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The Evolution of Electric Fishes: Comparative Taxonomic Analysis and Functional Insights

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Abstract
The main purpose of research is to determine the evolution of electric fishes. The research is based on comparative taxonomic analysis and functional insights. This work aims to shed light on the fascinating history of electric fishes through a comparative taxonomic analysis and an investigation of their functional insights. Their capacity to produce and detect electric fields is evidence of the effectiveness of convergent evolution as well as a source of ideas for new scientific research and technological advancement. We acquire a greater understanding of the intricacy and inventiveness of life on our planet by solving the riddles of these amazing animals. This investigation focuses on how form, behavior, and ecology interact to shape the variety of life on Earth. Over millennia, electric fish have refined their adaptations, demonstrating the continuing conversation between creatures and their surroundings. They have carved themselves niches where electricity rules supreme and are lords of their watery worlds. Finally, the development of electric fishes encourages us to be in awe of the intricacy of life and the amazing ways in which animals adjust to their surroundings. Gymnotiformes and Mormyridae's electric organ convergence is evidence of nature's capacity to solve related problems. We get a greater understanding of the marvels of evolution as we dig into the electrified realm of these aquatic creatures, and our interest in the mysteries of our natural world grows.

Keywords: Electric Fishes (EF), Taxonomic Analysis (TA), Functional Insight (FI).

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Introduction

Different kinds of fishes are present all over the world in other water bodies that range from the highest water streams to the deepest oceans. There is a wide range of fish that are present inside them. All of them vary in their body morphology and functioning. Some fishes among these are unique because they have some ability that differentiates them from the other species. The most evident example among these is electric fishes. When we hear the word, the first thing that comes to our mind is electricity. Yes, these fishes have a link with generating electric current. These fishes can generate electric current and sense electric fields even from the largest distance. The ability of the natural world to innovate is astounding, as seen by the emergence of new creatures with special adaptations that allow them to flourish in their various ecological niches. One of these adaptations that is especially interesting is the capacity of some fish species to produce and sense electric fields. The many taxonomic groupings that comprise the so-called "electric fishes" are fascinating examples of convergent evolution since they have separately acquired the unique ability to use electricity for predation, communication, and navigation. This research begins a thorough investigation into the evolution of electric fishes, providing a comparative taxonomic analysis and revealing the practical implications of this remarkable adaption (Arce, García-García, Corrales, & Botella, 2021; Dean, Bizzarro, & Summers, 2007). The freshwater ecosystems of South and Central America are home to most of the Gymnotiformes, also known as Neotropical knifefishes. This group includes well-known genera like Gymnotus (naked-back knifefishes), Electrophorus (electric eels), and Apteronotus (ghost knifefishes). Their modified muscle tissue-derived electric organs are adaptable instruments for communication, navigation, and prey sensing. The Mormyroidea, or African

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knifefishes, on the other hand, are indigenous to the waters of Africa, notably in its rivers and lakes. Within this category, notable genera include Petrocephalus, Campylomormyrus, and Mormyrus. Mormyroidea, like their Gymnotiformes relatives, have electric organs that they use for communication and prey detection.

Some fishes can only generate electric current, but others can also sense the electric fields. They can be regarded as a mixture of both fishes with these different abilities. These fishes are located mostly in freshwater or the deepest oceans of America and Africa. They are located in those areas because their body requires special features only available in those places. They can be wild because it is seen that when touching an electric fish, one can also get electric shocks from them. So, naturally, they are not available in common rivers but in freshwater-type areas.

All fishes that can detect the electric field do not come under the category of electric fishes because they are not generating the electric current in their surroundings. The most prominent example is that the sharks and rays do not generate electric current; they can only sense the electric field from the surroundings and large distances. So, as they cannot produce electric current, they are not regarded as electric fishes. Electric fish are a classic example of the phenomena of convergent evolution. Gymnotiformes and Mormyroidea have separately developed the capacity to create and decipher electric fields despite their geographical isolation and taxonomically disparate beginnings. This amazing convergence highlights the importance of electric communication and navigation for adaptation in aquatic environments and calls for a closer expression at the intricate functional principles behind these adaptations. Electric fields serve various fascinating and important purposes in the lives of electric fish. First, electric fish use their capacity for electric communication for various functions. These include the organization of group activities, the creation of dominance hierarchies, and mate attraction. The frequency and amplitude of the electric signals these fish generate can vary, revealing intricate details about the sender's identity, level of reproductive readiness, and social standing. Electric fish can better survive and reproduce by navigating the complex social dynamics of their groups using their electric language. Their intricate system of signals, known as their electric language, is utilized to attract mates, form dominance hierarchies, and coordinate group activities. The ability to develop complex mental maps of their surroundings, which allows electric fish to navigate in full darkness or muddy waters, is another astonishing navigational help provided by electric fields. The ability to detect even the slightest electric signals created by potential prey is perhaps the most remarkable aspect of how electric fields are a crucial element of their predatory prowess. Beyond biology, the development of electric fishes offers important insights. It has ramifications for sensory ecology, neuroscience, and bioengineering. The electric signals between them are responsible for communication even when there is a large distance between them (Farrell, 2011).

Electric fishes have specialized body organs for the generation of electric current. This organ differs when we talk about different types of fish. The functioning of different organs differs with each individual. This organ normally constitutes the major part of the body weight. This organ carries the electric current responsible for the electric field's production. The organ can be divided into many parts depending on the body of an organism. Those parts are separately responsible for the functioning of the body. These organs are responsible for the production of high voltage current or low voltage current. This is linked with the parts. Different types of fish are present worldwide, producing different kinds of electric currents of different voltages. Electric fishes generate a discharge, and this is actually in a wave-like manner, which further produces an electric current.

The question that arises in one's mind is how a fish evolved into an electric fish. Because it is not from the start that the fish can produce an electric current, this change happened in the fish bodies and made them capable of producing electric currents. This was a series of genetic changes in the fish bodies that took place and enabled the body of fishes to have modifications in them. Sodium channel gates are present in almost all fishes. There is also a duplicate of them in the bodies of fishes. Fishes turned off some duplicated gates and transmitted them to other cells. A new organ is formed, responsible for the transmission of electric current in their bodies and the ability to form electric fields in them. This was the basic evolution process of the fishes that adapted themselves in such a way that they can now form electric signals and transmit electric currents through their bodies, respectively. Scientists are finding ways to find why the electric fishes have turned off the sodium gates in their bodies, and it's still a mystery (Gallant, Losilla, Tomlinson, & Warren, 2017).

Electric fishes can just transmit electric current, so they must have some benefits. The first thing that they are blessed with is the prediction of prey. They can easily sense the animals that are coming towards them. These fishes then turn this ability into their sensory weapon because, with the help of these, they can sense and locate the prey, which ultimately turns out to be beneficial for them. It is seen that the two electric fishes of the same electric frequency do not hit each other; this is because of the non-hitting mechanism. With this help, the two fishes never bump into each other. The size of electric eels may vary. It is observed that the size of electric fishes is normally larger than the other normal fishes. This may be due to the function they had to perform. Electric fishes never end up shocking themselves; this is maybe due to the tissues present in the body, and the fishes never have a shock on them (Jason & Mitchell, 2022).

Mature electric fishes mostly feed on carnivores, insects, small fishes, etc. The lifespan of these fishes is still unknown. This is due to the large amount of diversity inside the water that makes it difficult to calculate the total life cycle of these fishes. Very few species of electric fishes are known, and there is still more to discover. They surely have a future if complete guidance is given to understand their adaptations and life cycle.

Research objectives:

This paper explains The Evolution of Electric Fishes related to the Comparative Taxonomic Analysis and Functional Insights

Literature Review:

This review is based on the overview of studies related to electric fishes, their evolution, their Taxonomic Analysis, and Functional Insights that can be useful. Recent studies have explained that the electric fish is the type of fish that can generate electric fields along with the production of electric field(O'Connell & Hofmann, 2011; Rezende & Diniz-Filho, 2011). They also can sense electric fields around them in the vicinity. There are different types of electric fishes depending upon their habitat and the type of skeleton they have. Recent studies explained that these fishes are marine as well as freshwater. Depending upon the type of skeleton, they have both types of skeletons, bony and cartilaginous(Dean et al., 2007). When the Morphology of these fishes was studied, it became known that they could produce electric fields because of their electric organs. This electric organ is a type of electrolyte that may be a modified muscle or nerve cell that can produce electric fields. The electric organ has various functions, ranging from locating prayer to courtship behavior(Pitchers, Constantinou, Losilla, & Gallant, 2016). This electrical field is also used as a defense against predators. Studies also explain that two types of electrical organs have specific functions in different species. These types of electrical organs are pulse electrical organs and wave electrical organs(Lavoué, Arnegard, Sullivan, & Hopkins, 2008). When research was conducted about the evolution of behaviors in fishes related to electrical organs, it was startling to know that many developed behaviors are related to electrical organs in the body. For example, in African sharp-tooth catfish, the electric field is used to locate prey such as mormyrids. The other behavior related to electrical fish is Batesian mimicry, used to dissuade predators(Delroisse, Duchatelet, Flammang, & Mallefet, 2018). When the process of evolution of these fishes is discussed, it came to know that all vertebrates have electrical signals in their body in the form of nerve impulses. This ability of electro reception is also present in cartilaginous fishes, platypus, and echidna.

In some vertebrates, these signals are powerful enough to repel predators(Wu et al., 2022). But some fish do not use electro reception such as stargazers. Recent studies also revealed that electro-reception is an ancestral trait, which means it was also present in the last common ancestor (Sullivan, Lavoué, & Hopkins, 2002). For electric fish, electric fields are a vital navigational tool. These organisms create a complex mental map of their environment by sending electric pulses into it and carefully analyzing the signals returning. Due to their sensory skill, they can travel through muddy waters or complete darkness with astounding accuracy. Perhaps the most fascinating use of electric fields in electric fishes' lives is their aptitude as adept hunters. These amazing critters use electromagnetic fields to locate and recognize their prey. Electric fish are very sensitive to the electric signals created by the motions of prospective food, including writhing larvae buried beneath riverbeds, tiny fish, and aquatic invertebrates. Electric fish can locate their prey with astounding precision because of their capacity to recognize these small electric clues. The integration of sensory awareness and predatory strategy that has developed over eons is exemplified by this one-of-a-kind hunting method, which portrays electric fish as aquatic tyrants.

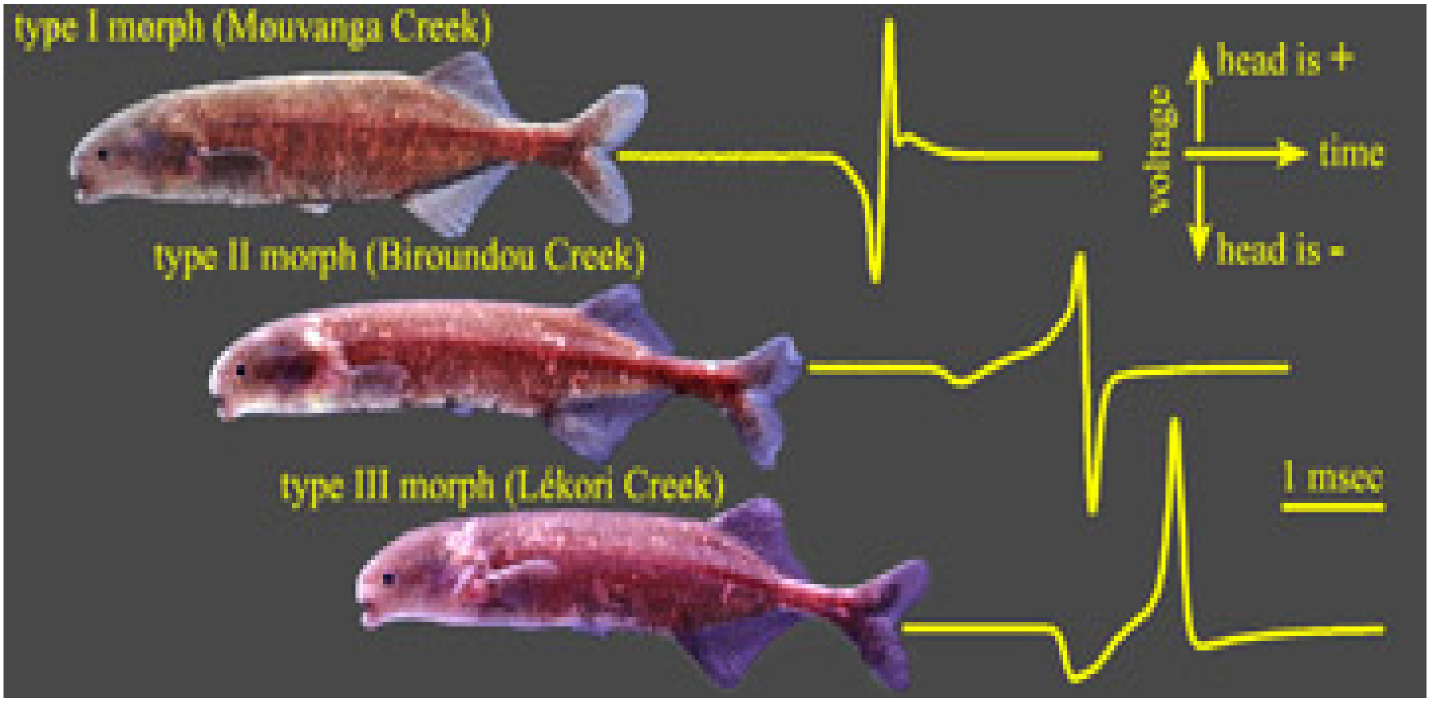
The ancestral form of the electric organ was called the ampullary electric organ because of its presence in the ampullae of Lorenzini. Then, this organ evolved into a lateral line in fishes like sharks, rays, lungfish, paddlefish, aquatic salamanders, and others. There are almost 350 known species of electric fishes. Research and studies explained that this electric organ evolved eight times in history, four times out of eight times produced such an electrical organ that was powerful enough to produce electrical shock(Gupta, Dwivedi, & Tripathi, 2018). Further studies on electrical organs revealed that this organ evolved from myogenic tissue, which is specialized to form muscles. In some groups, such as Gymnotiformes, this electrical organ forms from neurogenic tissue, which forms nerves in the body. There are different types of shock colors produced by these fishes such as actively electro-locating fishes are marked by small lightening of yellow colour(Arunrat, Sansupa, Kongsurakan, Sereenonchai, & Hatano, 2022). The other group of fish, which can produce electrical shock, shows a lightening of red color. There are also some passive electro-locating species whose lightening color is not so prominent. The electric organs in all fishes do not produce electrical shock of the same volt; for example, in weekly electric fishes, the volt of electrical shock is less than one volt(Huber, van Staaden, Kaufman, & Liem, 1997).

An essential part of understanding the complex evolutionary histories of electric fishes is comparative taxonomic study. Researchers may reconstruct evolutionary timelines and pinpoint critical junctures when electric organs and electric field sensing systems first appeared by tracking the phylogenetic connections among diverse species and genera within Gymnotiformes and Mormyroidea. The genetic, anatomical, and physiological alterations that underpin the evolution of these remarkable adaptations are clarified by this comparative approach. Studying electrified fish has provided functional insights that go beyond biology. They have ramifications for disciplines including sensory ecology, neuroscience, and bioengineering. Designing sensors and communication systems with bio-inspired features can be motivated by understanding how electric fishes produce, transmit, and perceive electric signals. Diverse industries, including underwater robots, medical diagnosis, and sensory prostheses, may benefit from these advancements. But in strong electric field-producing fishes, this electrical volt is large enough to stun their prey with the help of an electrical field. The working of this electrical organ depends upon its composition of electrolytes(Lavoué et al., 2012). This electrical organ comprises the electrolyte and other lsrge6, flat cells that help to create and store electrical energy. Some special types of sodium channels in them play an important role in electrical discharge. There are also sodium-potassium pumps that work against a concentration gradient to move ions(Giassi, Maler, Moreira, & Hoffmann, 2011). These electrolytes in the electrical organ are polar, stimulated by the signal from the nervous system. There is also a function of a main neurotransmitter called acetylcholine, which acts on acetylcholine receptors that cause the flow of sodium ions toward electrolyte(Butler & Hodos, 2005). In this way, some changes occur along the membrane of a nerve cell that produces a sudden electrical shock that can induce pain threshold in some species depending upon the strength of voltage produced. These electrical shocks may be used to communicate, such as to attract their mates or for a kind of territorial display in some species(Liu et al., 2016). This electric signal may indicate sexual behavior in some species, such as in brown ghost knife fish. This electrical signal may indicate anti-predator behavior with open mouth displays or, in some cases, bites to show anti-predator behavior in a few species, such as in catfish(Nishikawa, 2002).

These electrical signals produced by fish can also be used practically in a few industries. Recent studies have focused on using these electrical fishes for better purposes(Peterson et al., 2022). After these studies, they concluded that these electrical fishes can be used to design different types of electrosense machines. These fishes can also detect any kind of electrical field surrounding the exact location of any object producing an electrical or magnetic field(Gallant, Arnegard, Sullivan, Carlson, & Hopkins, 2011; Ying Wang & Yang, 2021). These fishes can also be used to induce changes in fish tissues for their modification of meat. These fishes also have applications in magnetic appliances because electrical fields can easily interact with magnetic fields(Arnegard et al., 2010). However, the capability of electric fishes to produce electric shocks may be the adaptation that most exemplifies their power. In particular, the electric eel (Electrophorus electricus) has become well-known for its ability to generate high-voltage electric discharges. These electric shocks have two functions: they immobilize victims and act as a powerful barrier against would-be predators. The electrifying powers of the electric eel provide a striking demonstration of how evolutionary processes may enhance a characteristic to the point where it can be used as a lethal weapon for both predation and self-preservation. Electric fish have evolved beyond the specific adaptations and behaviors that they have developed. It offers important insights into how convergent evolution works, which is when unrelated species independently develop similar features owing to shared selection forces. Gymnotiformes and Mormyroidea have repeatedly developed electric organs and electric field production, highlighting the adaptive importance of electric communication and navigation in their different settings. It emphasizes that nature frequently finds corresponding responses to comparable problems, illuminating the influence of natural selection in forming biological variety. After an overview of studies that are related to electrical fishes, their evolution, Taxonomy, and future Insights, we came to the point to conclude that different studies explained the Morphology, anatomy, and physiology of electric fishes along their way of evolution(Pomin, 2010). But after this overview, we learned that there is still a stringent need for further studies for better use of these electrical fishes for purposes other than meat(Rogers, Clarke, & Reynolds, 1999; Yueqi Wang et al., 2020).

Anatomical Specialties of Electric Fish:

Out of the major groups of animal kingdoms, fish are the only species that can possess and process electric signals. Electric fish have always been a focus for studying both sensory and electric organs. The most common of these fish groups are knife fish from South America and *corymbiform* species from Africa. Given their electric capacity, electric fish of any origin are classified as either strongly electric or weakly electric species. While studying the evolutionary changes, weekly electric and strongly electric fish take the course as they are involved in biological functions that can lead to better study of evolution in their electric organs. Weakly electric species are involved in electro location, during which these species discharge electrical signals and then identify objects in their vicinity by observing disruptions in those electric discharges(Wallach et al., 2022). They also can communicate through electric discharges they produce, i.e., electro communication(Scapin, 2020). This electro communication method helps them to communicate more efficiently and aids in processes like finding mates, selection, and recognition of species, either of the same or different kinds (Zakon et al., 2008). On the other hand, strongly electric species are involved in harsher actions as they produce deadly electric responses toward the predators, making them disabled and paralyzed. They use electric discharge as the weapon and protection agent to defend themselves against lethal predators.



Evolution of Electric Organs in Electric Fish:

Fish genetics has played a major role in developing electric organs in them. Sodium channels act as tiny muscle motors in fish bodies produced by the duplicate version of every gene(Rodríguez-Cattaneo et al., 2008). To evolve as electric fish, these species turned off one duplicate gene pair controlling sodium channels and transferred this gene from the fish to other cells. These tiny motors that initially played a role in muscle action, i.e., contraction, were reassigned to generate electric signals. In this way, new electric organs were born in the fish body, classifying these fish as electric fish(Zakon et al., 2006).

Now, there are different types of electric organs present in a fish, depending upon the source or origin. If the electric organs have evolved or derived through muscular tissues, they are called myogenic electric organs. Similarly, if the origin of electric organs has been nervous tissues, then they are termed neurogenic electric organs. The cells in these organs are called electrolytes, and help produce electric discharges by manipulating the action potential, especially in the case of myogenic electric organs(Nagel et al., 2017). These electrolytes have different distributions in different species and can vary largely in number. For example, electric fish like Gymnotiforms have two types of electrolytes depending on their site of origin.

One type of electrolytes arrives from the tail region of these species, and the other type has the site of origin located below the tail region, i.e., the germinative area. Other than producing electric discharges, electric fish also have the sensory organs to sense the electric charge present in their surroundings. They have specialized receptors named electroreceptors(Bray et al., 2022). The discharge patterns produced by these species are also unique in every species. Some show continuous and wave-type discharge that has no gaps in between. Some of them show discontinuous pulsating discharge with a gap of a pulse between them. The discharge shape produced by these types of fish is also variable(Wang & Yang, 2021). Some produce charges consisting of one phase only, i.e., monophasic discharge, while others may produce two or three-phased charges, i.e., di or triphasic discharge.

Taxonomic Analysis of Electric Fish:

Electric fish have had an evolutionary taxonomic history. Initially, the taxonomic history of electric fish started in the Mediterranean region and ancient Egypt when the catfish was known to produce electric discharge. Later, modern electric fish, i.e., *Electrophorus electricus*, was discovered in South America and gained popularity as the most evolved electric fish. In 1766, Carl Linnaeus named it *Gymnotus electricus*. However, in 1864, it was provided its genus, i.e., Electrophorus(de Santana & Crampton, 2011). With time, as the species evolved and more content on the evolutionary history of electric fish was disclosed, two more types of electric fish were added to the Electrophorus genus: *Electrophorus varii* and *Electrophorus voltai*. Both species had common traits like electrolytes, electroreceptors, electric organs, and development by ancient electric fish.

Functional Insights:

Electric fish has been of keen interest to researchers, given the information collected over time, as it has shown various functional insights. The electric discharge-producing capability of electric fish can be used to have applications in various fields of medicine. One of the breakthroughs has been made by electric fish in the biology of regeneration. These fish, especially weak electric fish species, have shown regeneration abilities in their tail. This functionality has applied markers in regenerating skeletal muscles and the amputated parts. The gymnotiform fish species investigate molecular and cellular processes through which these fish regenerate their electric organs. The stem cells of these fish are being focused on as biomarkers, which can be applied to regenerate different parts in different animals(Unguez, 2013).

Other than this, electric fish has shown other functional features, like providing insight for regenerating spinal cords and injured brain cells. These remarkable regenerative capabilities open the door to many new fields like medicine, surgery, and cell biology. Initially, the electrical discharges produced by torpedo fish were considered effective for headache and gout conditions. Later on, more studies on these fish revealed the concept of electrotherapy, which helps cure muscle spasms, stop thepage of disuse atrophy, and increase blood circulation (KELLAWAY, 1946). In this way, electric fish pave the way into medicine and cellular and molecular biology.

Correlations

		Electric Fishes 1	Electric Fishes 2	Electric Fishes 3	Taxonomic Analysis1
Electric Fishes 1	Pearson Correlation	1	-.076	-.142	.031
	Sig. (2-tailed)		.600	.326	.829
	N	50	50	50	50
Electric Fishes 2	Pearson Correlation	-.076	1	.194	.005
	Sig. (2-tailed)	.600		.177	.973
	N	50	50	50	50
Electric Fishes 3	Pearson Correlation	-.142	.194	1	.337*
	Sig. (2-tailed)	.326	.177		.017
	N	50	50	50	50
Taxonomic Analysis1	Pearson Correlation	.031	.005	.337*	1
	Sig. (2-tailed)	.829	.973	.017	
	N	50	50	50	50

***. Correlation is significant at the 0.05 level (2-tailed).**

Table 1

The result describes the correlation between the electric fishes and the taxonomic analysis between them. The overall result describes the positive and significant relation between one variable to another variable. The result describes the Pearson correlation values, the significant values that also describe a number of related observations. In addition, electric fish is a prime example of the complex interactions among anatomy, behavior, and ecology that shape the variety of life on Earth. Over millions of years, their adaptations have been refined, enabling them to accurately use their environs. The study of electric fishes provides a window into the continuing conversation that takes place between living things and the environments in which they live, showing how species adapt to shifting ecological dynamics through time. The result shows that values 0.031, 0.005, 0.337, and 0.82 show positive rates for each indicator.

Discussion and Conclusion:

The development of electric fishes stands out as a noteworthy chapter in the great story of life on Earth, demonstrating nature's inventiveness and its unrelenting drive for adaptability. We have been deep into the heart of convergent evolution on our voyage through the world of electric fishes, where two seemingly unrelated species, the Gymnotiformes and Mormyroidea, have separately weaved a narrative of electric mastery. As we draw to a close, we consider the main lessons learned and the significant ramifications of this study. With their astounding ability to produce and sense electric fields, electric fishes provide a special perspective through which we may evaluate the adaptability of life. Gymnotiformes and Mormyroidea's taxonomic variety underline how commonplace electric adaptations are as responses to the difficulties of water life. Electric fish have carved themselves niches where electricity rules supreme, from the lush waterways of South and Central America to the dynamic ecosystems of African rivers and lakes.

Our comparative taxonomic research has shown how the development of electric organs in these many lineages has occurred in an intriguing parallel fashion. These changes developed from altered muscle tissue and function as adaptable instruments for predation, communication, and navigation. They show that nature frequently finds comparable answers when subjected to comparable ecological challenges. This convergence shows how effective natural selection is at sculpting biological variety. Functionally, electric fishes amaze us with their electric language—a sophisticated system of signals that transmit a wealth of knowledge at the depths of aquatic ecosystems. In addition to serving as a means of communication, electric fields also serve as a navigational aid. This complex mental map leads these fish through the night and enables them to survive in situations that would be difficult for other species. Electric fields make their ability to detect even the smallest clues of food concealed in the aquatic tapestry possible, which is also essential to their effectiveness as predators. A high-voltage shock that subdues prey and deters attackers is the amazing weapon that the electric eel has evolved. The evolution of electric fish has implications beyond biology and into the fields of technology and human understanding. Research on these organisms may lead to bioengineering, neuroscience, and sensory ecology advancements. Bio-inspired technology, with uses ranging from underwater robots to medical diagnostics, can draw inspiration from the complex systems used by electric fish to produce, transfer, and interpret electric signals.

In conclusion, the development of electric fish is evidence of nature's limitless inventiveness. It displays the remarkable adaptations that may develop in reaction to the many difficulties given by aquatic settings. The fundamental interdependence of life, where form and function come together in the dance of adaptation, is also brought home to us by electric fish. Their well-crafted adaptations show how morphology, behavior, and ecology interact dynamically. Over millions of years, electric fish have perfected their skills and adapted to their environments to become masters of their domains. We have caught glimpses of the always-changing conversation between creatures and their surroundings in our quest to comprehend electric fishes. Their adaptations demonstrate species' tenacity as they constantly adjust to the shifting ecological dynamics influencing their way of life. The adaptations of electric fish’s impact and are influenced by the complex web of life, making them both products of and guardians of their habitats. Finally, the development of electric fishes encourages us to be in awe of the variety of life and the amazing ways it overcomes the obstacles of existence. The fusion of electric organs in Gymnotiformes and Mormyroidea exemplifies nature's capacity for innovation and optimization across taxonomical and geographic boundaries. We are left with a deep respect for the glories of evolution, awe at the complexity of life, and an abiding curiosity about the unexplored depths of our natural world as we reflect on the electric world of these aquatic marvels.

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