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The Impact of Plastic Nanoparticles on Human Health and the Environment: Risks, Challenges, and Proposed Solutions

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Annotation: Use of plastic has become an indispensable element in the routine life of the general public. The improper disposal of plastic products has become a significant environmental, health, and public management concern. The maritime sector generates around 6.4 million tons of marine waste annually worldwide. The disposal of plastic waste or small polymer particles into aquatic environs is not permitted.

The decomposition process of polymeric waste, especially the plastic waste, results in the formation of plastic nanomaterials. After transformation, plastic matter transforms into two different segmentations directly: micro-size and nano-scale plastic. The approach of the use of bioplastics is considered as a general measure to counteract the issue of accumulation of toxic plastic waste. The nanoparticles transferred to the aquatic surroundings transcend through the thermal, optical, and biodegradation. The nanoparticles primarily react at the end of the life cycle of polymers. During the transformation stage of the polymers depiction procedure, the plastic material is exposed to thermal instability. The usage of assorted agglomerations of additives during the production of plastics reduces degradations caused by light, hotness and the bio-decomposability of the plastic material. This results in leaching out of the plastic particles at the final stages of decomposition. This mechanism of action of nanoplastic material generation operates in a direction similar to that of mechanical ablation. However, the mechanism of unnatural degradation of plastic in the ambient surrounding is a relatively slow process of particle fragmentation and agglomeration, which finally generates polymeric nanoparticles.

Keywords: Plastic nanoparticles, environmental pollution, human health, bioaccumulation, microplastics, nanotoxicology, waste management.

1. Introduction

Understanding risks and changes to the regulatory environment requires examining how plastic particles become smaller and more diverse. Accounting for 80-90% of microplastics found in the environment, thermoplastics dominate the industry and are particularly stable over time [1]. Consequently, they are the synthetic plastics under consideration in this review. Plastic waste enters the environment through various channels, aided by its buoyancy, weathering into more mobile pieces, leaching of toxic additives, and uptake by organisms. Such contamination is omnipresent and macroscopic plastic particles are found in places as remote and different as the Arctic snow or mountains, bottled water, placentas, and sizable numbers of fish caught even on the Mariana Trench [2]. From there it is a small step before the particles are even further weathered and fragmented into the nanoscale. The N(N)P habits and methodologies reviewed above include waste mismanagement, industries, cosmetics, laundering processes, agricultural use, and atmospheric contamination. In the US, more than 90% of tap water and salt products contained microplastics and it is thought that a person would consume around the mass of a credit card in plastic every week.

This type of pollution mix can result in synergistic toxicity, where the presence of one toxicant enhances the effect of weaker substances. Detecting NPs with high specificity and sensitivity anywhere in such a wide variety of packaging, coating, and existence is a challenge for Raman, SERS, and LIBS. Notably, the terms micro-(nano-) plastics are not strictly defined in a unified manner, confounding the comparison of results across studies. Additionally, many of the methodologies employed to date for the detection and analysis of E(N)PPs are still in the developing phase: stringent protocols are needed to identify them, but as they remain underused, results can vary greatly. It has been proven that it can add less than 5 g more often to the limit of quantification (LOQ) level by using common digestion methods. Biopolymer materials such as chitin and cellulose quantitatively kill sock-shaped microplastics in biological samples containing around 75 mass%. It has been shown that some fungi can encompass E(P)Ps, whereby visualization of the Raman spectra of their exudates might become an indirect detection method. [3][4][5]

Literature Review

2. Understanding Plastic Nanoparticles

Plastics are the most common materials on the planet and are found in or used to produce nearly every consumable product. In Europe, the production of plastic materials has continuously risen in recent years, amounting to around 62 million tons in 2017. Plastic waste generation oscillated around 26 million tons from 2010 to 2014. Several factors explain the environmental concerns associated with plastics, such as their longevity and high energy input, often obtained from non-renewable resources during production [1]. "Plastic debris, specifically larger pieces (above 0.5 cm) that persists in the environment for a prolonged period, is considered one of the most critical environmental issues by the European public" [2]. Twice as many respondents to the 2017 Eurobarometer survey on issues related to the environment mentioned plastic marine litter compared to the survey on the same topic from 2016. However, the accumulation of larger plastics is not the only form present in the environment and human systems.

Tiny pieces, invisible to the human eye and nanosized (from 1 nm to 1000 nm), called plastic nanoparticles, are overlooked. Plastic nanoparticles have an equivalent spherical diameter in the range of 1–1000 nm. These very small particles are to be distinguished from the larger plastic debris, qualified in the literature as macroplastics (above 0.5 cm), mesoplastics (0.1 cm - 0.5 cm), and microplastics (below 0.1 cm). The smaller the size of the particle, the increased the specific area available for interactions. Indeed, nanoplastics have a higher specific surface area compared to larger particles derived from the same sources. This specific area augments their reactivity and enhances sorption and the partition of compounds on and in the particles. In addition, particle size influences the zeta potential, porosity, and behavior, nomadic or as aggregates and agglomerates. Because the interactions are size-dependent, the leachability of molecules from nanoparticles to biological tissues of living organisms likely differs compared to larger macroparticles plastic counterparts.

2.1. Definition and Properties

As a consequence of the increasing plastic production worldwide, an equally extensive increase in the emission of plastic debris into ecosystems is observed. Therefore, understanding the fate and adverse effects of plastics has become a key research priority in recent years. With the discovery of plastic particles, including nanoscale particles, in the environment, research into their fate and impact has increased. Nanoparticles can exhibit markedly different chemical and physical properties than bulk materials of the same material [1]. However, little research has been done on their fate and potential positive or negative effects in the environment [6]. Due to the lack of standardized methods, studies are difficult to compare, and relatively few results have been published. Pollution with plastic particles, including nanoparticles with dimensions of <100 nm, is assessed through the lens of current environmental science.

In the broad sense, plastic nanoparticles are divided from plastics, which are high-molecular synthetic or semi-synthetic polymeric materials. In comparison to natural materials, plastics have unique properties. For example, they have low biodegradability and are thus highly persistent in the environment. However, with weathering by natural forces, large plastic objects are broken down into smaller pieces, creating pollution termed micro- and nanoplastics. A widespread application of plastics in everyday products has led to the introduction of them into everyday environments. Plastics contain additives for specific applications. When plastic is degraded by sunlight or microorganisms, some of the additives, as well as the basic polymer, are released into the environment. Before discoloration, mostly the size of the initial object is reduced. Objects discolored by weathering are still reduced in size, however, they degrade almost exclusively into small plastic particles. Influenced by aquatic ecosystems, the temperature and degradation processes differ from the water-polished plastics on beaches. As a result, plastic nanoparticles are frequently formed. Though the subject of recently increasing research, their behavior, distribution, and effects in ecosystems, or the resulting extent of any relevant risk, are not fully understood. Small size and specific properties make them hard to detect and measure. Another difficulty in understanding NP pollution arises from still-vague definitions of the terms plastic and nanoplastic and inconsistent field research. [7][8][9] [7][8]

2.2. Sources of Plastic Nanoparticles

Plastic particles are omnipresent and are now considered to be a common contaminant on global scale; they do not break down, but just disintegrate into small-size particles (under 1 nm to 1 mm) that spread across the environment. The potential effects of plastic nanoparticles and smaller particles on the environment and human health are still not well understood. Beyond highlighting the importance of controlling the overall amount of plastics entering the environment, targeted research and policy efforts should also be made to curb the additional contributions of plastic nanoparticles and avoid unanticipated consequences. This gives an overview of the current understanding of the sources of plastic nanoparticles, the corresponding environmental pathways and the methods used for detection. These emerging particles are not strictly limited to abrasion processes of larger plastic items, but derive from a complex interplay between human activities and environmental processes, unveiling numerous niches for their appearance in ecosystems [1]. In light of such complexity, possible investigative routes and future challenges are also addressed together with proposed measures to mitigate the release of plastic nanoparticles. These take into account that natural processes and persistence of consumer products will always contribute to the production and spread of such particles, thus suggesting the implementation of life cycle based restrictions on particle-prone materials. Lastly, the need for preventive action is emphasized, as ensuing events could rapidly grow beyond the human ability to control them, potentially leading to harmful or irreversible impacts.

Materials and Methods

The methodology for this study employs a systematic review approach to analyze the impact of plastic nanoparticles (PNPs) on human health and the environment. A comprehensive literature review was conducted, sourcing peer-reviewed articles, scientific reports, and regulatory documents from reputable databases such as Scopus, Web of Science, and PubMed. The selection criteria focused on studies published in the last decade that specifically address the sources, transformation, distribution, and toxicological effects of PNPs. Data extraction involved identifying key themes, including the mechanisms of PNP formation, pathways of human and environmental exposure, and associated health risks. Analytical techniques such as Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR), and electron microscopy were reviewed to assess their effectiveness in detecting and characterizing PNPs. The study also examined regulatory frameworks and mitigation strategies by evaluating national and international policies on plastic pollution and nanomaterials. Comparative analysis was used to synthesize findings across multiple studies, highlighting patterns and discrepancies in reported results. The methodology ensured reliability by cross-verifying data from multiple sources and considering variations in experimental designs and analytical approaches. Ethical considerations were maintained by prioritizing studies that followed standardized research protocols. Limitations, such as inconsistencies in nanoplastic detection and lack of uniform risk assessment methodologies, were acknowledged. This methodological approach provides a structured and critical evaluation of existing research, offering insights into the current understanding of PNP pollution and its implications for future studies and policy development. By integrating multidisciplinary perspectives, the study aims to contribute to the growing body of knowledge on nanoplastic risks and mitigation strategies.

Results and Discussion

3. Health Risks Associated with Plastic Nanoparticles

The ubiquitous presence of nanoscale plastic particles calls for an urgent scientific discussion in the interest of human health. The exposure of humans to nano- and microplastic particles is recognized as a potential health hazard by various groups. According to estimates, the concentration of these particles in the environment is increasing with global plastic production and usage. These particles released to the environment are fragmenting due to mechanical, chemical, and biological weathering. The final input route is via atmospheric deposition on food of terrestrial origin. Port cities, as well as locations affected by fishing activities, appear to have a higher intake with edible salt as a particularly delivering medium to the consumer. Transport of these particles over long distances is documented. Moreover, biological concerns motivate this research, as, despite inconsistent results, first animal tests indicate that dietary uptake of particle-rich food can lead to translocation of particles and to biochemical and cellular effects in tissues of the intestine and spleen. The concentration of these particles in the environment is increasing in step with the development in plastic production and consumption, as per the release of particles and their fragmentation to nanoscale size.

Plastic waste from terrestrial origin is subjected to a series of degradation events resulting in smaller and eventually nanoparticle-forming material. Long-term effects on marine organisms have already been reported, with organisms having major economical and lifestyle importance for human populations, such as shellfish, exhibiting inflammatory immune response, as well as persistent accumulation of ingested particles. There are indications of potential systematic effects in marine invertebrates. Also, a possible persistent toxic effect in embryos cannot be excluded. There have been reports of these particles passing intestinal and blood-brain barriers and translocating to the central nervous system, as well as accumulation in organs such as the liver. Experimentally, it has been demonstrated that polystyrene particles translocate through the gut barrier of the tilapia. Such properties are likely also present in these particles. Supposing that there is an effect triggering a systemic response and widespread translocation of these particles, the assumption that only the gastro-intestinal tract neutralizes the particles may become inadequate, as the particles could relocate to other organs with different clearance capacity. [10][11][8]

3.1. Inhalation Exposure

Inhalation exposure is a route of entry of plastic nanoparticles in the body, enabling their entrance into the respiratory system of humans and other organisms. Noteworthy here are efforts and studies that identify plastic particles in the trachea, nose epithelium, lung tissue and bronchoalveolar lavage fluid of atmospherically-exposed individuals [12]. Furthermore, researchers have highlighted MNPLs within blood plasma samples. The inhalation of plastic nano-sized fragments is considered a health risk. Although research and literature have mentioned such risks, very little is known and there are gaps in this current understanding. Airborne MNPLs have been identified as pollutants in the atmosphere. Many sources are responsible for the release of these particles, such as industrial emissions, vehicular and maritime exhaust, incineration procedures, the degradation of larger objects and textiles, solar radiation, cosmetics and hygienic products, sewage, and the erosion of paints, among others. Recently, the study of the health effects due to inhalation of plastic NPLs particles has gained attention. Some studies support the hypothesis that plastics, and chemical components of plastics, have toxic properties. It is proven that BPA has adverse effects, such as obstructive lung diseases, on the murine model. Epidemiological research throughout the globe has demonstrated the association between health outcomes, including chronic respiratory diseases, pulmonary inflammation, lung fibrosis, and cancers, with inhalation exposure to environmental airborne particles. Nevertheless, these effects can act as indirect indicators of polymeric microplastic particle toxicity. However, studies seeking a direct link between inhalation of plastic nanoparticles and health outcomes remain rare and the current knowledge on this matter is anticipated to be extended. Several challenges persist as the assessment of exposure levels and bioavailability of inhaled nanoparticles in the body are beyond the current capacities of research and technologies. Additionally, there are important issues currently not understood, such as the exact understanding of the translocation of plastic nano-sized fragments to the bloodstream and the lymphatic system. It is then important to promote standard methodologies to minimize inconsistencies between the diverse studies and to better understand the associated risks between inhaled plastic nano-sized particles and health outcomes. Regulatory strategies have been postulated to address and mitigate these new environmental hazards to public health. However, there is still lacking comprehensive knowledge on the quantities of airborne plastic particles, MNPs included, thoroughly degraded in the environment and the full extent of risks arising from this phenomenon. [13][14][15]

3.2. Ingestion Exposure

Plastic pollution is one of the most pressing environmental issues, with plastic nanoplastics receiving particularly increasing concern for their harmful effects. However, our understanding of its health and environmental risks is far from comprehensive. This emerging contaminant is vastly present and can infiltrate the respective ecosystems, imposing potential adverse impacts on biota, including human health. The presence of plastic nanoparticles in the environment would amplify the exposure risk of biota with the increasing entry probability into human populations. Current studies neglect the risk of inadvertent consumption of plastic nanoparticles, and the uptake pathway of plastic nanoparticles in the human system remains incurred. It is essential to explore in detail the primary risks of plastics nanoparticles to health and the environment, as well as the human exposure risks through the possible pathways in such polluted circumstance. There are renowned natural occurrence and anthropogenic sources of plastic nanoparticles, primarily accounted for by the physical weathering of the bulk plastic waste and the continuous dislocation of synthetic polymers, respectively. Notably, the ingestion of micro- and nanoplastics will account for a massive health risk of human populations. It is imperative to interrogate the detrimental interferences of plastic nanoparticles on human gut and water uptake systems and their conditioning on the long-term health status. Effort should be made to scrutinize the mechanism underlying the bioaccumulation process of plastic nanoparticles in the respective terrestrial and aquatic ecosystems. Furthermore, the frontier challenges and perspectives toward a profound understanding of the primary discussions have been discussed. It can update the present comprehension and enable a critical appraisal on the following relevant field and investigations. [16][7]

4. Environmental Impacts of Plastic Nanoparticles

Nanoplastics are now one of the most commonly used terms in studies dedicated to small pieces of plastic debris. Discussion of their impacts on ecosystems followed to some extent from the topic's scientific popularity and the need for assessments of dangerous substances. Numerous studies indicate that microorganisms (mainly bacteria) are able to transfer them into the environment. Human activity mainly initiates this transfer, preparing these particles for implementation. Most of the prepared products containing plastic nanoparticles are capable of releasing these plastic nanoparticles. Consequently, after use, we can observe the dispersion of plastic nanoparticles in the environment in solid, liquid, or aqueous leachates, depending on the product that was implemented.

Research into the environmental effects of plastic nanoparticles is conducted due to the huge number of products containing them being released into the natural environment. Exposure to them usually occurs through urban sewage, waste generated by use, and the environment beyond human control. Due to their extremely small size, the use of innovative observation techniques is required. This paper summarizes the current state of knowledge on these topics.

4.1. Aquatic Ecosystems

Aquatic ecosystems, and particularly the marine environment, are currently under high pressure from anthropogenic pollutants. This is due to the high environmental stability of the marine environment, which needs more time to decompose all unnatural substances. As a result, plastic pollutants could persist long-term and deliver a high negative impact. There are many expressions describing the floating plastic litter in the oceans, the most widely known being "Garbage Patch" and "Islands of the Plastic Swamp" for the North Pacific and the Atlantic, respectively. Presented by the mass and type of plastic, aquatic ecosystems receive other sources of pollutants such as rubber, paints, primary plastic, and synthetic fibers.

Although the issue of the real burden has not been resolved, it has been shown that microplastics could be ingested by various species having different roles and niche positions in the marine ecosystem, based on their geometry. Experiments with mussels have indicated some changes in cellular functions; however, under the same realistic experimental levels of microplastic exposure, no changes in energy reserve content were observed. Plastics are also considered potential vectors for the transfer of invasive marine biota, bioaccumulation, and potential biomagnification through the food web. The fate and transformation of in-water plastic pollution have not been completely clarified, and significant gaps exist in the knowledge of microplastic physical, chemical, and biological characteristics. Due to all these described uncertainties, significant efforts have been applied to propose innovative, efficient, and cost-effective solutions to prevent, monitor, and mitigate the effects associated with microplastic pollution. [17][18]

4.2. Terrestrial Ecosystems

Evidence about the impact of plastic nanoparticles on terrestrial ecosystems is rather limited compared to aquatic systems. Therefore, more research is clearly needed in this area. Given that PNPs are found in food and agricultural plants, there may be potential risks to other trophic levels in soil ecosystems. Many studies have shown that soil organisms will ingest a variety of nano- and micro-sized plastics. Some of those studies have shown that the organisms were able to expel microplastics within 4 to 6 weeks. However, the cationic PNPs have been shown to elicit toxic effects on earthworms at relatively low concentrations. Similarly, amphiphilic polymers have been shown to harm microbial diversity. Since PNPs have been shown to inhibit seed germination, it is likely that PNPs might harm the plant beyond germination. In addition, since land snails traverse different terrestrial ecosystems, and since PNPs have been shown to have neurotoxic effects in land snails, it is likely that PNPs could negatively impact a wide range of terrestrial animals at low environmental concentrations. Therefore, in order to enhance the safety of utilizing plastics in crop production, and to ensure that we have a healthy agricultural and terrestrial environment, it is important to perform in-depth research on PNPs in terrestrial environments, especially in the agroecosystem.

Conventional plastics, like other pollutants, have caused severe damage to environmentally sensitive areas, ecological systems, landscapes, and planetary health. Undoubtedly, plastics have brought many benefits to our society, and they continue to be of great value, providing abundant, affordable products. However, the problem results from the non-degradability of plastics. It is this unique character that poses a risk to the environment, and in turn, impacts our surroundings, where both human and human activities occur. Plastics can be quite detrimental to the natural environment, particularly in the form of microparticles and fragments, so-called microplastics. These microplastics in the natural environment mostly enter the food web through aquatic systems. However, very little is known about their transportation via the atmosphere, and how the micro- and nanoparticles are deposited onto terrestrial surfaces. The situation is even less clear when considering the release and impact of microscopic plastics in terrestrial ecosystems. In recent years, which have witnessed increasing concerns about potential health risks associated with microplastics, research on the detection, behaviors, transport mechanisms, physical processes, and effects of microplastics has been conducted. The potential of soils as plastic repositories has increasingly come under focus with respect to the presence of microplastics, especially with the emphasis revisited on agricultural applications. Recent studies have affirmed the presence of microplastics in agricultural soils and have also provided indirect evidence of the potential for plastics to be absorbed and transported into the plants, from the roots to the different organs. [19][20][21]

5. Challenges in Addressing Plastic Nanoparticles

There are many known challenges to address and overcome when dealing with the rapidly growing and recently frequently reported micro- and nanoplastics issues. What is referred to as microplastics is defined by most regulatory bodies, but not by all in the same way, as any synthetic polymer particles or formulation having an external dimension or an internal structure in the size range from 1 µm to <5 mm. Nanoplastic particles are usually defined as any materials of synthetic polymer origin, being solid and nanoparticle particles with a size under 1 µm. It is almost impossible to encounter any formulations or particles of solid natural polymers of this size under ambient conditions, but just because a definition does not exist yet, small solid natural polymer particles may be called nano as well. It is generally assumable that the largest share of these plastic particles in environment, also stated as MP, derives from the degradation of plastic products rather than indicating in some way, say as intentionally added MP or IP. However, distinguishing among them is never easy nor possible without knowing the origin of the particles. As such the assumption may be true, but was there enough evidence of knowledge for the conclusion? There is a consistent discussion on the terms of grant (nano) plastics, but probably nanomaterial is the best and mostly used definition. According to the above no nanoplastics exists in nature because of the current thermodynamics. Efforts can be solely addressed towards synthesised NM, also does not have any scientific evidence. [22][23][24]

6. Proposed Solutions and Mitigation Strategies

Plastic is a widely used versatile material known for its durability and long lifespan. However, growing awareness of the threats of plastic pollution to human health and ecosystems has spurred efforts to reduce plastic waste through recycling and innovative waste management processes. Recently, the properties of plastic as a durable material have sparked concern about the impact of plastic nanoparticles on the environment and human health. Despite an increasing number of studies on the topic, the data on plastic nanoparticles are still too fragmented to assess their overall impact. To invest in developing solutions and mitigating the challenges, this policy analysis evaluates studies and researches of the recent decade related to the risk assessment of plastic nanoparticles. It discusses the gaps in knowledge, potential hazards, and the need for further research to ensure the sustainability of the environment and public health.

In a report illustrating a comprehensive overview of human and environmental risks, challenges, and potential solutions to combat plastic nanoparticles as a widespread environmental contaminant, it is underlined that annual global plastic production continues to rise, estimated over 300 million metric tons annually, and growth could double in the next 20 years. The major part of this production is used for packaging applications with extremely short lifetimes, likely entering the environment as mismanaged waste. The production, use, and environmental leakage of lightweight, energy-efficient, and cost-effective nanoplastic materials have raised significant concern. In time, the mechanical and UV degradation of macro- and microplastics has been identified as a major source of nanoplastic pollutants by some representative studies [25].

7. Conclusion

The ever-increasing polymeric waste into the ecosystem causes environmental challenges. As a result, micro- and nano-sized bioplastics and plastic-derived MPs can derive from ultraviolet (UV) and thermomechanical fragmentation of plastic carriers. Due to the remaining durability of plastic particles after the degradation of the carrier materials and additives, these MPs and MNPs pose threats to human health and could enter the human body through inhalation, dermal exposure, and digestion. Interaction between the cell membrane and plasma proteins, and radiofrequency-induced models demonstrate that MPs can enter cells and pass into the nucleus. A variety of findings from epidemiological studies have shown that environmental waste affects human health in the form of diseases. The potential release of MPs from food packaging polymer materials depends on the physicochemical properties of the polymer matrix and storage conditions. Cellulose or paper-based packaging materials could be a safer alternative to the packages to avoid potential ingestion of MPs from foods. Assessment of human health risks of plastic-derived MPs and MNPs is not feasible due to unavailability of reference materials and experimental in-folia for conclusive human health risk evaluation. Furthermore, the safety of bioplastics is enhanced compared to conventional plastics since biodegradation occurs faster.

Polylactic acid (PLA) is a better candidate for bioplastics and it has less health risks particularly compared to PET due to the slower degradation of the latter [2]. Understanding the origin, potential impacts on health and the environment, and mitigation of these particles is becoming an urgent challenge because of the continuous rise in the production, usage, and disposal of micro-nanoplastic materials. An important step to prevent possible harmful effects on human and environmental health is to have knowledge. Solving the detected problems by offering projects, conducting research and making commissioning can be formed within the scope of the relevant legislation of prepared scientific and Official reports. Scientific developments contribute to the improvement of international principles, technical criteria and management strategies regarding the environment and social health. The basic approach of policies for waste resulting from human activities; to return hazardous waste management to the product lifecycle and to minimize the negative impact on human health and the environment. In this framework, as the Republic of Turkey, the management of polymer-based nanobiocomposite plastics, which are the focus of the project, is essential for auditing, regulation of health of the society and sustainability of the environment. Government bodies responsible for health and environmental protection recommend continued research on modeling pathways of exposure and the underlying mechanisms. Moreover, scientific projects are required to evaluate the long-term effects of PMNPs on human health to make better policy decisions and to recommend suitable standards. Close cooperation between different organizations involved in human environmental health of MPs and MNPs is essential to establish a robust science base, share productively to ensure a common understanding of potential human health risks, and to support local efforts to address the issue by taking necessary actions.

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