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## Energy-Harvesting Nanomaterial-Based Smart Antennas for Self-Powered Biomedical and IoT Applications

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### ABSTRACT

The quick development of biomedical monitoring devices and the Internet of Things (IoT) has increased the need for communication systems that are not only compact and efficient but also capable of operating without frequent battery replacements. Energy-harvesting smart antennas offer a promising pathway by collecting energy from the surrounding environment, such as radio frequency (RF) signals, heat from the human body, and ambient light, and using it to power miniature sensors. This paper explores the theoretical foundations, design principles, and application opportunities of smart antennas based on advanced nanomaterials such as graphene, MXene, carbon nanotubes (CNTs), and flexible polymer composites. These materials allow antennas to be lightweight, highly conductive, flexible, and suitable for both wearable and implantable devices. The proposed antenna design shows reconfigurable behaviour they can adjust their frequency, polarisation, or beam direction depending on communication needs. Simulations based on electromagnetic and thermal multiphysics show how these Nanomaterial antennas perform when placed on the human body, exposed to varying environmental conditions, or used inside high-density IoT networks.

### 1. Introduction

The quick development of wearable biomedical sensors and the exponential growth of the Internet of Things (IoT) have fundamentally transformed modern healthcare delivery, environmental monitoring, and smart infrastructure development. Wearable and implantable biomedical devices now enable continuous and real-time monitoring of physiological parameters such as heart rate, blood pressure, glucose levels, neural activity, and body temperature. Similarly, IoT networks support large-scale sensing and communication for smart cities, industrial automation, precision agriculture, and environmental surveillance. These applications demand wireless communication systems that are compact, lightweight, energy-efficient, and capable of long-term autonomous operation while maintaining reliable data transmission under dynamic conditions [1]. The critical limitation of current wearable and IoT devices lies in their dependence on conventional electrochemical batteries. Although batteries have seen incremental improvements in energy density, they remain bulky, rigid, and have a finite lifespan. Frequent battery replacement or recharging is particularly problematic for implantable biomedical devices, where surgical intervention may be required, and for large-scale IoT deployments, where maintenance costs and accessibility issues significantly hinder scalability. Furthermore, battery disposal raises serious environmental concerns due to the generation of toxic chemical waste, motivating the search for sustainable and maintenance-free power solutions [2]. Energy harvesting has emerged as a promising alternative to conventional power sources by enabling electronic systems to extract usable energy from their surrounding environment. Ambient energy sources such as radio-frequency (RF) electromagnetic waves, thermal gradients between the human body and the environment, and ambient or indoor light are everywhere in modern living spaces. By converting these low-level energy sources into electrical power, energy-harvesting technologies can support self-powered or battery-less operation of low-power electronic devices, significantly extending system lifetime and reliability [3].

In this paper, smart antennas integrated with energy-harvesting mechanisms provide a powerful multifunctional platform that combines wireless communication and power generation within a single compact

structure. Smart antennas are capable of adaptively modifying their radiation characteristics, such as operating frequency, polarisation, impedance matching, and beam direction, in response to changing environmental conditions and communication requirements. This adaptability enhances link reliability, spectral efficiency, and interference mitigation, particularly in dense IoT environments and complex on-body communication scenarios [4]. The integration of energy-harvesting functionality directly into the antenna structure further improves system efficiency by eliminating additional components and reducing power losses. Antennas can simultaneously act as radiating elements for data transmission and as collectors of ambient RF energy, forming rectenna-based architectures for RF energy harvesting. When combined with thermal and optical harvesting modules, such hybrid systems can ensure continuous power availability under diverse operating conditions [5].

Recent advances in nanomaterials have opened new possibilities for the design of next-generation smart antennas. Two-dimensional and nanostructured materials such as graphene, MXene, carbon nanotubes (CNTs), and conductive polymer composites exhibit exceptional electrical conductivity, mechanical flexibility, chemical stability, and adjustable electromagnetic properties. These features enable the fabrication of ultrathin, lightweight, and conformal antennas that can be seamlessly integrated into clothing, skin-mounted patches, or implantable platforms. Moreover, nanomaterials support reconfigurability through electrical, thermal, or chemical tuning, making them highly suitable for adaptive and multifunctional antenna systems [6]. Nanomaterial-based antennas are particularly advantageous for biomedical applications, where flexibility, biocompatibility, and low specific absorption rate (SAR) are essential design requirements. In wearable and implantable scenarios, antennas must operate efficiently in proximity to human tissue, which is inherently lossy and dispersive. Smart antenna designs incorporating nanomaterials can mitigate tissue-induced detuning and absorption effects while maintaining stable performance across varying postures and environmental conditions [7].

This paper represents a comprehensive theoretical investigation of energy-harvesting nanomaterial-based smart antennas for self-powered biomedical and IoT applications. This study focuses on design principles, material selection, energy-harvesting mechanisms, reconfigurable antenna architectures and in multiphysics simulation methods, combining electromagnetic and thermal studies to evaluate antenna performance under realistic operating environments, including on-body conditions and dense IoT networks.

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## 2. Energy Harvesting Mechanisms for Smart Antennas

Energy harvesting enables smart antenna systems to operate autonomously by extracting usable electrical energy from ambient environmental sources, which is particularly important for wearable biomedical devices and IoT sensor nodes where the harvested power is typically low but sufficient for ultra-low-power electronics, intermittent data transmission, and duty-cycled operation. Energy harvesting mechanisms integrated with smart antennas are broadly classified into radio frequency (RF), thermal, and optical (photovoltaic) harvesting, each exhibiting distinct characteristics in terms of power density, availability, conversion efficiency, and application suitability [8]. RF energy harvesting exploits omnipresent electromagnetic radiation from cellular base stations, Wi-Fi access points, Bluetooth devices, broadcasting towers, and emerging 5G networks, making it especially attractive in urban and indoor environments for uninterrupted operation [9]. In RF energy-harvesting smart antennas, incident electromagnetic waves are captured by the antenna, converted into alternating current signals, and then rectified into direct current using a rectenna to power electronic loads or charge energy storage elements [10]. The harvested RF power  $P_{harv}$  at the antenna terminals can be expressed as:

$$P_{harv} = \eta_r G_r \frac{P_t G_t \lambda^2}{(4\pi R)^2}$$

where,  $\eta_r$  is the RF-to-DC conversion efficiency,  $G_r$  and  $G_t$  are the gains of the receiving and transmitting antennas, respectively,  $P_t$  is the transmitted power,  $\lambda$  is the wavelength of the incident RF signal, and  $R$  is the distance between source and receiver, highlighting the strong dependence on distance and antenna gain, highlighting the need for optimised antenna design [11]. Nanomaterial-based antennas employing graphene, MXene, and carbon nanotubes significantly enhance RF harvesting efficiency due to high electrical conductivity, flexible surface impedance, and support for surface plasmon resonances, which improve impedance matching and RF-to-DC conversion efficiency, while reconfigurable smart antennas dynamically adapt frequency and polarisation to maximise harvested power in fluctuating environments [12]. Thermal energy harvesting leverages temperature gradients between the human body and the environment, making it suitable for wearable and implantable biomedical devices, and is commonly realised using thermoelectric generators based on the Seebeck effect, where the generated voltage is given by  $V = S\Delta T$ , where,  $S$  is the Seebeck coefficient and  $\Delta T$  is the temperature difference. While wearable temperature gradients are small, advances in nanostructured thermoelectric materials such as graphene-based composites and MXene polymer hybrids have improved Seebeck coefficients and reduced thermal conductivity, enabling higher power output at low temperature differences. When integrated with smart antennas, thermal harvesting complements RF harvesting by providing a more stable energy source under weak or intermittent RF conditions, making hybrid RF thermal systems suitable for continuous biomedical monitoring and body area networks [13]. Optical energy harvesting utilises ambient sunlight or artificial indoor lighting through photovoltaic materials, with flexible and transparent PV layers integrated onto antenna substrates, and the output power is calculated as  $P_{opt} = \eta_{pv} A E_{light}$  where,  $\eta_{pv}$  is the photovoltaic conversion efficiency,  $A$  is the effective illuminated area, and  $E_{light}$  is the incident light irradiance.

Nanomaterial-based photovoltaics, including graphene-enhanced organic solar cells and quantum-dot PVs, offer flexibility, durability, and compatibility with curved surfaces, making them effective for outdoor IoT deployments and well-lit indoor environments [14]. To overcome the limitations of individual mechanisms, modern smart antenna systems increasingly employ hybrid energy harvesting architectures that simultaneously harvest RF, thermal, and optical energy, supported by smart power management units that regulate, combine, and distribute energy based on load requirements, thereby enabling fully autonomous, reliable, and maintenance-free biomedical and IoT systems through the integration of nanomaterial-based antennas with hybrid energy harvesters.

## 3. Nanomaterials for Smart Antenna Design

The performance of smart antennas is strongly influenced by the electrical, mechanical, and electromagnetic properties of the materials used in their fabrication, and while conventional metallic antennas based on copper or aluminium offer high conductivity, they suffer from rigidity, higher weight, corrosion, and limited compatibility with flexible and wearable platforms, motivating the adoption of advanced nanomaterials for next-generation systems [15]. Nanomaterials provide a unique

combination of high conductivity, low density, mechanical flexibility, and flexible electromagnetic behaviour, enabling ultrathin, lightweight, and conformal antennas suitable for wearable garments, skin-mounted patches, implantable biomedical devices, and compact IoT nodes, while also supporting frequency reconfigurability, bandwidth enhancement, and improved energy-harvesting efficiency through adjustable surface impedance and strong electromagnetic interaction [16]. As summarised in Table 1.

**Table 1** Properties of nanomaterials used in smart antennas

Material	Conductivity	Flexibility	Advantages
Graphene	Very High	Excellent	Adjustable conductivity, optical transparency
MXene	High	Good	High surface area, RF absorption
Carbon Nanotubes (CNTs)	High	Excellent	Mechanical strength, lightweight
Polymer Composites	Moderate	Excellent	Biocompatibility, stretchability

Graphene exhibits very high conductivity and excellent flexibility, offering key advantages such as flexible conductivity and optical transparency; MXene materials provide high conductivity with good flexibility, characterised by large surface area and strong RF absorption; carbon nanotubes (CNTs) combine high conductivity with excellent flexibility, mechanical strength, and lightweight characteristics; and polymer nanocomposites exhibit moderate conductivity but excellent flexibility, biocompatibility, and stretchability, making them ideal for wearable and implantable applications. Among these, graphene-based antennas are particularly promising due to their high carrier mobility, mechanical robustness, and ability to support surface plasmon polaritons that enable extreme miniaturisation and dynamic reconfigurability via flexible surface conductivity described by the Kubo formula  $\sigma_g(\omega, \mu_c, r, T)$  where,  $\omega$  is the angular frequency,  $\mu_c$  is the chemical potential,  $r$  is the scattering rate, and  $T$  is the temperature. allowing real-time adaptation of resonance frequency, impedance, and radiation characteristics for cognitive radio, body-area networks, and adaptive IoT systems, while also enabling integration with photovoltaic layers for hybrid RF optical energy harvesting [17].

In MXene based antennas, formed from two-dimensional transition metal carbides and nitrides, with the general formula  $M_{n+1}X_nT_x$  where MXenes exhibit metallic conductivity, strong RF absorption, and large surface area, making them highly effective for RF energy harvesting, rectenna enhancement, and electromagnetic shielding, with additional benefits of solution-processable fabrication, thermal stability, and compatibility with polymer substrates for wearable and implantable systems. CNT-based antennas leverage the extraordinary electrical conductivity, tensile strength, and flexibility of rolled graphene nanostructures to realise transparent, lightweight, and mechanically robust radiators that maintain stable performance under bending and stretching, enabling their integration into textiles, elastomers, and biocompatible polymers for smart fabrics and skin-conformal biomedical and IoT devices [18]. Polymer nanocomposites, which embed graphene, CNTs, or MXenes within flexible polymer matrices, offer a balanced trade-off between electrical performance and mechanical compliance, with flexible conductivity, dielectric properties, and stretchability achieved through controlled filler concentration, ensuring reliable antenna operation under deformation and long-term comfort and safety in biomedical monitoring applications. Overall, the selection of nanomaterials for smart antenna design is application-specific, with graphene favouring reconfigurable and miniaturised antennas, MXenes excelling in energy harvesting and shielding, CNTs providing superior mechanical durability, and polymer composites offering unmatched flexibility and biocompatibility, and by combining these complementary materials in hybrid architectures, high-performance, self-powered smart antenna systems can be realised for advanced biomedical and IoT applications [19].

## 4. Smart and Reconfigurable Antenna Architecture

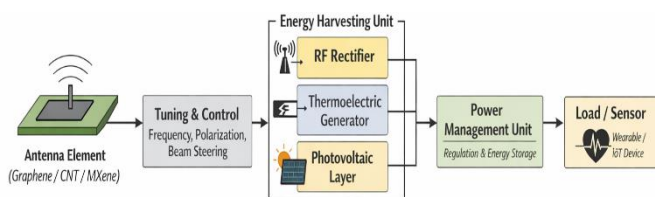
Smart and reconfigurable antenna architectures are central to enabling adaptive, efficient, and reliable wireless communication in energy-harvesting biomedical and IoT systems, as they can dynamically adjust their operating characteristics in response to environmental variations, body proximity, user mobility, multipath propagation, and interference, unlike conventional fixed parameter antennas. as shown in Fig. 1, a typical nanomaterial-based reconfigurable smart antenna system comprises a

radiating antenna element, a tuning or control unit, and an intelligent signal-processing or decision-making module integrated with energy-harvesting and power-management circuits, allowing simultaneous support for communication, sensing, and energy collection in compact multifunctional designs [20]. In such systems, adaptive control algorithms or AI-based controllers continuously optimise antenna parameters, including resonant frequency, impedance, polarisation, and radiation pattern, to balance communication performance with energy-harvesting efficiency, requiring careful trade-offs among bandwidth, gain, radiation efficiency, and harvested power. Frequency reconfigurability is particularly important for biomedical and IoT devices operating across multiple standards (Bluetooth, Wi-Fi, LTE, and 5G), where the resonant frequency of a planar antenna can be approximated by,

$$f_r = \frac{c}{2L\sqrt{\epsilon_{\text{eff}}}}$$

where,  $c$  denoting the speed of light,  $L$  the effective electrical length, and  $\epsilon_{\text{eff}}$  is the effective dielectric constant.

In nanomaterial-based antennas, tuning is achieved without physical resizing through electrically controllable surface conductivity in graphene or adjustable loading in MXene- and CNT-based structures. Polarisation reconfigurability further enhances link reliability in on-body and mobile environments by mitigating polarisation mismatch caused by random orientation changes, enabling switching between linear, circular, or dual-polarised modes using nanomaterial-based switches or reconfigurable feed networks, which also increases the probability of capturing ambient RF energy with varying polarisation states [21]. Radiation pattern reconfigurability and beam steering, realised through electronically controlled phase shifting, flexible impedance loading, or reconfigurable meta surface elements, allow smart antennas to enhance signal-to-noise ratio, suppress interference, and direct reception toward dominant RF sources, thereby significantly improving harvested power in dense IoT and urban environments while maintaining low size, weight, and power consumption compared to conventional phased arrays. Tight integration of the antenna with rectifying circuits and adaptive impedance-matching networks, as shown in Fig. 1, ensures maximum power transfer under changing operating conditions, while ultra-low-power power-management units regulate, store, and distribute harvested energy to sensing, processing, and communication modules. In biomedical environments, such reconfigurable architectures help compensate for detuning effects introduced by lossy human tissues, sweat, and motion, while in IoT networks, they improve robustness against fading, interference, and dynamic topology changes, collectively enabling compact, efficient, and autonomous nanomaterial-based smart antenna systems capable of long-term, battery-free operation [22].



**Fig. 1** Block diagram of a nanomaterial-based reconfigurable smart antenna integrated with energy harvesting, tuning control, and power management units

## 5. Multiphysics Simulation and On-Body Performance Analysis

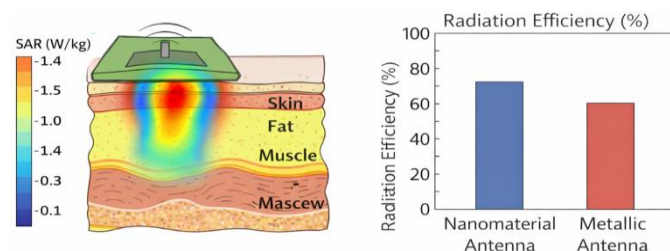
The performance of energy-harvesting nanomaterial-based smart antennas is highly dependent on their operating environment, particularly in wearable and implantable biomedical applications and dense IoT scenarios, where proximity to the human body and surrounding structures significantly affects electromagnetic behaviour, thermal response, and harvesting efficiency; therefore, accurate evaluation requires in multiphysics simulation frameworks that combine electromagnetic, thermal, and circuit-level analyses [23]. Electromagnetic (EM) simulations, typically performed using full-wave solvers based on the finite element method (FEM) or finite-difference time-domain (FDTD) techniques, are employed to analyse key antenna parameters such as reflection coefficient ( $S_{11}$ ), radiation pattern, gain, bandwidth, and radiation efficiency under both free-space and on-body conditions. As shown in Fig. 2, nanomaterial-based antennas incorporating graphene or MXene are modelled using surface impedance or conductivity-based formulations to accurately capture their frequency-dependent plasmonic behaviour, enabling realistic prediction of impedance matching, resonance shifts, and efficiency degradation caused by dielectric loading

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from human tissues. For on-body antenna modelling, multilayer human tissue phantoms representing skin, fat, muscle, and bone are employed with appropriate permittivity ( $\epsilon_r$ ) and conductivity ( $\sigma$ ) values, allowing assessment of resonance detuning, radiation efficiency reduction, and electromagnetic absorption in lossy and inhomogeneous biological media [24]. To ensure user safety, the Specific Absorption Rate (SAR) is calculated as:

$$SAR = \frac{\sigma |E|^2}{\rho}$$

where  $\sigma$  is the electrical conductivity of the tissue,  $|E|$  is the magnitude of the electric field, and  $\rho$  is the tissue mass density, with simulation results generally demonstrating that conformal nanomaterial-based antennas exhibit lower SAR and improved impedance stability compared to rigid metallic counterparts, the SAR distribution is shown in Fig. 2. Thermal analysis further evaluates the integration of thermoelectric energy-harvesting components by modelling heat transfer through conduction, convection, and radiation between the human body, antenna structure, and ambient environment, ensuring that temperature gradients across thermoelectric elements are sufficient for power generation without causing excessive localised heating or user discomfort [25]. RF energy-harvesting performance is assessed under realistic ambient conditions by coupling EM field simulations with nonlinear rectifier circuit models to estimate RF-to-DC conversion efficiency in the presence of multiple incident signals with varying frequencies, power levels, and polarisation states, where reconfigurable features such as frequency tuning and polarisation switching significantly enhance harvested power by adapting to dominant RF sources [26]. In dense IoT networks, multiphysics simulations incorporating multiple transmitting nodes reveal that beam steering and adaptive radiation control improve the signal-to-interference-plus-noise ratio (SINR) and enable preferential energy collection from high-power RF sources, thereby enhancing system autonomy [27]. Overall, the simulation results confirm that nanomaterial-based smart antennas maintain stable electromagnetic performance, reduced detuning, improved energy-harvesting efficiency, and enhanced safety under realistic operating conditions, validating their suitability for long-term, self-powered biomedical and IoT applications [28].



**Fig. 2** Simulated SAR distribution and radiation efficiency comparison of a nanomaterial-based wearable antenna under on-body conditions

## 6. Biomedical and IoT Applications

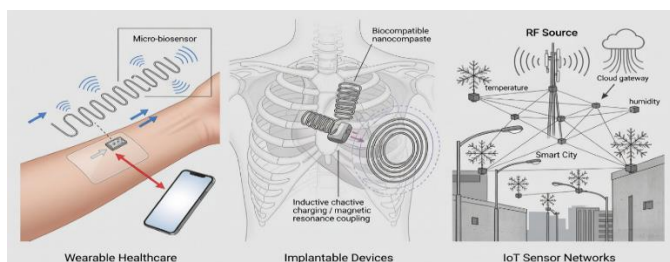
Energy-harvesting nanomaterial-based smart antennas enable a wide range of biomedical monitoring and IoT applications by supporting autonomous power operation, adaptive wireless communication, and enhanced system reliability, which are essential for next-generation pervasive sensing environments [29]. Their compact dimensions, mechanical flexibility, and reconfigurable electromagnetic behaviour make them particularly suitable for scenarios where conventional rigid, battery-powered communication modules are impractical or unsafe. In wearable biomedical monitoring systems, smart antennas integrated into garments, wristbands, or skin-mounted patches facilitate continuous wireless transmission of physiological parameters such as electrocardiogram (ECG), electroencephalogram (EEG), blood oxygen saturation ( $SpO_2$ ), body temperature, and motion activity, enabling real-time health assessment and preventive care [30]. Nanomaterial-based antennas fabricated using graphene, carbon nanotubes (CNTs), and flexible polymer composites maintain stable performance under bending, twisting, and motion-induced deformation, thereby preserving link reliability in dynamic body-area networks (BANs) [21]. Ambient RF and body-heat energy harvesting further enable long-term, battery-free operation, which is critical for uninterrupted health monitoring, while reconfigurable frequency and radiation characteristics mitigate detuning and channel variability caused by posture changes and surrounding electromagnetic conditions [25].

In implantable medical devices such as pacemakers, neural stimulators, drug delivery systems, and implantable biosensors, energy-harvesting smart antennas reduce dependence on internal batteries, thereby minimising the need for surgical replacement and lowering healthcare

risks and costs [31]. Graphene- and CNT-based antennas, owing to their ultrathin profiles, chemical stability, and flexible conductivity, enable efficient electromagnetic coupling through biological tissues while maintaining low specific absorption rate (SAR) and compliance with medical safety standards [32]. Beyond personal healthcare, self-powered smart antennas play a vital role in remote healthcare and telemedicine by enabling continuous data transmission from patients to cloud-based monitoring platforms, improving accessibility for elderly care, chronic disease management, and post-operative supervision. In Internet of Things (IoT) sensor networks, energy-harvesting nanomaterial-based smart antennas support long-term, maintenance-free deployment of sensor nodes for smart cities, environmental monitoring, industrial automation, and precision agriculture [33]. Their reconfigurable beamforming and frequency agility enhance connectivity, reduce interference in dense deployments, and improve spectral efficiency, while hybrid energy harvesting from RF, thermal, and optical sources ensures reliable power availability across diverse operating environments [34].

Similarly, in smart infrastructure and environmental monitoring applications such as structural health monitoring, air quality assessment, and traffic management, nanomaterial-based smart antennas enable seamless integration into buildings, bridges, and public infrastructure, offering durability, conformability, and continuous self-powered operation under harsh environmental conditions [27].

These various application scenarios are shown in Fig. 3, which highlights the deployment of energy-harvesting nanomaterial-based smart antennas in wearable healthcare, implantable devices, and large-scale IoT sensor networks. Overall, across biomedical and IoT domains, such smart antenna systems provide battery-free or battery-assisted operation, enhanced communication reliability through reconfigurability, improved user comfort and safety, and reduced maintenance and environmental impact, positioning them as a foundational enabling technology for autonomous wireless networks of the future [35].



**Fig. 3** Application of energy-harvesting nanomaterial-based smart antennas in wearable healthcare, implantable devices, and IoT sensor networks

## 7. Conclusion

This work shows that energy-harvesting smart antennas made with advanced nanomaterials can play a vital role in the future of biomedical and IoT technologies. By using materials such as graphene, MXene, carbon nanotubes, and flexible polymer composites, antennas can be made lighter, thinner, more flexible, and better suited for wearable and implantable devices than traditional metal antennas. The integration of RF, thermal, and optical energy harvesting directly into smart and reconfigurable antenna structures makes it possible for devices to operate for long periods without relying on frequent battery replacement or recharging. Simulation studies that combine electromagnetic and thermal analysis demonstrate that these antennas can work reliably near the human body, maintain low energy absorption for user safety, and adapt their performance to changing environments and communication needs. The discussed applications clearly show their potential in continuous health monitoring, implantable medical devices, smart cities, and large-scale IoT networks. Overall, energy-harvesting nanomaterial-based smart antennas offer a practical and sustainable solution for building self-powered, reliable, and user-friendly wireless systems, and further experimental studies and real-world testing will help bring these technologies closer to everyday use.

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