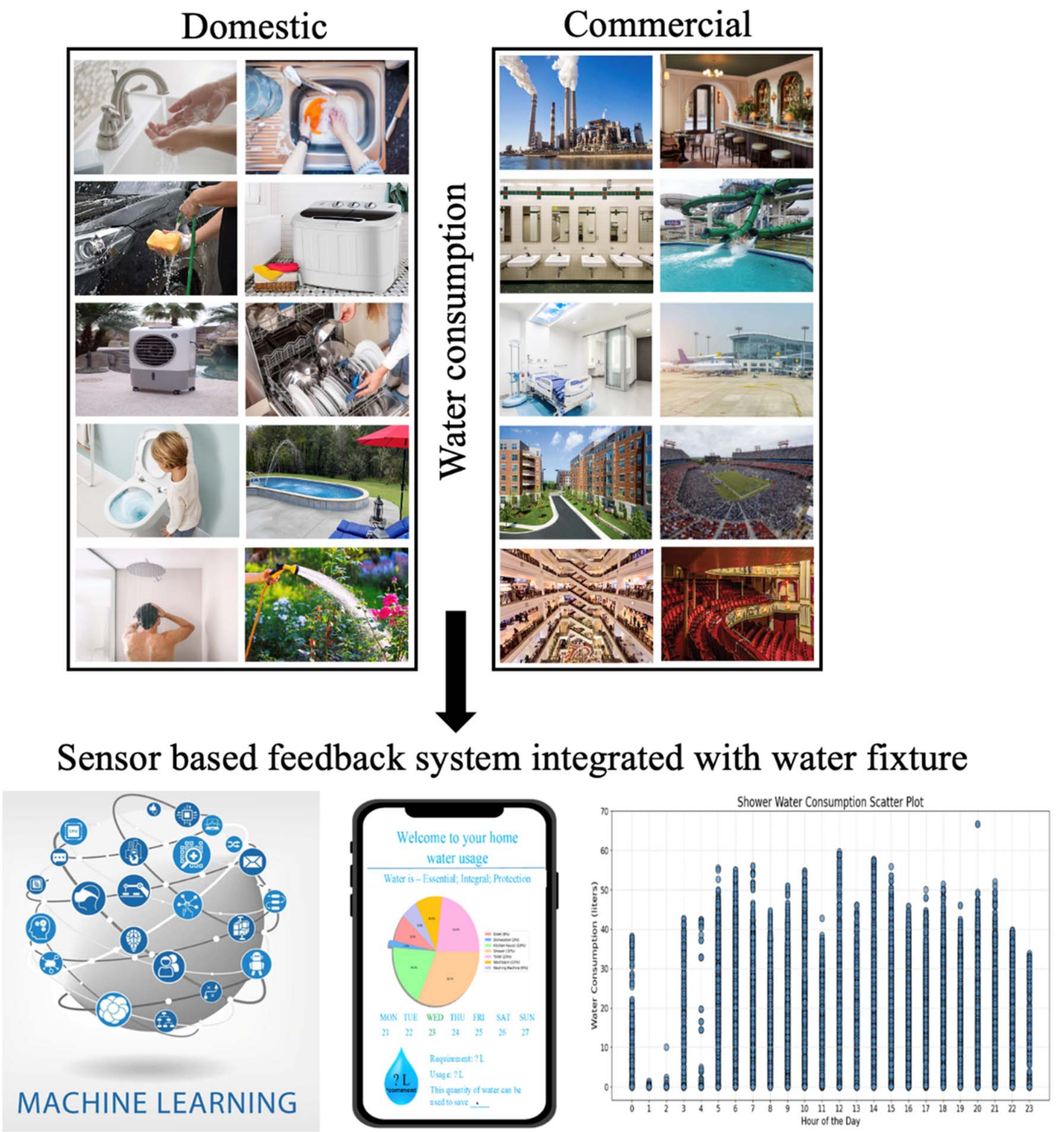

Fig. 1 Proposed smart sensor-based feedback system integrated with water fixtures.

within their communities. The goal is to support a subconscious response, prompting individuals to use less water each time they interact with the system at office/workplace, domestic and commercial places.

Impact of real-time feedback systems on water conservation

Real-time feedback systems have demonstrated significant potential in reducing water consumption and promoting sustainable practices. Studies have shown that providing individuals with real-time data on their water usage can lead to substantial reductions in consumption. For instance, a study conducted by researchers from the University of Surrey, University of Plymouth, and Universidad de Alicante examined the impact of displaying water usage data to hotel guests during showers. Over 17 500 showers, empirical evidence revealed that continuous eco-feedback resulted in a 25.79% reduction in water runtime during the first intervention. In a second intervention, the most effective message designed to reflect selfless value orientation while requiring high-effort behavior further led to a 23.55% reduction. This study highlighted how immediate feedback influenced user behavior, encouraging shorter shower durations and subsequently reducing water consumption, energy use, and carbon emissions. Notably, these reductions occurred despite participants being unaware of the experiment, having no economic motivation to conserve resources, and engaging in private behavior without direct peer pressure.[5] A similar application in India further emphasizes the role of real-time monitoring in sustainable water management. At Indian Institute of Technology (IIT) Jodhpur, a smart graded-water supply grid equipped with IoT-enabled sensors was implemented to monitor real-time water flow, pressure, and quality within the campus.[6] While primarily designed for operational efficiency, this initiative also showcases how technological advancements can be leveraged to minimize wastage and optimize resource distribution at institutional levels. These findings underscore the feasibility of using sensor-based systems to improve water management, promote behavioral adaptation, and enhance long-term sustainability. However, existing studies primarily focus on consumption data and short-term behavioral responses, rather than addressing long-term behavioral transformation. By integrating planned behavior theory and nudge theory into feedback mechanisms, these systems could drive a more holistic and enduring shift in user behavior. Planned behavior theory suggests that individuals' actions are guided by intentions, attitudes, and social norms, which can be reinforced through continuous feedback. Meanwhile, nudge theory emphasizes the subtle psychological prompts that can guide people toward sustainable behaviors without restricting their choices. Incorporating such behavioral insights into real-time feedback mechanisms by designing personalized messages and adaptive prompts can enhance the effectiveness of water conservation efforts. Providing immediate visibility into consumption patterns, alongside behavioral nudges, has the potential to empower individuals and organizations to adopt more mindful practices, ensuring long-term sustainability in water management.

Global applicability and implementation

To maximize its impact, this system must be adaptable across different regions and cultures. Communicating informative messages through visuals and text tailored to local contexts is essential for effectiveness. The sensor technology can seamlessly integrate with existing plumbing fixtures without requiring major modifications; however, the design of feedback mechanisms must be customized to ensure cultural relevance and acceptance. Visual and text-based messaging strategies, customized to local languages and cultural norms, can enhance user engagement and promote long-term behavioral changes. The benefits of this system extend beyond individual water savings; it can significantly reduce overall consumption and decrease the pollution load on treatment facilities. Ultimately, this would contribute to a more sustainable and resilient water future. However, a critical examination of its limitations and potential unintended consequences such as sensitivity to local conditions and recognition, is necessary for a balanced perspective. For instance, in water-scarce regions of sub-Saharan Africa, messaging could reference local (traditional) water-fetching practices or highlight the burden on women and children, who are often responsible for collecting water. In contrast, in urbanized areas of East Asia, where water usage tends to be high in bathing and hygiene routines, culturally resonant messages might emphasize respect for shared community resources or ancestral responsibility toward nature. Language is another crucial aspect. In multilingual societies such as India or South Africa, feedback system should support local languages to maximize understanding and emotional resonance. Messages delivered in a native tongue tend to be more impactful and better retained. Similarly, using locally relevant imagery or symbols such as regional landmarks, or traditional motifs can further personalize the experience and make conservation messages more relatable. As demonstrated by Buccione[7] in Jordan, the use of religious framing led to a 17% reduction in water use among women attending religious classes, highlighting the power of culturally rooted communication. Water-use behaviors also vary widely. While some cultures emphasize ritual cleansing or water-based hospitality, others may associate water conservation with austerity or poverty. Designing feedback that aligns with positive cultural values (*e.g.*, stewardship, frugality, and harmony with nature) rather than guilt or deprivation can ensure broader acceptance and long-term impact. Nonetheless, certain contextual challenges remain. In regions with water pricing disparities or weak infrastructure, real-time feedback may not yield uniform results. Some users might adopt temporary conservation habits, while others could experience feedback fatigue, reducing long-term efficacy. Moreover, concerns about privacy, data security, and equitable access are particularly relevant in low-income communities where digital literacy and technological infrastructure are limited. Despite these challenges, the potential of real-time feedback systems extends beyond individual behavior change.

To ensure effective and scalable deployment, a phased implementation roadmap can be adopted. Priority should be given to institutions and communities where the infrastructure for water use is centralized and data can be easily collected, such as educational campuses, hospitals, government buildings, and high-footfall commercial zones like airports and malls. These settings offer controlled environments suitable for pilot testing and data-driven refinement of the system. Following this, scale-up efforts can be directed toward urban residential communities with high water usage, using municipal partnerships to support widespread adoption. The conceptual deployment framework includes four key stages: (i) Pilot Phase: select controlled environments for initial trials and feedback refinement; (ii) Evaluation Phase: assess behavioral impact, water savings, and user engagement; (iii) Policy Integration Phase: involve local governments to create incentives, such as subsidies or rebates; and (iv) Expansion Phase: deploy to wider public, incorporating lessons learned and customizing feedback systems for cultural and linguistic contexts. Collaborations with water utility companies, municipal bodies, and educational institutions will be essential at every stage to ensure context-specific rollout and operational sustainability. Successful implementation requires a multidisciplinary approach, incorporating engineering, behavioral science, and policy frameworks to ensure scalability and effectiveness across diverse settings. Adapting these sensor-based interventions to local contexts while addressing behavioral and structural challenges will play a crucial role in achieving a more sustainable and resilient global water future.

Challenges and strategic resolutions

Implementing sensor-based water conservation systems in homes and public facilities presents several challenges. However, with well-planned strategies, these challenges can be transformed into opportunities to improve water management and conservation on a large scale.

Cost and implementation

The initial cost of installing sensor-based systems may hinder widespread adoption. However, a comprehensive cost-benefit analysis, considering long-term water savings and financial returns, can demonstrate economic feasibility. Governments and organizations can subsidize installations or negotiate bulk-purchasing agreements with technology providers to reduce costs. Moreover, incentives such as tax credits or rebates can encourage adoption, ensuring affordability across various demographics.

Data privacy concerns

Users may be apprehensive about the collection of water usage data and the privacy aspects involved. To address these concerns, ensure ethical feasibility, and promote public trust, sensor-based systems should implement strong data privacy safeguards. Governments and officials can help build public interest by explaining how data will be utilized and safeguarded. These include anonymization techniques (such as differential privacy, which adds statistical noise to data to prevent individual identification), user consent protocols that clearly inform users about data collection and usage, and compliance with relevant data privacy regulations (*e.g.*, General Data Protection Regulation[8] or local equivalents such as Digital Personal Data Protection Act[9]) to ensure transparency and accountability. Educational forums that address these privacy issues can ease public concerns and encourage participation. Additionally, privacy-enhancing technologies like federated learning and homomorphic encryption can be used to process data securely without exposing raw user information. Furthermore, it will be possible to show the advantages of data collection toward minimizing overall water usage, whereby trust between members of various communities will be fostered. Governments and responsible organizations should transparently communicate these safeguards to build public trust and ensure the ethical feasibility of large-scale deployment.

Long-term behavior change

It will be noteworthy that the effect of change management in water conservation measures may not be immediately tangible because of the human psychological factor where individuals may initially ignore changes in their water usage. In order to bring about long-term changes in the behavior of the users, the system should also give feedback about water consumption patterns. This concept may not yield immediate results due to human psychology. People often need repeated exposure to a message before taking action. Therefore, while initial exposure might be ignored, consistent repetition can gradually shift behavior. This can lead to automatic water conservation practices even without external prompts. Importantly, this phenomenon naturally sparks discussions about the topic, fostering community involvement and promotion without additional funding.

To address feedback fatigue and ensure sustained behavior change, a multifaceted approach incorporating several key strategies proves beneficial. Regularly updating conservation messages and feedback prompts through message rotation keeps user interest piqued and prevents habituation.[10] Integrating gamification, which involves elements like points, badges, or rewards for consistent conservation efforts, can provide ongoing motivation.[11] Providing users with anonymized comparisons to similar households or community averages has been shown to reduce water use by up to 4.8% in field experiments.[12] Setting personalized, sustainability-focused targets that consider individual household size and usage patterns can drive persistent behavior change.[13] The synergistic effect of combining these approaches can effectively sustain long-term engagement and solidify conservation habits.

Potential benefits across sectors

Engaging diverse demographics (children, adults, and workplaces) in water conservation efforts can be challenging. The sensor-based systems can be installed in various sectors. Children to adults can be involved in different sectors such as schools, colleges, offices, and workplaces because water would be accessible everywhere. This system can be deployed across a wide range of residential, commercial, and institutional settings, which would support the target goal of saving water and reducing pollution loads in water bodies overall. This directly affects the economy of the country and locals, offering significant benefits through small efforts with big outcomes for environmental conservation. Additionally, it may help solve multiple issues, leading to various advantages such as economic growth, employment generation, pollution reduction, water footprint savings, environmental conservation, reduced treatment load burden, and education.

Increased water conservation behavior

Encouraging immediate and mindful water usage can be difficult without proper feedback mechanisms. Smart water meters that give feedback to the users at the time of usage may reduce the wastage of water unconsciously. Thus, making the quantity and quality of the consumed water easily recognizable, such people are likely to modify their behavior.

Reduced water treatment burden

High water consumption places a strain on treatment facilities and contributes to pollution. Lower water consumption lessens the strain. By reducing overall water usage through sensor-based systems, the burden on treatment facilities can be alleviated. This reduction can lead to lower operational costs and decreased pollution levels, benefiting both the environment and local economies.

Improved public awareness and engagement

Raising awareness and understanding of water conservation practices can be challenging. Utilizing social media platforms to promote water conservation initiatives can enhance public understanding and engagement. This concept could eventually evolve into social media and WhatsApp messages to automatically promote water conservation among communities. It's not just a plan or idea; it has the potential to be adopted and make life easier from a future sustainability perspective. Everyone knows right from wrong, but seeing their own mistakes repeatedly can lead to automatic internal corrections, not just external ones. Public awareness campaigns and educational initiatives are already in place, providing a foundation for further efforts. Smart water meters: existing technology can be leveraged to track water usage and provide valuable data to homeowners, enhancing the effectiveness of conservation efforts.

Addressing global water challenges

Water scarcity and inadequate sanitation pose significant threats worldwide. According to the World Bank and WHO/UNICEF,[14,15] 2.2 billion people lack access to safely managed drinking water services, with 771 million lacking even basic drinking water access. 3.5 billion people lack safely managed sanitation, with 419 million practicing open defecation. 2.3 billion people lack basic handwashing facilities. 2 billion people live in regions experiencing high water stress. Implementing widespread water conservation measures can drastically reduce these figures, improving global water access and sanitation conditions. Even if only a fraction of the estimated five billion water facilities worldwide implemented conservation measures, the cumulative water savings would be transformative. Moreover, 90% of natural disasters are water-related, including floods and droughts.[16] Excessive water consumption contributes to environmental degradation, exacerbating these challenges. By promoting conservation, we can mitigate disaster impacts and enhance resilience against climate-induced water crises.

Gaps in access to water supply and sanitation, growing populations, more water-intensive growth patterns, increasing rainfall variability, and pollution are converging to make water one of the greatest risks to economic progress, poverty eradication, and sustainable development. Addressing these challenges can contribute to achieving economic stability, poverty reduction, and sustainable development at various scales.

Conclusion

Addressing water-related challenges requires an integrated approach that combines technological innovation, behavioral interventions, and policy support. Sensor-based water conservation systems provide a scalable and effective solution, capable of reducing consumption, alleviating stress on treatment facilities, and improving sanitation worldwide. By fostering public engagement and leveraging existing technologies, we can transform conservation from an individual effort into a global movement, ensuring a sustainable water future for all. Further research and pilot programs are necessary to fully assess the potential of this approach and its impact on global water conservation efforts. The potential benefits extend beyond water savings, positively impacting the environment, economy, and public awareness.

Data availability

No primary research results, software or code or any other results have been included and no new data were generated or analysed as part of this article.

Conflicts of interest

There are no conflicts to declare.

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