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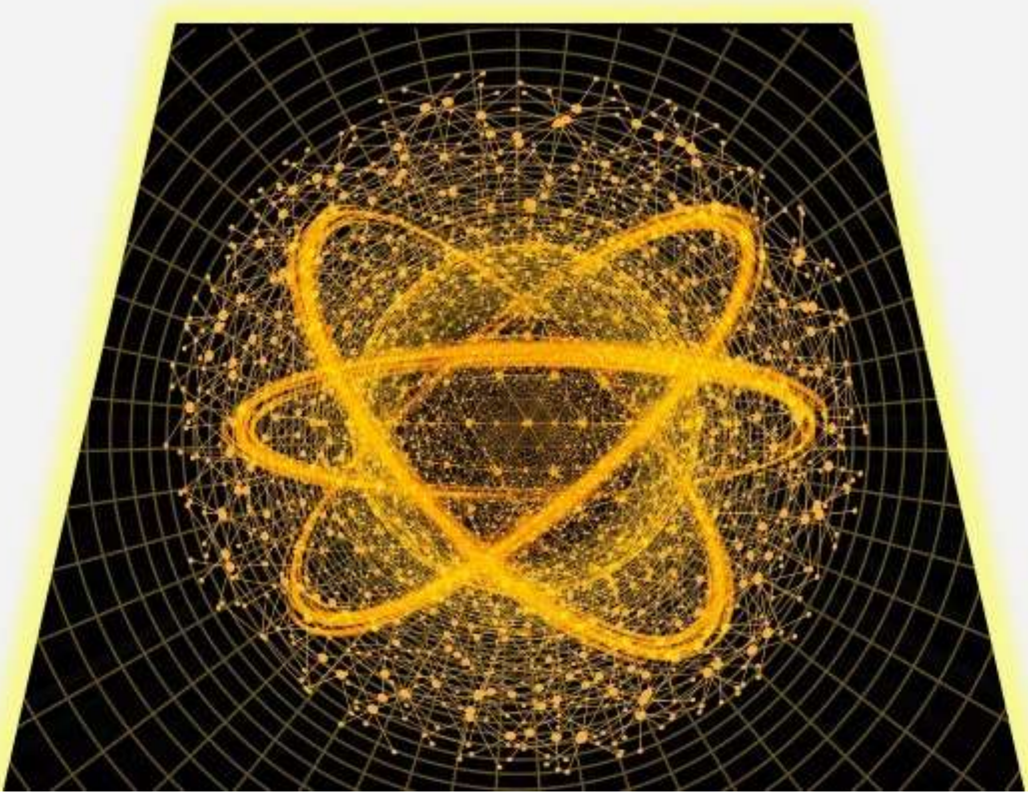

TREND AND INNOVATIVE RESEARCH IN NATURAL SCIENCE AND MATHEMATICS

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CONTENT

Current Distribution of the Coypu (*Myocastor coypus* (Molina, 1782)) in Turkish Thrace

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INTRODUCTION

The coypu (*Myocastor coypus* (Molina, 1782)), which is highly adapted to a semi-aquatic lifestyle, is native to southern South America (Bolivia, southern Brazil, Paraguay, Uruguay, Argentina, and Chile). In the early 1900s, coypus were intentionally introduced by humans to many parts of the world to be farmed for their highly valuable fur and as a food source. The first coypu breeding farm was established in Argentina, followed in subsequent years by the establishment of farms across North America, Europe, and a wide region extending from Russia to Japan [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

Following escapes from farms or their deliberate release into the wild—particularly after the collapse of the fur industry in the 1940s—coypus established feral populations in slow-flowing rivers and lakes with grassy and wooded banks. Today, feral populations of coypu are found across North America, Europe, Africa, Asia, and the Middle East. In parts of central Africa, coypus were even used as a biological control agent to manage excessive aquatic vegetation in lakes [11, 12].

Coypus are large, herbivorous, semi-aquatic rodents that feed primarily on wetland vegetation and agricultural crops. One of their most significant characteristics is their invasive nature. Adults typically weigh between 5–9 kg, with a body length of 40–60 cm and a tail length of 30–45 cm. Their hind feet are webbed. The fur is brown to yellowish-brown, the tail is cylindrical and sparsely haired, the eyes are positioned high on the head, and the incisors are bright orange. Coypus can breed throughout the year, usually producing two litters annually. Sexual maturity is reached between 3–10 months; gestation lasts 127–138 days, and litter size ranges from 2–9 offspring. Due to their semi-aquatic lifestyle, their mammary glands are positioned laterally, allowing females to nurse their young even while in water. When coypu populations increase excessively in wetlands, they cause severe habitat degradation, posing serious threats to rare marsh plant species, birds, fish, and invertebrates [3, 4, 5, 6, 7, 8, 9, 10].

As a medium-sized mammal, the coypu tends to become an environmental nuisance when its population increases excessively. It lives in feral populations in wetlands, lakes, and adjacent vegetated streams and rivers, with the capacity to disperse to nearby wetland systems as population density increases. Coypus can transmit various parasites and diseases to wildlife, livestock, and humans. Their burrowing along riverbanks and dam foundations damages irrigation infrastructure. By cutting and consuming the roots, rhizomes, and young shoots of reeds—without regrowth occurring—coypus cause the reduction and eventual disappearance of reed beds. Overpopulation can completely remove aquatic plant beds, transforming them into open water surfaces. This indirectly threatens reed-nesting birds by destroying their breeding habitats and disrupts fish spawning grounds, thereby indirectly harming fisheries. They also consume rare plant species, leading to local extinctions. Due to such impacts, coypu populations have been eradicated in several countries, such as the United Kingdom [8, 13, 14, 15].

Humans are the primary predators of coypus. Around Gala Lake National Park, coypus are sometimes hunted to feed farm guard dogs. They are also preyed upon by dogs, foxes, jackals, and, more rarely, large birds of prey [17]. In Gala Lake, farm dogs have been observed hunting coypus collectively (personal communication). Although local people often believe that coypus attack humans, in reality, coypus do not exhibit aggressive behavior toward humans.

Distribution of Coypu in Türkiye

Coypu is one of the 14 alien invasive species recorded in Türkiye. Currently, it persists in Iğdır and in the Turkish Thrace region within the provincial borders of Edirne, Kırklareli, Tekirdağ, and Çanakkale. Although previously classified as a protected wild animal in Türkiye, the species was reclassified as a non-protected wild animal according to the Ministry of Agriculture and Forestry Wildlife List published in the Official Gazette dated 10 August 2022 (No. 31919), under the decision that "invasive alien species may be controlled according to procedures and principles determined by the Ministry" [18].

It is highly likely that coypus reached Armenia and the Seymen Lake near the Turkish border either following the closure of breeding farms in Russia or through escapes from farms, subsequently dispersing into the wetlands of Iğdır [19, 20]. The presence of feral populations in Türkiye was first documented in 1973 by Mursaloğlu based on four specimens captured in the slow-flowing sections of the Karasu/Aralık and Arpaçay rivers near the borders of Türkiye, Armenia, and Iran [19, 20, 21]. The Iğdır population is confined to a specific wetland area and, due to surrounding unfavorable geographical conditions, shows no evidence of dispersal or migration to other regions [22, 23, 24, 25, 26, 27] [Fig. 1].

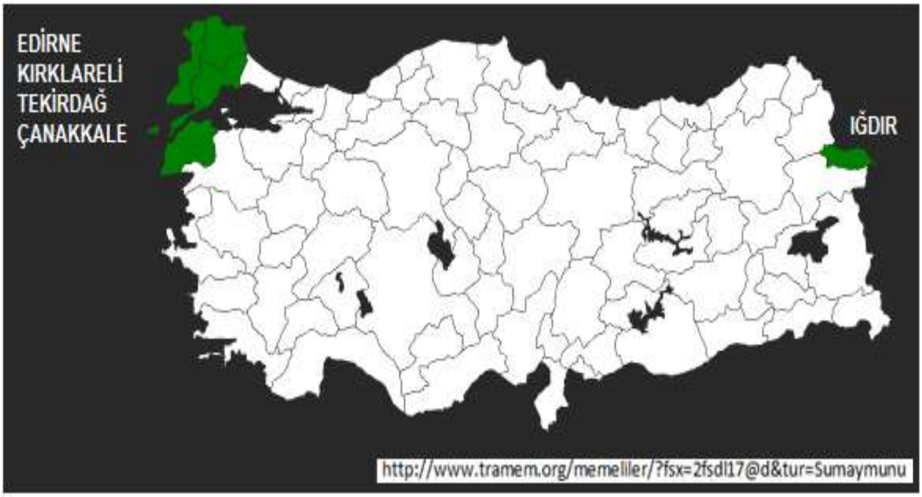

Fig. 1. Current distribution of the coypu in Türkiye.

The presence of the coypu in Turkish Thrace was first recorded in 1984, when a juvenile individual was shot by hunters in the Gölbaba wetland near the Tunca River close to Edirne. Subsequently, additional specimens were obtained in 1989 from the Maritsa/Evros River near Edirne (Fig. 2 and 3). Since the 1990s, the population has expanded along the Meriç River and its tributaries, reaching the river's delta where it flows into the Aegean Sea [28, 29, 30] [Fig. 3]. Later, a significant population increase was recorded in Gala Lake within the boundaries of Gala Lake National Park.

Today, records of the coypu are available from both Bulgaria and Greece. The coypu was introduced to Bulgaria in 1948 from Germany by a hunting enterprise called Sherba, with the aim of breeding it in fur farms. In 1953, it was introduced to Lake Mandrensko near the city of Burgas on the Black Sea coast in western Bulgaria, as well as to the Arkutino Nature Reserve. Subsequently, fur farms were established in different parts of the country, and in later years, coypus that escaped from these farms or were deliberately released spread to other regions of Bulgaria. It is assumed that the population in the Tundzha (Tunca) River in Turkish Thrace originated from these introductions. At present, the coypu is known to occur more densely along the Bulgarian stretch of the Maritsa (Meriç) River, particularly near the cities of Plovdiv (Filibe) and Harmanlı. In Greece, the coypu has been known since 1965 from Lake Agra in western Greece. Currently, it is distributed along the Maritsa/Evros (Meriç) River and in the wetlands of the Evros Delta [31, 32, 33, 34, 35, 36] [Fig. 3].

Fig. 2. Taxidermied coypu (Trakya University Faculty of Science, Department of Biology, Vertebrate Museum).

Due to the hydrological connectivity of rivers and wetlands in Turkish Thrace, the expanding coypu population has recently spread beyond Edirne into neighboring provinces, including Kırklareli, Tekirdağ and Çanakkale and continues to expand [Fig. 1, 3].

In determining the distribution of the coypu in Turkish Thrace, in addition to the findings obtained through our scientific field surveys, information gathered from interviews with local hunters, fishermen, and residents was also utilized.

When examining the process of the coypu's distribution in Turkish Thrace, it can be stated that the species has been present in the region for more than 40 years. Its occurrence in the Tunca River, which joins the Maritsa River near the city of Edirne, as well as in the floodplains and the Gölbaba marsh located between Büyük Döllük and Değirmenyeniköy—where the Tunca River also connects—has been known by elderly local residents since 1976. A juvenile individual captured and taxidermied in the Gölbaba marsh in 1982 represents the first verified evidence of the presence of the coypu in Turkish Thrace. This specimen has been preserved in the Vertebrate Museum of the Department of Biology, Faculty of Science, Trakya University.

In 1994, records of 11 individuals were documented in the Maritsa, Tunca, and Arda rivers near Edirne. During the 1990s, it was determined that the coypu had spread along the Meriç River as far as its outlet to the sea, and shortly thereafter was also observed in Lake Gala. Our field studies on the coypu revealed that the species expanded further inland in Turkish Thrace by following streams, lakes, ponds, and wetlands connected to Lake Gala and the Maritsa River.

In May 2018, a group of coypus was observed and photographed in the Korudağ region, passing through Yenidibek village (Malkara, Tekirdağ), within forested areas and a wind turbine site. In March 2019, coypus were recorded in Şeytan Stream and Kırklareli Dam, and in October 2019, one adult individual was captured in the Burgaz industrial zone of Kırklareli and in Köprüaltı Stream in Lüleburgaz. This individual was handed over to the Kırklareli Directorate of Nature Conservation and National Parks and, after the necessary records were taken, was released back into the area where it had been captured.

Coypus were reported by villagers to have been observed between 2020 and 2024 in Çokal Dam, located on the borders of Çanakkale and Tekirdağ provinces, and in Kocadere Stream passing through Kavakköy in Gelibolu (Çanakkale). Although the coypu is generally thought to avoid highly polluted waters, local farmers reported in June 2025 that the species was observed inhabiting the Ergene River, which is known for its pollution and flows through central Turkish Thrace before joining the Maritsa River near the district of Meriç.

Scientific studies on coypu in Turkish Thrace have mainly focused on the Meriç River Basin and Gala Lake, particularly in the Enez and İpsala districts of Edirne Province. Records from other parts of Turkish Thrace have been obtained from literature sources, field surveys, and direct observations in lakes, ponds, rivers, streams, and surrounding habitats, as well as from interviews with local farmers, fishermen, hunters, and residents.

Fig. 3. Current distribution limits of the coypu in the Turkish Thrace region.

Coypu Researchs in the Maritsa/Meriç River Basin

The Meriç/Maritsa River Basin provides the most suitable habitat for coypus in Turkish Thrace. Population growth in this basin, particularly around Gala Lake, has caused significant agricultural and environmental damage. In Gala Lake National Park, excessive coypu populations have consumed aquatic vegetation, posing a major threat to the lake's flora and indirectly to bird populations and fish spawning grounds. For example, coypus have eliminated the white water lily (*Nymphaea alba*) from the lake by feeding on it, resulting in the loss of breeding habitats for whiskered terns (*Chlidonias hybridus*) and forcing these birds to abandon the area. The consumption of vegetation by coypus has also expanded open water areas and caused other waterbirds that nest and shelter among lilies, reeds, and rushes to leave the lake [37, 38, 39].

To assess and mitigate this threat, projects such as the "Implementation of Coypu (*Myocastor coypus* (Molina, 1782)) Control Activities in the Meriç River Basin of Edirne Province and the Medium/Long-Term Management and Restoration/Rehabilitation Plan," conducted on 24.10.2024 and 29.11.2024, were implemented in the Meriç River Basin. One of the primary objectives of these projects was to reduce the coypu population and prevent potential damage. However, practices involving the capture of coypus in wetlands and their placement in the Keşan Animal Rehabilitation Center cannot be considered successful [24].

Results from these studies indicate that the coypu population in Gala Lake initially increased excessively and later stabilized at a high level due to migration and environmental factors. Although local farmers claim significant damage to rice cultivation, sufficient evidence has not been obtained. Similarly, despite claims that coypus consume waterfowl and their eggs, analyses of stomach and intestinal contents during project studies revealed only plant material, algae, and reed root remains, with no evidence of bird or egg consumption [37, 38, 39, 40] [Fig. 4].

Fig. 4. Coypu and its impacts in Gala Lake (Gala Lake National Park).

Other factors limiting or reducing coypu population growth in the Meriç River wetlands include predation by wolves, jackals, and dogs—particularly on juveniles—hunting by livestock owners to feed their dogs, seasonal water level reductions, and severe freezing winter conditions.

When first observed in new areas, coypus were often immediately targeted for eradication by local people and attracted media attention [Fig. 5]. Today, however, the species has largely been accepted by local communities as part of the region's wildlife. Coypus are also hunted by coordinated packs of dogs in wetlands near settlements [personal communication, 2017]. Individuals captured alive by local residents are released back into their original habitats after inspection by officials from the General Directorate of Nature Conservation and National Parks and after public awareness activities [Fig. 6].

EDİRNE GÜVENİLİR HABERCİLİĞİN ADRESİ

HUDUT

GÜNLÜK SİYASİ BAĞIMSIZ GAZETE

21 ARALIK 2010 SALI

Meriç'te su maymunu!

- Edirne Meriç Nehri kıyısında ıslah çalışmaları gerçekleştirilen kum ocağı şantiyesinde yakalanan fare olduğu ileri sürülen 80 santim boyunda, 5 kiloluk 'dev kemirgen' görenleri şaşırttı...
- TÜ Fen Fakültesi Biyoloji Bölümü Öğretim Üyesi Yrd. Doç. Dr. Beytullah Özkan, geçmişte çiftliklerde posta için yetiştirilen bu hayvanların barındıkları yerlerden kaçarak Meriç Nehri'ne kadar geldiklerini söyledi... Haberi S. 4'te

Öğretim Üyesi Yrd. Doç. Dr. Beytullah Özkan

21 Aralık 2010 HUDUT GAZETESİ 4

Meriç'te su maymunu

Sevcan KALIPÇİNDEN

Yrd. Doç. Dr. Beytullah Özkan: Yakalanan hayvan su maymunu

"Saçan değil"

Fig. 5. Coypu news in local media (21.12.2020).

Fig. 6. Coypu captured in Şeytan Stream, Kırklareli (12.10.2019).

Fig. 7. Edirne – Sazlıdere village (22.01.2015).

CONCLUSION

In recent years, coypus have been distributed across more than half of the Turkish Thrace region [Fig. 3]. During dispersal and nocturnal movements, they are frequently killed by vehicles on roads. They may pass through villages and even confront humans and dogs during migration. In addition to wetlands, they also use shrublands and forests as movement corridors [30]. New reports of coypu sightings continue to appear in local media [Figure 5].

According to our recent invastigations, observations, and findings on coypu, which was previously distributed only within the borders of Edirne province, it is now also distributed within the borders of other Turkish Thracian provinces, namely Kırklareli, Tekirdağ, and Çanakkale, and continues to do so. Migrations, human pressure, hunting by carnivorous mammals, road accidents, and harsh winter conditions have kept the coypu population at stable levels. The local people have now also accepted the coypu.

If current trends continue, it is anticipated that the coypu population will spread throughout the entire Thrace region in the near future. Although the species was previously known to inhabit clean freshwater wetlands, recent observations have documented coypus in the polluted waters of the Ergene River, supported by interviews with local residents. Coypus have also been observed entering the brackish waters near the mouth of the Meriç River [personal communication, 1991].

In conclusion, the available evidence indicates a high likelihood that the coypu will spread throughout Turkish Thrace. There is also a potential risk of the species crossing into Anatolia via the Dardanelles or reaching nearby islands by sea. Under such circumstances, coypus would likely be able to establish and persist in suitable habitats in Anatolia, as they have done in Turkish Thrace.

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Lithium in Aquatic Ecosystems: Impacts, Trends, Challenges

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ABSTRACT

The most important element of the world is water. While the value of water cannot be fully understood in its abundance, its absence is synonymous with death. Aquatic ecosystems consist of aquatic plants, animals and other organisms. The quality of aquatic ecosystems is very important for the health of the whole world. Aquatic ecosystems face many threats arising from anthropogenic activities. Lithium is a naturally occurring metal throughout the world. It is located all over the world. Lithium occurs naturally in groundwater and surface water. Recently, the areas of use of lithium have been increasing rapidly around the world, and it is estimated that the demand for lithium will increase worldwide in the coming years. Although the lithium content of lake and sea waters is low, it is easy and economical to obtain lithium, especially from lake waters. Lithium has a polluting impact on water, and its effects on lithium and aquatic ecosystems have been discussed in recent years. This study focuses on lithium in aquatic ecosystems. Lithium has the ability to accumulate in the food chain. The presence of lithium in aquatic ecosystems may pose a threat to the health of aquatic organisms and therefore humans in the long term. On the other hand, there is no recommended regulatory standard value for lithium in aquatic ecosystems and drinking water in the world and in Turkey regarding pollution and health issues. As a result, the use of lithium as a parameter in water quality and pollution monitoring studies should be widespread. However, international and national standard values for lithium in aquatic ecosystems and drinking water should be determined. This situation is very important for the protection of animal and plant organisms in aquatic ecosystems and human health.

Keywords – Aquatic Ecosystems, Ecotoxicology, Impact, Lithium, Recycling

INTRODUCTION

Water is necessary in agriculture, growth of plants and animals, regulation of climate, energy production, transportation, many industrial activities and the survival of ecosystems. The amount of fresh water is decreasing in many parts of the world. The decrease in usable water causes a decrease in industrial and agricultural production, heavy ecological losses, serious threats to human health and an increase in the potential for international conflict. Population growth, global warming, climate change, decrease in precipitation, excessive evaporation, unconscious agricultural irrigation, water waste, rapid consumption, increase in pollution and incorrect implementation of water management policies cause global water problems. Excessive use of water resources should be prevented, national and international water target strategies should be determined and safe and clean drinking water should be provided (Kavanagh et al. 2017). Therefore, global water problems must be tackled and water must be used more carefully.

Although lithium is abundant as a reserve, lithium is difficult to extract and process. Lithium plays a critical role in many of the things we use in our daily lives. Lithium is found as a trace element in many geological environments. The Earth's mantle layer contains 1.6 ppm, ocean crust 4.3 ppm and rocks 20 ppm. According to its abundance, lithium ranks thirtieth among the elements, behind copper but ahead of lead, tin, and silver. Lithium is an extremely soluble element. Lithium tends to be carried in solution by streams to the seas and oceans during the weathering of rocks. Therefore, lithium is expected to accumulate in seas and oceans. However, seawater contains less than 1 ppm lithium. This is the result of seawater lithium being transported by trace amounts of clay minerals and accumulating in seeps on the sea floor (Ertürk and Yalçın, 2022). Due to the widespread use of portable electronic devices and electric cars, the importance and usage areas of lithium-ion batteries, which are the basic components of these devices, have been increasing in recent years. However, developments in the automotive industry with the development of electric cars cause lithium-ion batteries to become widespread and lithium consumption to increase. Although lithium-ion batteries have been used in portable electronic devices since the 1990s, they are recently used as power sources for electric vehicles. (Celep et al. 2022). While global lithium production was 28100 tons in 2010, it increased with a rapid trend to 100000 tons in 2021. Lithium-ion battery consumption accounts for 74 percent of its total production as of 2021 (Shakoor et al. 2023). It is predicted that lithium production will reach 740000 million tons in 2041. In this context, lithium, with its low recycling rate and increasing production and usage rate, will accumulate in very significant amounts, especially in aquatic ecosystems, in the coming years. This study concerns lithium in aquatic ecosystems.

Lithium and Its General Properties

Lithium is the metal with the lowest density, coming after hydrogen and helium in the periodic table. Lithium's atomic number is 3 and its atomic weight is 6.941. In the periodic table, lithium is a group 1A alkaline metal element with the symbol Li. The density of lithium is around 0.534 g/cm^3.

Lithium boils at 1814 degrees Celsius and melts at 179 degrees Celsius. The name lithium is derived from the Latin word "lithos", meaning stone. Lithium was first identified by Johan August Arfvedson in 1817. The concentration of lithium on Earth is approximately 0.006 percent. Its production is mainly carried out from pegmatites, sedimentary rocks and salt water reservoirs. Lithium is the lightest of all metals. It is in the alkaline group due to its chemical structure. Lithium has high reactivity, is not found in native form, and is difficult to produce from ore (Akgök and Şahiner, 2017).

Lithium and Its Usage Areas

Lithium has been used in the field of psychiatry in the production of sedative drugs since ancient times. It has a wide range of uses, including oil additive in the automotive industry, alloying element in the metallurgy industry, and lithium minerals in the glass and ceramics industry. With the expansion of the battery sector, its use in battery production, which was 7 percent in 1994, reached 31 percent in 2016. Other uses of lithium include pesticides, alloys, cement and concrete additives, dyes and pigments, industrial bleaching, sanitation products, organic synthesis, pharmaceuticals and pool chemicals (Ulusoy, 2016). Lithium, the lightest of metals, has high energy density, specific capacity and oxidation potential, wide operating temperature range and low self-discharge rate. Due to these properties, it is advantageous to use metallic lithium as the anode active material in rechargeable lithium batteries. The first commercial lithium-ion battery was developed and released by a Japanese company in 1991. This developed lithium ion battery has high energy density and high discharge voltage value, and it is a battery in which graphite is used as the anode active material and lithium with a layered structure is used as the cathode active material (Patat et al. 2014). In addition, with developing technology, the usage areas of lithium are expanding. Recently, lithium has become a key material in the production of electric car batteries. Lithium is one of the main ingredients in the production of optical modulators and electronic devices, especially mobile phones. Since it has high drying and moisture retention properties, it is among the sought-after elements in the chemical industry. Since it also has strong basic properties, it is used in the processing of alkaline components. Lithium is an element that has lubricating properties at high temperatures and can prevent oxidation. Lithium is also an important component in energy production and is used effectively in the production of rocket fuel, the weapons industry and nuclear energy (Terzi, 2019). While previous lithium batteries could not be recharged, new generation lithium batteries can now be charged. This situation is a revolution for mobile technologies.

Occurence and Obtaining of Lithium in Nature

Lithium occurs naturally mostly in aquatic and terrestrial habitats. But it is not present in very high concentrations. Lithium exists in ionic form in water. It reacts with water to form lithium hydroxide and hydrogen. Lithium concentration in fresh and salt water is at ppm level. Lithium is present in surface waters at levels ranging from 1-10 ppm. Seawater contains approximately 0.17 ppm lithium, while groundwater and sometimes wastewater contain 3 ppm lithium. Lithium is obtained in high efficiency from water sources, including sea water and salty lake water. Therefore, if an efficient lithium recovery technology can be developed, there is great potential to recover lithium from water resources. Many technologies have been used so far to recover lithium from water resources. The most widely used technology is evaporation with solar energy. Another alternative method is the precipitation process. Solvent extraction method is another method used to obtain lithium (Aral and Sadus, 2008; Xu et al. 2016; Yalçınkaya, 2019). Lithium occurs in nature in a silver-white color.

Lithium is basically obtained from two types of sources. The first of these sources is brines, which are expressed as lake waters and sea waters. The second is mining areas containing lithium minerals. Approximately 64 percent of the world's lithium production is made in lake and sea waters, called brine (Ulusoy, 2016). Although the lithium content of lake waters is low, obtaining lithium from lake waters is easy and economical. The most important parameter for obtaining lithium is the Magnesium/Lithium ratio contained in the lake water, and this ratio is desired to be at most 6/1. As this ratio increases, the cost of the work to be done for the process increases (Yıldız, 2016). While lithium is not found in elemental form in nature, it is found in various compounds and minerals. There are approximately 150 different lithium minerals in the world. Lithium-containing minerals are mostly found in granite deposits. The most important of these are spodumene, petalite, lepidolite and amblygonite. Lithium, like other alkali metals, is very soft and can be easily cut with a steel knife. (Hu, 2012; Demir, 2015).

Lithium Reserves in the World and Turkey

The 66 percent of global lithium reserves are brine reservoirs. Production is mainly carried out from this type of bed. Lithium brine reservoirs are located mainly in Chile, Argentina, Bolivia, China and Tibet. The world's largest lithium salt basin is located in the north of Chile, with an area of 3 thousand square kilometers. Pegmatite type deposits constitute 26 percent of the world's lithium reserves. In these deposits, conventional open pit or underground production techniques are used. Lithium extraction from pegmatites is very costly compared to brine reservoirs. Sedimentary type deposits contain 8 percent of the world's lithium reserves in clays. Lithium element is generally found in clays as smectite mineral. Hectorite mineral is another common lithium ore mineral (Akgök and Şahiner, 2017). Lithium reserves worldwide are around 17 million tons in total. Chile has approximately 44 percent of the world's lithium reserves, followed by Australia (22 percent), Argentina (9 percent) and China (7 percent). Australia is the largest lithium producer, with approximately 50 percent of the world's total lithium production (Dalini et al. 2020; Celep et al. 2022).

There are lithium resources in different regions of Turkey. However, there are no lithium resources of economic value in Turkey. However, although the presence of lepidolite in pegmatites in Sorgun district of Yozgat is known, no significant results could be obtained from the studies carried out. In studies conducted in some lakes in Turkey, it was observed that the lithium content did not exceed 40 ppm, and 325 ppm lithium was detected in Tuz Lake. Lithium content approaching 2000 ppm has been detected in clays in boron fields in Turkey. It has been determined that the lithium content in the Bigadiç and Kırka regions, where boron is mined in Turkey, is higher than in the Kestelek and Emet regions. In these fields, an inverse relationship was observed between boron content and lithium content, and it was determined that lithium content increased as grain size decreased (Akgök and Şahiner, 2017). The average lithium value of the water of Lake Van, the largest soda lake in the world and Turkey, is 0.3 ppm (Yiğit et al. 2017). In this context, it would be very useful to first determine possible exploitable reserves for lithium in Turkey and establish policies for lithium production and marketing.

Ecotoxicological Impacts of Lithium in Aquatic Ecosystems

Lithium levels in natural waters vary depending on geology, topography, hydrogeology and other variables (Kavanagh et al. 2017). There is very little data on lithium levels in water around the world, and large variations are observed in these data. While lithium levels in streams of Europe range from <0.005 to 350 µg/L, lithium levels in bottled water from different countries have been reported to range from 0.1 to 10000 µg/L (Krachler and Shotyk, 2009). Very high lithium levels ranging from 8-1000 µg/L have been detected in drinking water in northern Argentina. Little information is available on the potential long-term toxicity of exposure to lithium through drinking water. It has been observed that exposure to lithium through drinking water in northern Argentina may impair thyroid function. It has also been found that lithium crosses the placenta easily and that exposure to lithium through drinking water during pregnancy is associated with a shortened duration of labor (Krachler and Shotyk, 2009; Concha et al. 2010; Harari et al. 2015; Harari et al. 2017).

Lithium's usage areas have been increasing rapidly recently. Accordingly, lithium has emerged as a new pollution parameter and is widely found in aquatic ecosystems. The impacts of lithium on aquatic ecosystems cause concerns. About the negative effects of lithium on aquatic organisms Bacillariophyceae, Scyphozoa, Bivalvia, Gastropoda, Cephalopoda, Polychaeta, Malacostraca, Echinoidea and Actinopteri were the groups examined, and developmental inhibition, malformations, cellular and metabolic disruptions, and behavioural impairments were some of the effects (Barbosa et al. 2023). Thus, lithium causes negative impacts in aquatic ecosystems.

In terms of human health, metallic lithium is slightly toxic when taken orally. However, physical tolerance varies between individuals. Lithium is used therapeutically on membrane transport proteins when treating manic depression. Lithium is chemically similar to sodium, but lithium is more toxic. Lithium metal reacts with water to form lithium hydroxide and hydrogen, usually in water in the lithium ionic form. In some cases, the lithium content on earth can reach 100 ppm or more. In these cases, lithium creates a toxic impact in ecosystems like a heavy metal. In studies conducted for water quality and pollution in the marine ecosystem, lithium, boron, zinc, vanadium, uranium and selenite values and biological accumulation were examined. The order of toxicity for all species and life stages is determined as vanadium = zinc > selenite > lithium = uranium > boron. Spodumene is an aluminium silicate that is an important source of lithium. It contains up to 8 percent lithium oxide, and the lithium in this structure is tightly bonded to the crystal structure. Therefore, spodumene alone does not pose a toxicological problem. However, when spodumene is ground, it produces silica-rich powder. Ground lithium minerals are more susceptible to water and dilute acid leaching due to the increased surface area (Aral and Sadus, 2008; Yalçınkaya, 2019). This situation may create a negative situation for health and aquatic ecosystems.

The symptoms that may occur from lithium deficiency in healthy people are unknown, as food sources meet the potential dietary need for lithium. However, deficiency symptoms are observed in kidney failure and dialysis patients. On the other hand, long-term lithium intake at normal levels may improve or prevent behavioural disorders. The results of lithium deficiency tests in goats and mice provide evidence for the need for lithium in these species. Delayed growth, reproductive disorders, reduced milk production, and shortened lifespan have been observed in goats subjected to a lifelong lithium-deficient diet. Since lithium is a powerful agent, it has numerous beneficial and harmful impacts on plants, animals and humans. The target organ for lithium is the central nervous system. For this reason, lithium is used in the treatment of manic depression. Lithium is chemically more toxic than sodium. The 5 g of lithium chloride can cause fatal poisoning in humans. In psychiatry, lithium carbonate is administered in doses close to the maximum intake level. At a level of 10 ppm in the blood, the person is in mild lithium poisoning. At a level of 15 ppm, speech disorder is observed in the person. There is a risk of death at levels of 20 ppm. Damage to the central nervous system and kidneys has been reported at therapeutic doses. Additionally, permanent neurological, heart, liver, and kidney abnormalities have been reported as a result of lithium poisoning (Aral and Sadus, 2008; Schafer 2012; Demir, 2015). Lithium is a drug widely used in the treatment of mood disorders, especially bipolar disorder. Although the factors affecting the treatment, pharmacokinetics and clearance of lithium are adequately defined, lithium poisonings are still encountered recently and the appearance of poisonings with different clinical pictures causes delays in diagnosis and treatment. Increased intake or decreased excretion is always responsible for poisoning. Death due to poisoning mostly results from progressive renal failure due to acute poisoning on a chronic basis or due to long-term overdose in chronic poisoning. As with any drug, poisoning due to this drug may occur as long as lithium is used. This should not overshadow the fact that lithium is useful in treating bipolar disorder. By knowing the risk factors and causes well and taking protective measures, the frequency of poisoning will decrease, when it occurs, its rapid recognition will facilitate its treatment, and effective and rapid treatments will eliminate the possibility of sequelae (Kesebir et al. 2011).

Many bio-ecological studies have reported lower suicide rates in areas with slightly higher lithium levels in drinking water. A study examining the relationship between lithium concentrations in drinking water and suicide deaths in Austria found that geographical regions with higher natural lithium concentrations in drinking water provided strong evidence that they were associated with lower suicide death rates (Kapusta et al. 2011). High doses of lithium are given to patients with emotional disorders to treat and prevent suicide. It is stated that there is a relationship between lithium found in drinking water and a decrease in suicide attempts. Lithium exposure levels from drinking water were linked to recorded data on 3.7 million adults in Denmark between 1991 and 2012. The average lithium level is 11.6 μg/L, varying between 0.6 and 30.7 μg/L. The suicide rate decreased from 29.7 per 100 thousand person years at risk in 1991 to 18.4 per 100 thousand person years in 2012. According to these findings, it was determined that exposure to lithium at levels below 31 μg/L in drinking water did not have a protective impact on suicide cases (Knudsen et al. 2017). Therapeutic doses of lithium treat bipolar disorder and may reduce violent crimes committed by people with the disease. It was investigated whether lithium, which is naturally found in drinking water on Japan's Kyushu Island, reduces violent crime rates in the general population. Accordingly, the results showed that even very low levels of lithium in drinking water may play a role in reducing crime rates in the general population (Kohno et al. 2020).

Since the 1960s, scientists and engineers have been working to produce batteries that take up little space, provide high energy and can be easily charged. Because it is a requirement for people that electronic devices be portable. The development of electronic devices with lithium-ion batteries has accelerated. Electronic devices such as mobile phones, tablets, laptops and electric cars have entered people's lives. For these devices and automobiles that require high energy, batteries had to take up little space. Lithium ion batteries provide exactly this. Recently, interest in advanced technology has caused an increase in the demand for energy. The global economy depends on technological processes that are causing fossil fuels to be depleted faster than anticipated. This has resulted in greenhouse gases being released into the environment, endangering human health and causing adverse climate conditions. Significant changes have recently begun to be made in the energy sector in order to limit the impacts of global warming and climate change and to get rid of greenhouse gases caused by fossil fuels. In order to reduce the threat posed by global warming, many countries use renewable energy sources such as sun, wind and water. Electricity generation from these sources is expected to become the dominant source of global zero-carbon energy in the future. In addition to the widespread use and ease of application of renewable energy, an electrochemical energy storage device such as a battery is considered a suitable option to store energy for a certain period of time when these resources cannot be used effectively. Rechargeable batteries are very efficient for both portable and stationary storage. In this context, with the constantly increasing use of lithium-ion batteries in portable devices, electrical networks and transportation, these batteries are needed more and more. The use of these batteries, especially in electric vehicles, is seen as an excellent alternative to control high fossil fuel usage due to their environmental friendliness. Since the lifespan of these batteries is generally 5-8 years or 100-150 thousand kilometers, the number and quantity of end-of-life lithium-ion batteries is increasing day by day. Long-term economic viability and sustainable resource use raise concerns as the reserves of the metals used in the production of these batteries decrease day by day (Kouhestani et al. 2020; Ma et al. 2021; Panichello and Buschman, 2021; Avcı and Özdemir, 2023). For this reason, recycling of waste lithium-ion batteries that will be generated as a result of the end of life of used electrical device and vehicle batteries is of great importance globally. The recovery of lithium in end-of-life batteries is of great importance in terms of environmental, economic, health and safety of aquatic ecosystems and organisms. In this context, recycling of lithium-ion batteries should be supported, especially for the protection and sustainability of aquatic ecosystems.

Although lithium mining is described as a relatively cheap and effective process, it consumes a lot of water. Lithium extraction requires a significant amount of water, approximately 2 thousand tons per ton of lithium. In northern Chile, lithium extraction by various companies consumes 65 percent of the region's water resources. This has not only created extreme water scarcity, but has also had a significant impact on local farmers' ability to grow crops and sustain livestock. An additional environmental impact of lithium mining is that it damages soil, pollutes air and already limited water resources. With this, it is pointed out that the raw brine produced during the mining of lithium mines in salt lakes may lead to salinization of soil and water by changing the physicochemical properties of the soil. Additionally, extracting lithium and converting it into commercially usable forms can produce toxic waste that can leach into the environment. The leakage of these wastes into aquatic ecosystems harms fish and other organisms. During lithium production processes, the surrounding natural life also experiences ecological stress. However, rechargeable lithium batteries enable more energy to be stored for longer periods of time, and the use of more electric cars contributes to the fight against global warming by producing less greenhouse gases and emissions. In this context, lithium mining is not considered a long-term and fair solution as it contributes to water depletion and water pollution (Sarıcan, 2020). For these reasons, lithium mining studies in aquatic ecosystems, which are of great importance for humans and biodiversity, should be carried out very carefully. Otherwise, it would be beneficial not to conduct lithium mining activities in aquatic ecosystems. However, there is a great need to develop better recovery technology for lithium to protect aquatic ecosystems.

CONCLUSION

Hydrosphere is one of the layers on Earth and is indispensable for organisms. All the water in the world forms the hydrosphere. Water is of vital importance in the life of organisms. Water is essential for life. Water is where life began on the earth. In the natural structures of the oceans, seas, lakes, streams and groundwater that make up the hydrosphere, there are substances that are beneficial and harmful to life in different amounts and types dissolved or suspended. Vegetable, animal and other living creatures in aquatic ecosystems and in mutual relationship with the waters therein are connected to each other through a food chain. Water is one of the most important factors for the health of organisms. By analysing water, it should be checked and monitored whether the water is suitable for life, whether it is clean and hygienic, and whether it is suitable for health in terms of the minerals it contains. All kinds of water pollution not only harm all organisms around and in it, but also paves the way for the extinction of various species and biological communities. Water pollution has the potential to become one of the biggest problems faced by humanity if necessary precautions are not taken. The quality and pollution of water should be examined in all its dimensions, sustainable practices should be standardized and people should be made aware. Recently, human activities have been affecting lithium levels in aquatic ecosystems. Human activities increase lithium levels in aquatic ecosystems and increase its bio-ecological accumulation. Lithium has toxicological impacts on aquatic ecosystems and humans. In recent years, lithium has affected aquatic ecosystems more than ever before, posing widespread risks through the food chain. The absence of lithium in the list of parameters analysed in water quality and pollution monitoring studies in the world and in Turkey is a major deficiency. Therefore, lithium should be used as a parameter in water quality and pollution monitoring studies. However, there is no internationally or nationally recommended standard value or maximum limit value for lithium in aquatic ecosystems and drinking water. Therefore, it is very important to determine international and national standard values for lithium in aquatic ecosystems and drinking water.

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A Modern Platform for Electrochemical Pharmaceutical Analysis: Polymer-Modified Pencil Graphite Electrodes (PGE)

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ABSTRACT

Pencil graphite electrodes (PGEs) have emerged as a practical electroanalytical platform due to their cost-effectiveness, disposability, and favorable properties, such as low background currents (Akanda et al., 2015; Pandey et al., 2019). Despite these advantages, native PGEs can exhibit variable and sometimes electro-inactive behavior in complex matrices, necessitating surface activation and functional modification to obtain reliable performance (Srinivas and Kumar, 2023). Electrochemical pretreatment serves as a key transitional strategy to enhance electrocatalytic activity and sensitivity, as evidenced in drug determination studies (Parvizi-Fard et al., 2018). Building upon this foundation, polymer modification has become a dominant approach to engineer interfacial charge transfer and introduce recognition. Conducting polymers, such as polypyrrole-based architectures, have demonstrated high sensitivity for pharmaceutical assays in biological fluids (Kuralay et al., 2020; Omar et al., 2023). Conversely, molecularly imprinted polymers (MIPs) prioritize selectivity through template-specific binding sites, often integrated with nanoparticle doping to maximize active surface area in complex matrices (Moaaz et al., 2025; Shama et al., 2023). This chapter synthesizes the transition from bare and activated PGEs to sophisticated polymer-modified architectures. It provides a comparative analysis of conducting polymers and MIPs regarding their selectivity, stability, and sensing mechanisms. Finally, the chapter evaluates which polymer-based strategies offer the most promising performance for drug analysis in complex clinical and pharmaceutical matrices based on recent empirical evidence (Hassan et al., 2022; Kuralay et al., 2020; Moaaz et al., 2025; Mohamed et al., 2019; Parvizi-Fard et al., 2018; Shama et al., 2023).

Keywords – Pencil graphite electrodes (PGE), Polymer-modified electrodes, Conducting polymers, Molecularly imprinted polymers (MIP), Pharmaceutical analysis

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INTRODUCTION

1. Why PGEs Became "Modern" in Drug Electroanalysis:

PGEs have been increasingly adopted in electrochemical sensing because they are very low cost, widely available, and easy to modify, enabling disposable and accessible sensing formats (Akanda et al., 2015; Pandey et al., 2019). Reviews focusing on PGE electroanalysis describe PGEs as viable substitutes for more expensive conventional electrodes (e.g., glassy carbon and noble metals) because they can provide low background currents, good sensitivity, and reproducibility, particularly when surface area and interfacial chemistry are engineered (Akanda et al., 2015; Pandey et al., 2019). At the same time, more recent critical discussion emphasizes that native PGE behavior can be unpredictable due to the complex composition of commercial pencil leads and that surface pretreatment/activation is often preferred to reliably render PGE surfaces electroactive for analytical applications, especially in complex matrices (Srinivas and Kumar, 2023). This combination has driven a progression from bare PGE use toward systematic activation and, ultimately, polymer-based functional coatings (Pandey et al., 2019; Srinivas and Kumar, 2023) .In contrast to early studies relying on bare PGEs, the consensus in later literature is that performance gains for drug analysis are most consistently achieved through surface engineering, including pretreatment and functional modification with polymers and composites that enhance charge transfer, increase effective surface area, and control interfacial interactions with analytes and interferents (Akanda et al., 2015; Pandey et al., 2019; Srinivas and Kumar, 2023) .

2. From Bare to Activated: Electrochemical Pretreatment as the Bridge to High-Performance PGEs

A recurring theme is that bare PGEs, while attractive, often require electrochemical pretreatment/activation to improve analytical sensitivity and electrocatalytic response (Pandey et al., 2019; Srinivas and Kumar, 2023). Parvizi-Fard et al. demonstrated that pretreating PGEs increased electrocatalytic activity relative to non-pretreated PGEs and enabled voltammetric quantification of diclofenac sodium with a reported detection limit of 0.12 μM and good recoveries in biological and pharmaceutical samples (Parvizi-Fard et al., 2018). Importantly, that work compared pretreatment strategies and concluded potentiostatic pretreatment provided better analytical sensitivity than a potentiodynamic strategy, indicating that "activation" is not a single step but a tunable design variable (Parvizi-Fard et al., 2018). Building upon the broader recognition that carbon electrodes can suffer from surface passivation/fouling in certain chemistries, polymer film strategies are often framed as the next step beyond pretreatment, because polymeric coatings can both stabilize the interface and mitigate fouling-related signal loss in carbon-based systems (Pandey et al., 2019; Rana and Kawde, 2015). Although Rana and Kawde focused on phenols rather than drugs, they explicitly positioned electrochemical polymerization as a means to overcome well-documented carbon-electrode fouling phenomena, supporting the mechanistic plausibility of polymer coatings improving robustness for analytically challenging targets (Rana and Kawde, 2015).

3. Polymer-Modified PGEs: Design Rationale and Major Modification Routes

3.1. Why polymer modification?

Polymer coatings are repeatedly used because they offer controllable interfacial chemistry and can be formed directly on PGE surfaces by electropolymerization or by casting/coating approaches, while enabling integration with other enhancers (e.g., nanoparticles, ionic liquids) (Akanda et al., 2015; Mohamed et al., 2019; Pandey et al., 2019). In PGE-based reviews, combining polymers with other modifiers is highlighted as a key direction to improve surface area, electron transfer, and analytical performance in practical sensing tasks, including pharmaceuticals (Akanda et al., 2015; Pandey et al., 2019). In complex biological matrices, polymer-containing composite designs have additionally been used to improve anti-interference behavior (e.g., serum compatibility in rivastigmine sensing) (Mohamed et al., 2019).

3.2. Electropolymerization on PGE (film growth in situ)

Electropolymerization is widely used on PGEs because it enables direct, controllable polymer-film deposition under electrochemical control (e.g., cyclic voltammetry) (Kuralay et al., 2020; Omar et al., 2023; Soysal, 2019). Soysal reported cyclic voltammetry-based electropolymerization of 4-amino-3-hydrazino-5-mercapto-1,2,4-triazole (Purpald®) on disposable PGEs and explicitly compared polymer-film-coated and naked PGEs using ferri/ferrocyanide redox probes, illustrating the general approach of diagnosing interfacial changes after film deposition (Soysal, 2019). In drug sensing, Omar et al. employed electropolymerization of 1,5-diaminonaphthalene to form a poly(1,5-DAN) film on disposable PGEs and showed that the polymerization mode (CV vs chronoamperometry) significantly affected electrode resistivity and sensitivity, with the CV-prepared film providing superior analytical performance for flufenamic acid (Omar et al., 2023). Beyond standard film deposition, the architectural engineering of the electrode surface plays a vital role in sensitivity. For instance, Sardohan Koseoglu and Demirhan demonstrated that nanowire-structured electrodes significantly enhance the voltammetric determination of cloxacillin. By leveraging the high surface-to-volume ratio of nanowire-modified PGEs, the sensor achieved high sensitivity for this critical antibiotic, which is widely used in treating bacterial infections (Sardohan Koseoglu and Demirhan, 2025). Kuralay et al. described electrochemical preparation of a polypyrrole/polypyrrole-3-carboxylic acid copolymer on single-use PGEs and demonstrated its use for acetaminophen detection, reinforcing electropolymerization as a pragmatic and reproducible route for PGE functionalization in pharmaceutical assays (Kuralay et al., 2020).

3.3. Polymeric membranes on graphite sensors (potentiometric drug analysis)

A distinct polymer strategy is the use of polymeric membrane coatings (frequently PVC-based, plasticized, and incorporating ion-pair complexes) to create pencil-graphite-based potentiometric sensors for drug assays (Hassan et al., 2022; Nashed et al., 2020; Sakur et al., 2021). Sakur et al. reported pencil graphite sensors in which the graphite bar was coated with a membrane containing an ion pair, PVC, and plasticizers for potentiometric estimation of desloratadine and montelukast sodium in dosage forms, positioning the approach as “green” and practical for pharmaceutical analysis (Sakur et al., 2021) . Nashed et al. similarly constructed polymeric-membrane-coated graphite electrodes for potentiometric determination of fexofenadine hydrochloride and montelukast sodium in pure mixtures and combined dosage forms, emphasizing the membrane/ion-pair strategy as an electrochemical approach for combined drug products (Nashed et al., 2020) . Hassan et al. extended this general design logic to sildenafil citrate (vitamin V), using ion-pair complexation embedded into a PVC matrix on a pencil-fabricated graphite sensor electrode and demonstrating applicability to marketed tablets and human urine samples via potentiometry and potentiometric titration (Hassan et al., 2022). Collectively, these studies show that polymer membranes on pencil graphite platforms can prioritize operational simplicity and matrix applicability in dosage forms and biological fluids (Hassan et al., 2022; Nashed et al., 2020; Sakur et al., 2021).

3.4. Hydrogels and polymer composites on PGEs (emerging coatings)

Recent work has also explored hydrogel polymer coatings on “cheap and disposable” PGEs, with characterization by cyclic voltammetry, differential pulse voltammetry, and square-wave voltammetry, indicating an expanding polymer toolbox beyond thin conducting films and PVC membranes (Ramesh et al., 2024). In this direction, Ramesh et al. described PGE surface modification with poly(acrylamide-co-AMPS) and poly(acrylamide-co-AMPS)/polyaniline hydrogel coatings and characterized sensing behavior electrochemically while confirming polymer structure by FT-IR, illustrating how mechanically distinct polymeric matrices (hydrogels) are being adapted to pencil graphite platforms (Ramesh et al., 2024). While Selvaraj et al. focused on methylene blue detection rather than pharmaceuticals, their use of polyaniline/polypyrrole-based poly(acrylamide-co-AMPS) hydrogels further supports the methodological feasibility of hydrogel–conducting polymer hybrid coatings on PGEs (Selvaraj et al., 2024).

3.5. Biopolymer-like coatings for biointerfaces (supporting drug–biomolecule assays)

Polymer coatings can also serve as biofunctional interfaces. For example, poly-L-lysine coatings on PGEs were prepared electrochemically and applied to ultrasensitive DNA hybridization detection, demonstrating polymer-enabled attachment/interaction with biomolecules on pencil graphite transducers (Kuralay et al., 2018). This biointerface capability conceptually aligns with drug–DNA interaction sensing approaches previously built on polymer/nanocarbon modified PGEs (e.g., polypyrrole/MWCNT plus DNA immobilization for 6-mercaptopurine) (Karimi-Maleh et al., 2015), even though that anticancer example precedes the recent five-to-seven-year timeframe defined for this synthesis. The versatility of PGEs extends to the detection of toxic metallic impurities in pharmaceutical and environmental contexts. Percin Ozkorucuklu et al. reported the voltammetric determination of mercury(II) using a PGE modified with 4-(4-methylphenyl aminoisonitrosoacetyl)biphenyl. This demonstrates that functionalizing the graphite surface with specific organic ligands provides a robust platform for the selective monitoring of heavy metal ions (Percin Ozkorucuklu et al., 2017).

4. Conducting Polymers vs. Molecularly Imprinted Polymers (MIPs): Selectivity and Stability

4.1. Conducting polymers: sensitivity and interfacial kinetics as primary drivers

Conducting polymer coatings are repeatedly presented as enabling functionalized, electrically active surfaces with favorable physical properties, which can translate into improved analytical performance when deployed as electrode coatings (Higgins et al., 2011; Kuralay et al., 2020). On PGEs specifically, conducting-polymer film formation and electrochemical characteristics (including electrostability) have been studied for polyaniline-derivative coatings, supporting the idea that conducting polymer films can be systematically optimized for robust electrochemical behavior on pencil graphite substrates (Arslan and Hur, 2014). In pharmaceutical sensing applications, conducting polymer films have delivered strong sensitivity: poly(1,5-DAN) /PGE achieved extremely low detection limits for flufenamic acid and was reported to exhibit good accuracy, repeatability, storage stability, and selectivity in biological fluids and pharmaceutical formulations (Omar et al., 2023), while polypyrrole-based copolymer coatings on single-use PGEs were demonstrated for acetaminophen detection (Kuralay et al., 2020). These findings are consistent with the PGE review-level conclusion that surface modification (including polymers) is central to improving PGE sensitivity and analytical utility for pharmaceuticals (Akanda et al., 2015; Pandey et al., 2019).

Stability/reproducibility: Omar et al. provide direct evidence that polymer performance is strongly dependent on deposition method (CV vs chronoamperometry), implying that reproducibility and stability are not intrinsic to "the polymer" but are co-determined by film-growth protocol and resulting film resistivity/morphology (Omar et al., 2023). This methodological sensitivity is consistent with the broader emphasis that PGE platforms often require careful surface activation/control due to variability in native PGE surfaces (Srinivas and Kumar, 2023).

4.2. MIPs: selectivity by design, often enhanced by nanoparticle doping

MIPs are widely recognized as selective recognition layers because they contain template-shaped binding sites that preferentially rebind target analytes, and electrochemical sensing with MIP films includes strategies such as electropolymerized MIP membranes and composite membranes containing conductive materials and polymer binders (Blanco-Lopez et al., 2004). On PGEs, recent MIP studies emphasize integrating nanoparticles to increase electroactivity and surface area while retaining recognition: AgNP-doped MIP-coated PGEs were used for cortisol detection in aqueous solution and biological samples by DPV, explicitly describing performance improvements from nanoparticle-doped MIP architectures (Shama et al., 2023). Similarly, AuNP-modified MIP-coated PGEs were used for selective bisphenol A detection in aqueous and real water samples, with AuNPs explicitly introduced to increase electroactivity and surface area (Yılmaz et al., 2024). Karthika et al. further demonstrated an electropolymerized pyrrole-based MIP on reduced graphene oxide modified PGEs (for picric acid), combining computational interaction analysis, template extraction, and electrochemical/surface characterization, thereby exemplifying modern "MIP + conductive scaffold" design logic on pencil graphite (Karthika et al., 2022). A specialized approach within MIP-PGE design involves the use of overoxidized polymers to create highly selective cavities. Sardohan Koseoglu and Demirhan developed a novel molecularly imprinted overoxidized polypyrrole (OPPy) electrode for the determination of sulfasalazine. This study highlights how the removal of template molecules from the overoxidized polymer matrix creates precise recognition sites, allowing for the selective determination of anti-inflammatory drugs in complex samples (Sardohan Koseoglu and Durgut, 2020).

Stability and matrix transfer: Within the provided PGE-focused evidence base, MIPs are strongly evidenced for selectivity and for performance enhancement via nanoparticle/scaffold doping (Karthika et al., 2022; Shama et al., 2023; Yılmaz et al., 2024), but fewer examples explicitly demonstrate broad pharmaceutical validation in complex drug matrices relative to conducting polymer and composite antifouling strategies (e.g., serum and tablets) (Hassan et al., 2022; Mohamed et al., 2019; Omar et al., 2023). Thus, while MIPs offer a clear mechanistic route to selectivity (Blanco-Lopez et al., 2004), the most matrix-validated drug results in these references are more frequently associated with conducting polymer films and polymer-containing composite antifouling architectures (Mohamed et al., 2019; Omar et al., 2023).

4.3. Promising approaches for complex drug matrices

Based on studies that explicitly report biological fluids (serum/urine) and pharmaceutical formulations, the most promising approaches for complex matrices appear to be:

a) Polymer-containing composite antifouling/anti-interference designs, validated in serum: rivastigmine sensing using a PGE modified with lepidocrocite nanoparticles supported on N-chitosan carbon nanosheets plus an ionic liquid (PAS) demonstrated low-nM detection and excellent anti-interference in human serum and tablets (Mohamed et al., 2019).

b) Conducting polymer films with demonstrated biological-fluid applicability and stability metrics, as shown for flufenamic acid in biological fluids and formulations using poly(1,5-DAN) /PGE (Omar et al., 2023).

c) Polymeric membrane potentiometric sensors validated in urine/tablets for drugs such as sildenafil citrate, emphasizing operational robustness in real sample matrices via ion-pair/PVC membrane strategies (Hassan et al., 2022), with related dosage-form assays for montelukast/fexofenadine and desloratadine/montelukast (Nashed et al., 2020; Sakur et al., 2021).

In contrast, MIP-PGE architectures are highly promising where selectivity is paramount and have been demonstrated in biological samples for cortisol (Shama et al., 2023); and for selective binding-driven strategies for electro-inactive drugs such as memantine (Moaaz et al., 2025), but the current reference set supports a cautious interpretation: the strongest evidence for complex drug matrices is concentrated in composite antifouling designs and membrane potentiometry rather than in a broad suite of MIP-on-PGE drug validations (Hassan et al., 2022; Moaaz et al., 2025; Mohamed et al., 2019; Omar et al., 2023).

5. Recent Applications of Polymer-Modified PGEs for Drug Analysis by Class

5.1. Anti-inflammatory and analgesic drugs (NSAIDs and related)

Flufenamic acid (NSAID): Omar et al. developed a disposable PGE modified with electropolymerized poly(1,5-diaminonaphthalene). Critically they compared CV vs chronoamperometry prepared films, concluding that CV electropolymerization produced a sensor with higher sensitivity and lower resistivity (Omar et al., 2023). Under optimized conditions, the reported LOD was 4.97 × 10^{-10} M using square-wave anodic stripping voltammetry, and the sensor was reported applicable to biological fluids, pharmaceutical formulations, and pharmacokinetic studies, with good accuracy, repeatability, storage stability, and selectivity (Omar et al., 2023). This study is highly supportive of the claim that conducting polymer films can transform PGEs into ultratrace drug sensors when deposition parameters are optimized (Omar et al., 2023).

Acetaminophen (analgesic): Kuralay et al. fabricated polypyrrole/polypyrrole-3-carboxylic acid copolymer coatings on single-use PGEs and demonstrated application to acetaminophen detection, explicitly positioning conducting polymer coatings as routes to functionalized surfaces with good electrical/mechanical/physical properties (Kuralay et al., 2020). Although the abstract emphasizes preparation/characterization and application, it supports the broader conclusion that conducting polymer films on disposable PGEs remain an active and practical strategy for common analgesics (Kuralay et al., 2020), consistent with PGE review frameworks emphasizing polymer modifiers for pharmaceuticals (Akanda et al., 2015; Pandey et al., 2019).

Diclofenac (NSAID; pretreatment comparator): As a counterpoint to polymer modification, Parvizi-Fard et al. showed that electrochemical pretreatment alone can produce a versatile PGE platform for diclofenac sodium in biological and pharmaceutical samples with LOD 0.12 μM, and that potentiostatic pretreatment yielded better sensitivity than potentiodynamic pretreatment (Parvizi-Fard et al., 2018). In contrast to polymer-film studies, this highlights that simpler activation routes may suffice for certain NSAIDs depending on target detection limits and resource constraints (Parvizi-Fard et al., 2018), aligning with the view that surface activation is often preferred to address native PGE variability (Srinivas and Kumar, 2023).

Practical challenges: Across these NSAID/analgesic examples, a consistent practical issue is the strong dependence of performance on surface preparation protocol (pretreatment strategy or polymerization route), indicating reproducibility is linked to fabrication control rather than merely to electrode choice (Omar et al., 2023; Parvizi-Fard et al., 2018; Srinivas and Kumar, 2023).

5.2. CNS/neurological drugs and related bioanalysis targets

Rivastigmine (acetylcholinesterase inhibitor): Mohamed et al. reported a "triple amplified" PGE-based biosensor architecture: lepidocrocite (γ-FeOOH) nanoparticles dispersed in N-chitosan carbon nanosheets on PGE plus pyrrolidinium acid sulfate ionic liquid to amplify the signal (Mohamed et al., 2019). The sensor was characterized by PXRD/FTIR/SEM/EDX and evaluated by CV/DPV/EIS, with key operational parameters optimized (pH, scan rate, casting volume, nanocomposite concentration) (Mohamed et al., 2019). The reported analytical performance included LOD 0.99 nM and a linear range of 3.0–90.0 nM, with successful application to pharmaceutical tablets and spiked human serum and excellent anti-interference ability (Mohamed et al., 2019). This study is strongly supportive of polymer-containing composite designs as among the most mature pathways for complex biological matrices on PGE platforms (Mohamed et al., 2019), complementing broader modification narratives in PGE reviews (Akanda et al., 2015; Pandey et al., 2019).

Memantine (electro-inactive drug; MIP-enabled indirect analysis): Moaaz et al. introduced an MIP-based indirect voltammetric technique targeting electro-inactive memantine through selective interaction with an MIP and monitoring the decrease of a redox-active probe signal at the electrode surface, using in-situ electropolymerization on PGE (Moaaz et al., 2025). This work supports a distinct promise of MIPs in pharmaceutical electroanalysis: enabling selectivity-driven strategies even when the drug itself is voltammetry-inactive (Moaaz et al., 2025), consistent with broader MIP-film sensing concepts (Blanco-Lopez et al., 2004). While detailed matrix validation is not fully specified in the provided abstract, the methodological concept directly addresses a common limitation in electroanalysis—electro-inactive targets—by shifting the measurement paradigm to binding-induced probe modulation (Moaaz et al., 2025).

5.3. Hormones and biomarkers relevant to drug monitoring

Cortisol (bioanalytical target with pharmaceutical relevance): Shama et al. reported AgNP-modified MIP-coated PGEs for cortisol detection by DPV in aqueous solution and biological samples, explicitly attributing improved performance to nanoparticle-doped MIP architectures and large surface area effects (Shama et al., 2023). Although cortisol is not a "drug class" as such, it is a clinically relevant analyte for therapeutic monitoring contexts, and the study supports the feasibility of combining MIP selectivity with nanoparticle-driven signal enhancement on PGEs in complex biological matrices (Shama et al., 2023), consistent with the general approach of integrating recognition layers with conductive modifiers in MIP electrochemical sensors (Blanco-Lopez et al., 2004).

5.4. Combination drug products and dosage-form analytics by polymeric membrane PGEs (potentiometry)

Antihistamine/leukotriene antagonist combinations: Nashed et al. described polymeric-membrane-coated graphite electrodes for potentiometric determination of fexofenadine hydrochloride and montelukast sodium in pure, synthetic mixtures, and combined dosage forms, emphasizing the membrane/ion-pair architecture to construct sensitive electrodes for combined products (Nashed et al., 2020). Sakur et al. similarly described pencil graphite sensors using polymer membrane coatings (PVC plus plasticizers and ion-pairs) for desloratadine and montelukast sodium in binary dosage forms (Sakur et al., 2021). These studies collectively support that polymer membrane PGEs are particularly suitable where dosage-form matrices and combined analytes are central, because potentiometric designs can be engineered via ion-pair chemistry and membrane composition (Nashed et al., 2020; Sakur et al., 2021).

Sildenafil citrate (tablets and urine): Hassan et al. developed pencil graphite polymer sensor electrodes for sildenafil citrate using ion-pair complexes embedded in a PVC matrix (pre-plasticized), demonstrating application to marketed tablets and human urine via potentiometry and potentiometric titration (Hassan et al., 2022). This strengthens the conclusion that polymer membrane approaches are among the most immediately “translatable” PGE-polymer technologies for routine pharmaceutical/clinical sample handling, at least within the evidence base provided here (Hassan et al., 2022), consistent with the general attractiveness of low-cost pencil graphite platforms (Akanda et al., 2015; Pandey et al., 2019).

6. Synthesis: Findings and Contrasts

6.1. Highly supported conclusions

The synthesized evidence from recent studies allows for the establishment of several key conclusions regarding the evolution and performance of PGE-based sensing platforms:

a) PGEs are cost-effective, widely available, and readily modifiable, which underpins their adoption in electroanalytical sensing including pharmaceuticals (Akanda et al., 2015; Pandey et al., 2019).

b) Surface activation/pretreatment is commonly necessary because native PGEs can behave unpredictably and may require controlled generation of electroactive surface functionalities (Srinivas and Kumar, 2023), with demonstrated sensitivity enhancement in drug analysis (diclofenac) after pretreatment (Parvizi-Fard et al., 2018).

c) Polymer modification (especially electropolymerization) is a central strategy for transforming PGEs into sensitive drug sensors, as evidenced by conducting polymer films for flufenamic acid (Omar et al., 2023); and polypyrrole-based copolymer films for acetaminophen (Kuralay et al., 2020), consistent with PGE review syntheses emphasizing polymer modifiers (Akanda et al., 2015; Pandey et al., 2019).

d) Complex matrices are best addressed by polymer-containing composites and membrane approaches that explicitly target interference and real-sample validation, such as serum rivastigmine analysis with chitosan-derived nanocomposites and ionic liquids (Mohamed et al., 2019); and urine/tablet assays with PVC membrane sensors (Hassan et al., 2022). Similarly, the direct electrochemical synthesis of graphene oxide/cobalt oxide nanocomposites on PGEs demonstrates the efficacy of synergistic carbon-metal oxide hybrids for the sensitive detection of large biomolecules, such as insulin, in pharmaceutical formulations (Razmi et al., 2019).

6.2. Contrasting findings

Preparation method dependence: Omar et al. showed that film growth route (CV vs chronoamperometry) materially changes resistivity and sensitivity for polymer-modified PGEs, implying that "polymer-modified" is not a single performance category but a fabrication-dependent outcome (Omar et al., 2023). Parvizi-Fard et al. similarly showed pretreatment method (potentiostatic vs potentiodynamic) changes analytical sensitivity (Parvizi-Fard et al., 2018). Together, these studies challenge any simplistic expectation of universal performance improvements without rigorous optimization (Omar et al., 2023; Parvizi-Fard et al., 2018).

Selectivity vs validation breadth: MIP theory and prior MIP-film sensing strategies strongly emphasize selectivity through imprinting (Blanco-Lopez et al., 2004), and recent PGE implementations show selective, nanoparticle-enhanced MIP sensing in biological matrices (cortisol) (Shama et al., 2023), and selective binding-based indirect analysis for electro-inactive drugs (memantine) (Moaaz et al., 2025). However, within the specific recent drug-focused PGE literature provided here, conducting polymer and composite approaches show more numerous and explicit real-sample (serum/urine/tablets) validations across multiple drug contexts (Hassan et al., 2022; Mohamed et al., 2019; Omar et al., 2023) than MIP-on-PGE drug examples (Moaaz et al., 2025; Shama et al., 2023). This indicates a present evidence-weighting toward conducting polymer/composite/membrane designs for immediate complex-matrix deployment, while MIPs remain especially compelling for selectivity-critical or electro-inactive targets (Blanco-Lopez et al., 2004; Moaaz et al., 2025).

7. Practical Challenges in Polymer-Modified PGE Drug Analysis (as reported/implicit in the literature)

Native PGE variability and need for activation: The need for surface pretreatment is repeatedly emphasized due to unpredictable native behavior and complex pencil-lead composition, which can influence electroactivity in complex matrices (Srinivas and Kumar, 2023).

Method-dependent reproducibility: Both pretreatment and polymer film deposition routes can alter sensitivity/resistivity, making fabrication protocol control a principal determinant of analytical performance (Omar et al., 2023; Parvizi-Fard et al., 2018). To address the challenges of stability and matrix interference, the use of covalently bonded or strongly adsorbed functional groups is essential. Asri et al. utilized a furfurylamine-bonded keto-oxime modified electrode for the determination of nickel(II) ions in water samples. Such modifications ensure that the PGE remains a reliable tool for analyzing inorganic components within the broader scope of pharmaceutical and environmental safety (Asri et al., 2026).

Attribution in multi-component films: High-performing systems often combine polymers with nanoparticles and ionic liquids (e.g., rivastigmine sensor), complicating mechanistic attribution of gains to any single component (Mohamed et al., 2019), even while aligning with review-level conclusions that combined modifiers frequently yield strong PGE performance (Akanda et al., 2015).

Matrix interference and fouling: Carbon electrode fouling is a known issue in relevant chemistries, motivating polymerization-based approaches to stabilize the interface and mitigate passivation (Rana and Kawde, 2015), consistent with the deployment of anti-interference composite designs for serum analysis (Mohamed et al., 2019).

8. Future Trends and Outlook

Drawing upon recent advancements in surface engineering and material science, the future trajectory of PGE-based pharmaceutical analysis is expected to be shaped by the following strategic trends:

a) Hybrid polymer architectures (polymer + nanomaterial + ionic liquid) will remain central because demonstrated serum-compatible and anti-interference drug sensing on PGEs has been achieved via composite designs rather than single-component coatings (Mohamed et al., 2019), consistent with modification trends in PGE reviews (Akanda et al., 2015). Similarly, the direct electrochemical synthesis of graphene oxide/cobalt oxide nanocomposites on PGEs points toward a future of "in-situ" fabricated surfaces that simplify sensor preparation while maintaining high sensitivity for complex biomolecules like insulin Razmi et al., 2019).

b) Greater emphasis on standardized activation and fabrication protocols is implied by strong method-dependence findings in both pretreatment and electropolymerization studies (Omar et al., 2023; Parvizi-Fard et al., 2018), aligning with the argument that activation is preferred due to native PGE variability (Srinivas and Kumar, 2023).

c) Expansion of MIP strategies for selectivity-critical and electro-inactive drugs appears particularly promising, as illustrated by MIP-based indirect voltammetric concepts on PGEs for memantine (Moaaz et al., 2025) and nanoparticle-doped MIP sensing in biological matrices for cortisol (Shama et al., 2023), consistent with broader MIP electrochemical sensing concepts (Blanco-Lopez et al., 2004).

d) Polymeric membrane PGE sensors will likely continue to grow for dosage-form and routine clinical matrices because they have been repeatedly demonstrated for combined products and urine/tablet testing via ion-pair/PVC membrane approaches (Hassan et al., 2022; Nashed et al., 2020; Sakur et al., 2021).

e) Future trajectories also point toward multi-functional derivatives that bridge different analytical techniques. Gul et al. described an imidazole-functionalized boron-dipyrromethene (BODIPY) derivative for the dual detection of ions, enabling spectrophotometric fluorescence detection of Fe^{2+} and electrochemical sensing of Cu^{2+} on PGEs. These hybrid platforms represent the next generation of 'smart' interfaces that combine high-fidelity optical signaling with the cost-effective electrochemical power of pencil graphite (Gul et al., 2026).

f) Hydrogel and mechanically adaptive polymer coatings may broaden application space, as recent studies demonstrate hydrogel polymer coatings on PGEs and electrochemical characterization of sensing behavior, suggesting future directions beyond thin films and PVC membranes (Ramesh et al., 2024).

CONCLUSION

The emergence of PGEs as a modern platform for drug analysis is best understood as a staged evolution from low-cost, accessible bare electrodes to rigorously engineered interfaces that address sensitivity, selectivity, and matrix robustness (Akanda et al., 2015; Pandey et al., 2019; Srinivas and Kumar, 2023). Evidence shows that electrochemical pretreatment can significantly enhance PGE electrocatalytic activity and enable reliable NSAID measurements in biological and pharmaceutical samples, but pretreatment outcomes depend strongly on the chosen activation protocol (Parvizi-Fard et al., 2018). Building upon this transitional stage, polymer modification has become central to high-performance PGE drug sensing: conducting polymer films deposited by electropolymerization can provide ultralow detection limits and practical stability in biologically relevant matrices, yet their performance remains highly dependent on deposition method and film properties (Kuralay et al., 2020; Omar et al., 2023). In parallel, MIP coatings on PGEs offer a mechanistically clear pathway to selectivity through templated binding sites and can be strengthened through nanoparticle doping and conductive scaffolds, with demonstrated biological-sample applications (e.g., cortisol) and promising strategies for electro-inactive drugs (e.g., memantine via indirect probe modulation) (Blanco-Lopez et al., 2004; Moaaz et al., 2025; Shama et al., 2023). For complex drug matrices, the strongest support within the provided recent literature currently favors polymer-containing composite antifouling designs and polymeric membrane potentiometric sensors because they most consistently report successful validation in serum/urine/tablets and emphasize anti-interference performance (Hassan et al., 2022; Mohamed et al., 2019). Overall, future progress will likely depend on continued hybridization (polymer + conductive enhancer), improved protocol standardization to address PGE variability, and selective MIP-based paradigms tailored to electro-inactive or highly interferent-prone pharmaceutical targets (Akanda et al., 2015; Moaaz et al., 2025; Srinivas and Kumar, 2023).

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