REVIEW ARTICLE

Tenets of Magnetoreception: Cryptochrome as a promising player

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Abstract

Living organisms are constantly being impacted by the Geomagnetic field (GMF), which is known to affect a number of biological processes, and for plants on Earth, it is an inevitable environmental factor. Several hypotheses have been proposed by scientists to explain the mechanism of magnetoreception, but none have received widespread acceptance. The magnetite-based concept, the radical pair model, and the ion-interference mechanism are only a few of the mechanisms that have been proposed in recent years to answer the riddle of animal magnetoreception from various perspectives. It has been proposed that Cryptochromes may function as magnetoreceptors since the physiological processes of CRY, such as growth inhibition, seedling de-etiolation, or blooming initiation, have been demonstrated to respond to mild magnetic fields. This review provides insights into various theories on magnetoreception and also includes a bibliometric analysis of literature on "cryptochrome and magnetism."

Keywords: Geomagnetic field, Magnetoreceptors, Cryptochrome, Bibliometric analysis.

Highlights

- Plants and animals both experience Geomagnetic fields, but animals being mobile respond to it in different ways when compared to plants.
- Several mechanisms including the magnetite-based model, the radical model, and the Ion-Interference mechanism in sensory biology are established.
- Cryptochromes have been involved in the light-dependent magnetoreception in both plants and animals.
- Research on 'magnetoreception and animals' is older than 'magnetoreception and plants', which is the latest and upcoming field with the first publication on it in 1995.
- USA is the largest key player working in the field of 'magnetoreception and plants.

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Introduction

Geomagnetic field (GMF) is an unavoidable environmental component for plants on the Earth. GMF is continuously affecting living things and is recognized to have an impact on a variety of biological functions. First, it appears that humans are unable to detect magnetic fields. The notion that animals can sense the Earth's magnetic field has gone from being laughed at to being a well-established reality. Numerous studies have now established the existence of internal compasses in a wide variety of animal taxa, including bees, salamanders, sea turtles, and birds (Johnsen and Lohmann 2008). All plants also have to experience the effects of GMF during the evolution process. Different geomagnetic signals such as inclination, polarity, or even intensity can be perceived by different organisms, but animals being mobile respond to and utilize the geomagnetic field in different ways, when compared to plants. A remarkable diversity exists for magnetoreception and it is imperative to explain and understand the mechanism behind the puzzling phenomenon of magnetoreception. The fact that biological tissue is transparent to magnetic fields further complicates matters since, unlike the majority of other sensory receptors, magnetoreceptors can be found everywhere throughout the body of an animal, not just on its surface. Large auxiliary structures for concentrating and otherwise modifying the field are another barrier. Researchers do benefit substantially from the field's weakness in that it significantly reduces the number of potential physical detection mechanisms. A very sensitive detector, amplifying magnetic interactions, or seclusion from the thermal bath are all likely requirements for any workable system. Scientists have made attempts to provide several models for elucidating the mechanism of magnetoreception, but none has been generally accepted yet. To solve this current key problem in sensory biology, several mechanisms including the magnetite-based model, the radical pair model, and the Ion-Interference mechanism, have been presented in recent years in an effort to address the mystery of animal magnetoreception from several angles. Table 1 provides the summary of different theories given for magnetoreception.

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Table 1: Various theories of magnetoreception in proposed in biological systems

Theory	*Description*	*Proposer/ Year*	*Biological Basis / Examples*	*Strengths*	*Weakness*
Ferrimagnetism	Magnetic particles (e.g., magnetite) align with Earth's magnetic field to provide directional cues.	Joseph L. Kirschvink / 1979	Found in some birds, fish, and insects. Magnetite particles in beaks or tissues.	Physically plausible, direct detection of magnetic field.	Mechanism for signal transduction to nervous system not fully understood.
Ion-Cyclotron Resonance	Biological effects caused by resonance frequencies in ions under magnetic fields	Liboff / 1985	Hypothetical; proposed in some fish and birds.	Explains field sensitivity at very low levels.	Requires very specific conditions (ion concentration, resonance frequencies) rarely observed.
Ion-Interference Mechanism	Quantum interference of bound ions causes biological changes	Binhi / 1997	Suggested in electroreceptive animals like sharks.	Can work in conjunction with other sensory modalities.	Lacks direct empirical evidence; hard to isolate magnetic effects.
Electromagnetic Induction	Movement through magnetic fields induces voltages detected by sensory organs	Kalmijn, Murray / 1962-1978	Used by fish like rays and sharks via ampullae of Lorenzini.	Mechanistically well-understood; fits aquatic environments	Works primarily in conductive environments (like water); not applicable to all animals.
Radical Pair Mechanism	Magnetic fields influence spin states of radical pairs in chemical reactions	Schulten / 1978	Found in birds' eyes involving cryptochrome proteins.	Supported by molecular and behavioral evidence in birds.	Requires light; sensitive to interference and not fully understood

Ferrimagnetism

Ferromagnetic minerals such as magnetite (Fe_3O_4) and greigite (Fe_3S_4) is found in the living organism. These ferromagnetic minerals form single-magnetic domain crystals. These crystals are membrane-bound and are known as magnetosomes (Blackmore 1982). Magnetosomes have been demonstrated as magnetoreceptors (Johnsen and Lohmann 2008). They are commonly found in magnetotactic bacteria, a variety of protists, and many animals. Magnetosomes are synthesized by bacteria, but the protists might have acquired them by ingestion of bacteria containing magnetosomes (Neves *et al.,* 2003). The magnetosomes are arranged in chains and provide a permanent magnetic dipole moment to the organism. The cells align parallel to the magnetic field lines, just like a compass needle (Blackmore 1982). Such magnetic alignment along with active swimming is magnetotaxis and is common in magnetotactic bacteria (Bazylinski 2004).

Magnetite-based receptors has been documented in birds like trout and homing pigeons. In trout, confocal and atomic force microscopy (AFM) suggested the presence of single-domain magnetite crystals in the cells. These magnetite crystals were sensitive to magnetic stimuli and were present near to a nerve. Pigeon's beak too possesses a complex array of magnetic minerals. These are coupled to a nerve that is megnetoresponsive (Johnsen and Lohmann 2008). Presently, the physiological function of magnetite's in plants is elusive. However, the assumption that ionic channels in cell membranes contain magnetite particles, then under weak magnetic field such particles would be able to generate torque.

Ion-Cyclotron Resonance

In 1985, Liboff came up with the idea of ion-cyclotron resonance (ICR). This model explains the effects of low-frequency magnetic fields on living systems, and relies on the assumption that effects due to magnetic fields require the presence of two types of magnetic fields viz. (i) static magnetic field (B_{DC}) and (ii) alternating magnetic field (B_{AC}). Alternating magnetic fields have frequencies that are specific for ions. For example, Ca^{2+}, K^{+}, Mg^{2+}, etc. in case of biological system. The resulting biological response would depend on the ratio of two types of magnetic fields, the alternating magnetic field's frequency and the static magnetic field's flux density. The effects due to ICR have been observed (in vitro), even with simple electrolytes. Zhadin *et al.,* (1998) observed that when a combination of static and alternating magnetic fields is provided to glutamic acid, narrow resonance frequency bands for magnetically induced ion currents were recorded.

Ion-Interference mechanism

In (1997a) Binhi came up with an ion-interference mechanism to explain the biological effects of $\mathbf{B}_{DC}$ that were incomprehensible by ion-cyclotron or ion-parametric resonance mechanism. Ion interference mechanism is based on the interference of quantum states of ions that are bound to proteins inside an idealized cavity. The superposition of ion states due to interference causes a non-uniform pattern of the probability density of the ion (Binhi *et. al.,* 2001). Demonstrated the effect of a static magnetic field on the confirmation of DNA-protein complexes (nucleoids) in *E. coli* cells.

In DC fields, a non-uniform pattern rotates within the cavity with the cyclotron frequency. However, when exposed to AC fields the rotation impedes. Thus, in such cases ion escapes from the cavity. This escape brings about changes in the equilibrium of biological reactions to show a biological effect eventually.

Electromagnetic induction

Magnetoreception in marine organisms is suggested to happen due to Electromagnetic Induction. Electromagnetic induction can explain magnetoreception in a limited number of animals and for plants, it has no relevance. When fishes such as sharks and rays, swim in different directions in the sea. These elasmobranchs cross geomagnetic field lines at different angles. This induces variable voltages at their electric organs known as ampullae of Lorenzini (Murray 1962). Electromagnetic induction could also be observed in aquarium fish and duck-billed platypus. As the magnetic field of the earth is very low, when the animals move at a moderate speed a highly sensitive electroreceptive system to detect such minute-induced electromotive force is required. Sharks have several long canals with resistive walls in their head that begin as a small pore at the surface of the skin. The canals are filled with highly conductive jelly-like fluid. This fluid functions as an electric cable for the transmission of voltages. These canals end at a point where ampullae of Lorenzini are present. This group of cells is very sensitive to even minute changes in the voltage (Kalmijn 1978).

Radical Pair Mechanism

It would be difficult to realize that chemical reactions could be sensitive to geomagnetic fields as the energy of interaction of a molecule with an average of 50 μT earth's magnetic field is about 600 times smaller than the strength of a chemical bond (Rodgers and Hore 2009). The birds can sense the geomagnetic field direction, and this sense is provided by a chemical reaction (Wiltschko 1968; Ritz and Schulten 2000; Wiltschko and Wiltschko 2006). These chemical reactions involve radical pairs. Radical pairs are pairs of molecules with an unpaired electron, produced together in a reaction. Radical pair reactions that can act as magnetoreceptors was first proposed by Schulten in 1978, and has been supported by many more evidences. In the radical-pair mechanism A molecule 'A-B' generates two radicals i.e. $A^{\bullet}$ and $B^{\bullet}$ after homolysis. These radicals can exist together as a pair having anti-parallel spins of their unpaired electrons (Wigner's conservation rule). Thus, these radical pairs exist is the singlet state $^1[A^{\bullet} B^{\bullet}]$. In the process of inter-system crossing (ISC), the radical pair is interconverted to triplet state, $^3[A^{\bullet} B^{\bullet}]$ where the electron spins are parallel to each other. The singlet radical pair $^1[A^{\bullet} B^{\bullet}]$. can recombine to form the parent molecule 'A-B', but the triplet radical pair $^3[A^{\bullet} B^{\bullet}]$ cannot do so (Fig. 1). In quantum mechanics singlet $^1[A^{\bullet} B^{\bullet}]$ and triplet $^3[A^{\bullet} B^{\bullet}]$ states refer to specific configurations of electron spins within atoms or molecules, influencing their magnetic properties, energy levels, and reactivity. In singlet state $^1[A^{\bullet} B^{\bullet}]$ electrons are paired with opposite spins (↑↓), resulting in a total spin quantum number $S = 0$. Consequently, the spin multiplicity, given by the formula $2S + 1$, equals one, hence the term singlet. Singlet states are diamagnetic and therefore, not attracted to magnetic fields. Conversely, in triplet state $^3[A^{\bullet} B^{\bullet}]$ the electrons are unpaired with parallel spins (↑↑ or ↓↓), resulting in a total spin quantum number $S=1$. The spin multiplicity results into three ($2S + 1 = 3$) and therefore the name triplet. The triplet state arises because there are three possible orientations of the total spin due to parallel spins in the unpaired electrons. Triplet states are paramagnetic, that is, they are attracted to magnetic fields due to the presence of unpaired electrons. The inter-system crossing (ISC) is prone to external and internal magnetic fields. Thus, the application of an external magnetic field can generate either singlet or triplet radical pairs. Internal magnetic fields generated by magnetic moments of nuclei, also known as hyperfine coupling modulate inter-system crossing (Galland and Pazur 2005).

Radical pair should be held together for a relatively longer time to the order of 10^{-6}s, and it is only after this time that the spins get randomized (Galland and Pazur 2005). Experimental evidences and theoretical predictions suggest that magnetic fields prolong the lifetime of radicals. This increase in turn increases their average concentrations and also the probability of radical reactions with cellular components (Schulten *et. al.,* 1976; Scaiano *et. al.,* 1994; Walleczek 1995). Such preconditions also take into account the enzymatic reaction of radical pair formation and recombination (Grissom 1995; Eichwald and Walleczek 1996). In many organisms (birds and salamanders) radical-pair

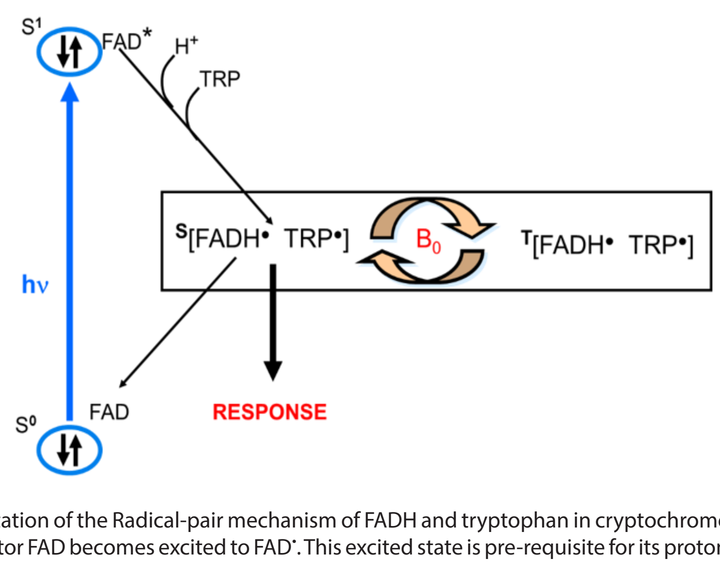

Fig. 1: A diagrammatic representation of the Radical-pair mechanism of FADH and tryptophan in cryptochrome: Cryptochrome when exposed to blue light, its fully oxidized cofactor FAD becomes excited to $FAD^{\bullet}$. This excited state is pre-requisite for its protonation resulting in the formation of $FADH^{+}$. But once electronically excited flavin is in $FADH^{+}$, an electron from the nearby tryptophan enters into the hole left by the excited electron which results in semiquinone FADH form of the cofactor. FADH and tryptophan together forms the radical pair, which could be in singlet state (responsive) or triplet state (non-responsive). The interconversion of singlet and triplet states is modulated by external magnetic field, thereby suggesting its effects on biological systems.

mechanism is also light-dependent and is photogenerated, and is essential for magnetic compass orientation (Wiltschko and Wiltschko 1981). The role of cryptochrome (a FAD containing blue-light photoreceptor) in magnetoreception is not limited to migratory birds but is also documented in other organisms (Möller *et. al.,* 2004; Mouritsen *et. al.,* 2004; Gegear *et. al.,* 2008). Radical pair formation of cryptochromes in birds' eyes have not been shown yet. Cryptochromes-dependent and independent mechanisms of magnetoreception have been documented in the literature (Dhiman et. al., 2023) for plants. Plants grown in magnetic field strength of 500 μT grew remarkably slower as compared to those grown at 50 μT. Such an effect was observed only under blue light (Cryptochrome responds to blue light only) and not under red light or in darkness. Since cryptochrome is a ubiquitous molecule, a bibliometric analysis for articles on 'cryptochrome and magnetism' has also been done in this review.

Cryptochrome: A Ubiquitous molecule

Cryptochromes are the ubiquitous blue light photoreceptors associated with many blue light-dependent functions in both plants and animals (Wang et. al., 2014). They were called so because their function remained cryptic for a long time since they were discovered. In plants, they are involved in photo morphogenetic responses including inhibition of hypocotyl growth (Ahmad and Cashmore 1993), in anthocyanin accumulation (Chatterjee et. al., 2006), in leaf and cotyledon expansion (Cashmore et. al., 1999; Lin and Shalitin 2003), transition to flowering (El-Din El-Assal et. al., 2003), stomatal opening (Wang et. al., 2020) and regulation of blue light-regulated genes (Jiao et. al., 2003). Cryptochromes have been implicated to play a direct role in circadian rhythms as part of circadian pacemakers in both plants and animals (Somers et. al., 1998; Gould et. al., 2013; Busza et. al., 2004; Zhu *et. al.,* 2008). They have been identified to be involved in the light-dependent magnetoreception in both plants and animals.

Cryptochromes structurally resemble photolyases, which are flavin-containing light-dependent enzymes used in the process of repairing UV-damaged DNA through electron transfer. Cryptochromes do not exhibit photolyase activity but are widely believed to be the descendants of photolyases, because of the shared structural similarity (Cashmore *et. al.,* 1999). Most Plant CRY proteins are 70-80 kDa proteins and have two specific domains. The N-terminal domain of this protein shares a marked sequence similarity to photolyases and is known as PHR (Photolyase Homology Region). Similar to photolyases, cryptochromes' PHR also has a three-dimensional structure that is characterized by an N- and C-terminal --helical domain. The presence of C-terminal extensions of varying lengths separates cryptochromes from photolyases (Fig. 2) and these regions provide specific functions to cryptochromes including nuclear cytosol trafficking and protein-protein interactions (Lin and Shalitin, 2003).

These extensions are usually longer in most of plant cryptochromes than in animal cryptochromes (Liedvogel and Mouritsen 2010) Cryptochromes possess two noncovalently bound cofactors necessary for the function of cryptochromes. One of them is FAD (Flavin adenine dinucleotide), and the other one is a light-harvesting chromophore, which has been assumed to be either 8-hydroxy-5-deazariboflavin (8-HDF) or 5,10- methyl-tetrahydrofolate (MTHF), based on the sequence and structural similarity of both photolyases and cryptochromes (Malhotra *et. al.,* 1995; Hsu *et. al.,* 1996).

The light-harvesting chromophore after excitation can transfer its energy to the catalytic cofactor, as there is a spectral overlap in the absorption spectra of FAD and the fluorescence of the antenna cofactor (Park *et. al.,* 1995). The transfer of electrons from FAD to amino acid residues of cryptochrome forms a significant process for the radical-pair mechanism (Ritz *et. al.,* 2000). Animal cryptochromes are more similar to type 6-4 photolyases whereas plant cryptochromes show closer sequence similarity to type I microbial photolyases (Kanai *et. al.,* 1997) therefore, it has also been suggested that plant and animal cryptochromes have been evolved independently from different ancestral photolyases.

Cryptochrome and Geomagnetic field

The physiological functions of CRY like growth inhibition, seedling de-etiolation or flowering initiation have been shown to respond to weak magnetic field (Ahmad et. al., 2007) and therefore, it has been suggested that Cryptochromes can act as magnetoreceptors (Maeda et. al., 2012). Cry magnetosensitivity express itself in low light conditions in plants (Vanderstraeten et. al., 2018). It has been documented in literature that cryptochromes are involved to orient insects, amphibians, and birds in the geomagnetic field (Liedvogel and Mouritsen 2010; Ritz et. al., 2011). Table 2 lists the role of cryptochrome in geomagnetic field detection. The known mechanism for light-dependent magnetic compass orientation for these Cry magnetoreceptors depends upon the formation of radical pairs by it (Hore and Mouritsen 2016). The flavin cofactor is initially present before the light activation of Cry magnetoreceptors in its fully oxidized FAD state and is promoted to the excited FAD• state after absorbing blue light photons. After gaining one proton from the adjacent aspartic acid, FAD• is then protonated to FADH+. This results in the induction of light-

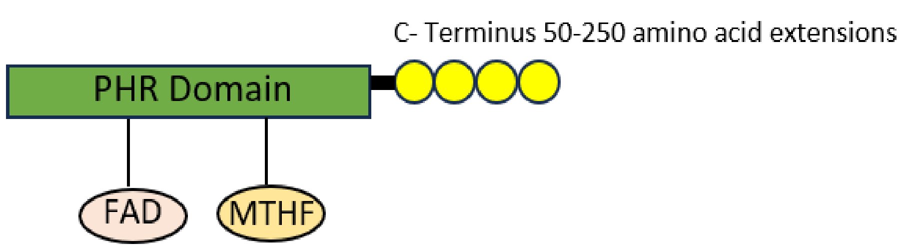

Fig. 2: The schematic structure of cryptochrome: The structure shows a N terminal Photolyase Homology Region (PHR) domain along with C-terminal extensions of varying lengths, along with the two co factors Flavin adenine dinucleotide (FAD) and 5,10-methenyltetrahydrofolic acid (MTHF).

Table 2: Role of cryptochrome in geomagnetic field detection.

Aspect	*Details*	*Key References*
Protein Involved	Cryptochromes (Cry1a, Cry2, Cry4) – flavoproteins found in photoreceptor cells	Maeda et al., 2008; Xie et al., 2019
Location	Retinas of birds (e.g., European robin, zebra finch), insects (*Drosophila*, butterflies), some mammals	Liedvogel & Mouritsen, 2010
Activation Requirement	Light-dependent (especially blue or UV light)	Ritz et al., 2000; Gegear et al., 2008
Mechanism	Radical Pair Mechanism: Light excites cryptochrome → forms radical pairs → spin states influenced by geomagnetic field	Ritz et al., 2000; Schulten et al., 1978
Type of Compass	Inclination compass: detects angle (not polarity) of magnetic field lines	Wiltschko & Wiltschko, 2005
Supporting Species	Birds (European robin, zebra finch), *Drosophila*, monarch butterflies	Niessner et al., 2013; Gegear et al., 2010
Experimental Evidence	Orientation disrupted in birds by radio-frequency fields; genetic knockout in insects affects orientation	Ritz et al., 2004
Strengths	Molecular basis identified; compatible with known biology; consistent with behavioral data	Rodgers & Hore, 2009
Limitations	Requires light; unclear if effective in darkness; not fully confirmed in all magnetosensitive animals	Hore & Mouritsen, 2016
First Formal Model	Radical pair mechanism proposed in context of avian magnetoreception in 2000	Ritz, T., Adem, S., & Schulten, K. (2000).

induced electron transfer. Experiments by Solov'yov *et. al.,* 2007 in *Arabidopsis* have shown that the ability of cryptochrome to mediate magnetic responses depends upon three tryptophans, numbered Trp400, Trp377 and Trp324 (Fig. 3).

Cryptochrome signaling begins with the photoreduction of FADH+ as an electron jumps from the nearby tryptophan, Trp400 forming FADH + Trp400+. Another electron then jumps from Trp377 to Trp400, thereby forming FADH+ Trp377+. Subsequently, another electron jumps from Trp324 to Trp377, thereby forming FADH + Trp324+. Finally, Trp324+ becomes deprotonated to Trp324dep, eventually forming FADH + Trp324dep, and fixing the electron on the FADH cofactor. The active signaling state of cryptochrome is achieved when flavin cofactor is in a semireduced state. The external magnetic field can photoreduction of FAD cofactors (FADH + Trp400+, FADH + Trp377+ and FADH + Trp324+) via a radical pair mechanism (Solov'yov *et. al.,* 2007).

Bibliometric Analysis

The articles included in the present study were collected form SCOPUS database. The search was made within 'Article Title, Abstract and Keywords' with a combination of different search words 'geomagnetism AND magnetoreception', 'magnetoreception AND animals', 'magnetoreception AND plants' and 'cryptochrome AND magnetism'.

The document type that has been included in this study comprises of 'Articles, Reviews, Conference Paper, Editorial, and Notes'. In the current study for all the search combinations, we evaluated the (i) annual scientific production, (ii) the most relevant sources using the Bradford's Law and (iii) three field plots of Author, Author country, and Affiliations, as depicted in fig. 4, 5 and 6 respectively. The above-mentioned analysis was done by using a Bibtex file obtained from SCOPUS and subsequently, processed in Biblioshiny.

An investigation of annual scientific production reveals that 'magnetoreception and animals' is the oldest research and the most worked upon amongst the others (Fig. 4B). The first published document on 'magnetoreception and animals' was reported in Scopus in 1981, whereas the research on 'magnetoreception and plants' is the latest and upcoming field as the first publication appeared in 1995.

For the search words 'geomagnetism and magnetoreception' 70 publications have been indexed from 1995 till date (October

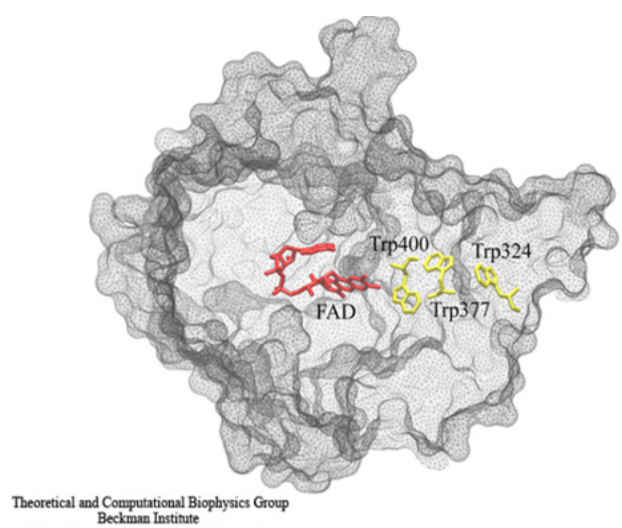

Fig. 3: Computational Model of Cryptochrome: Cryptochrome showing the positions of cofactor FAD and the nearby chain of three tryptophans which are involved in the light-induced photoreduction pathway. The active signalling state or semi-reduced state (i.e. semiquinone form) is achieved by the photoreduction pathway which involves a chain of three tryptophans, viz. Trp400, Trp377 and Trp324. (Solov'yov et al., 2007).

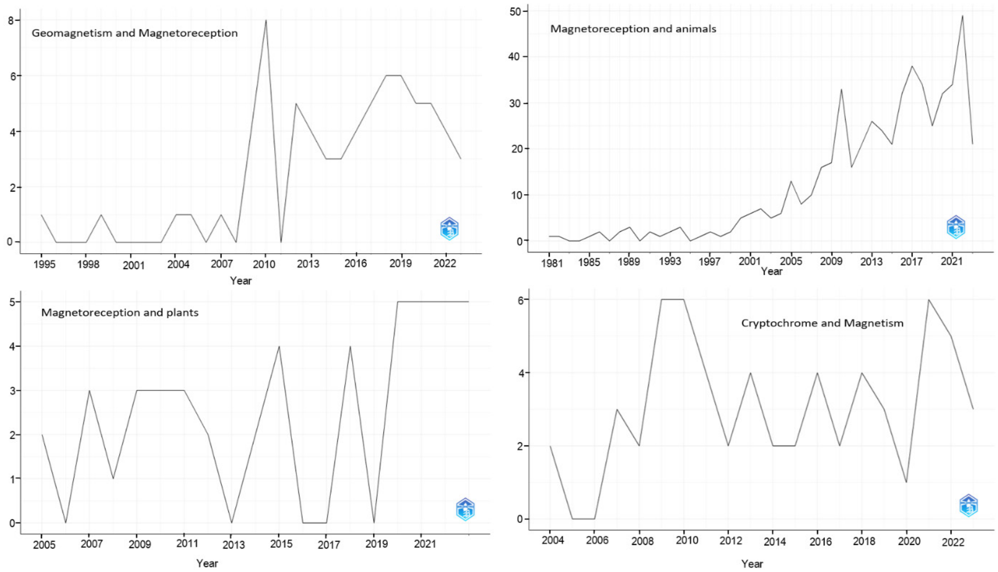

Fig. 4(A-D): Growth of literature over the years in various fields: (A) 'Geomagnetism and Magnetoreception' (B) 'Magnetoreception and Animals' (C) 'Magnetoreception and Plants', and (D) 'Cryptochrome and Magnetism'.

2023) with an annual growth rate of 4% and an average of 2.5 articles published annually (Fig. 4A). The maximum number of articles (8) in the said field were published in the year 2010. The average citation per document is 29.3. The search words 'magnetoreception and animals' showed 523 documents with an annual growth rate of 7.52% and an average of 12.4 articles published annually. Recently, in the year 2022, the publications on 'magnetoreception and animals' recorded the highest spike with 49 publications (Fig. 4B). The average citation per document is 40.73. These 523 articles appeared in 208 Journal.

Amongst all the search fields, the least numbers of documents (47) have been published in the field of 'magnetoreception and plants. The topic shows an annual growth rate of 5.22% and an average of 1.6 articles is published annually (Fig. 4C). Although the field is new, the average citation per document is 50.04, which is the highest among all the search items of the present study. The database showed 61 documents published on 'cryptochrome AND magnetism' from 2002 till date (Fig. 4D). Thus, an average of just 3 articles is published annually on this topic. The first report on cryptochrome and magnetism appeared in the year 2002 (with 2 articles). Years 2009, 2010 and 2021 showed the maximum number of articles published on the said topic. Bradford's law helps to identify the most relevant journals and is important to know the dispersion of scientific literature. Fig. 5A-D shows the most relevant journals for the different search terms used during the present study. In the field of 'Geomagnetism and magnetoreception' Journal of Royal Society Interface (JRSI) has published a maximum of articles i.e. 14 articles (5A). Other journals such as Chinese Science Bulletin, Bioelectromagnetics, and Journal of Chemical Physics published 4, 3, and 3 articles, respectively. Core journals in the field of 'magnetoreception and animals' are Journal of Experimental Biology, Journal of the Royal Society Interface, Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology, PloS One, Scientific Reports and Proceedings of the National Academy of the Sciences, USA where 43, 39, 33, 21, 21, 16 articles were published, respectively (Fig. 5B). This constitutes a total of 173 publications out of 523 total publications. Thus 33% of papers appear in these 6 Journals. Rest of the 350 articles appeared in other 202 Journals. Fig. 5C shows the core journals for the field of 'magnetoreception and plants', wherein the JRSI has published the maximum articles viz. 3. JRSI along with 7 other journals (refer to Fig. 5C) form the 33% of the publications. Thus, in these 8 core journals, 17 articles are published and another 30 articles have been published in 30 different journals. Core Journals in the field of 'cryptochrome and magnetism' were identified and Bradford's law (Fig. 5D).

The 61 articles analyzed in the present study were published in 38 Journals. Of these, 4 were identified as core Journals, which published about one third (21 publications) of the total articles, and the remaining 40 articles were scattered in 34 journals (Fig. 5). It shows the journals publishing the maximum number of articles in a subject area and is considered as core Journal.

The three-field plot (Fig. 6A-D) study shows the relationship between the Authors, the Authors' Country and Institutional Affiliations. The plots suggest that Germany has been the top key player in all the areas that were studied in the present data, other than the 'magnetoreception and plants' where USA has taken a lead. In the field of 'geomagnetism and magnetoreception' Kattnig has published 12 articles and other authors published 11 articles (6A). Germany is the key player with 31 articles published by all the authors from this country. In the field of 'magnetoreception and animals' Mouritsen H has published 146 articles, out of this 114 he published from Germany, during his affiliation with University of Oldenburg (Fig. 6B).

Fig. 6C suggest that USA is the largest key player working on the field of 'magnetoreception and plants' with 27 papers to its credit from all the authors mentioned in the three-field plot. Ahmad M is the largest contributor and has worked in three countries viz. USA, Germany and France. Second top

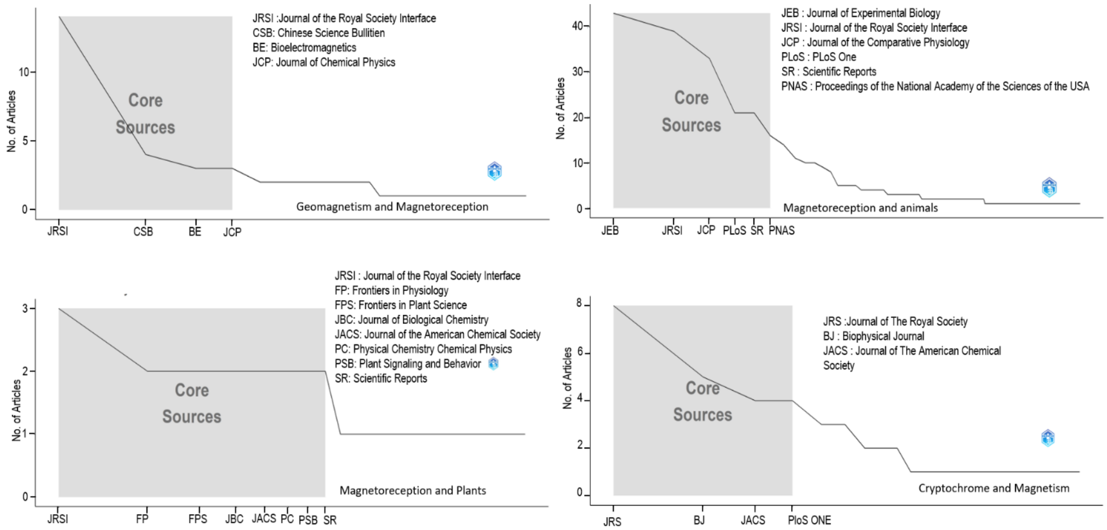

Fig. 5(A-D): Top Publishing Journals as per the Bradford Law: Depiction of core journals in the field of (A) 'Geomagnetism and Magnetoreception' (B) 'Magnetoreception and Animals' (C) 'Magnetoreception and Plants', and (D)'Cryptochrome and Magnetism'.

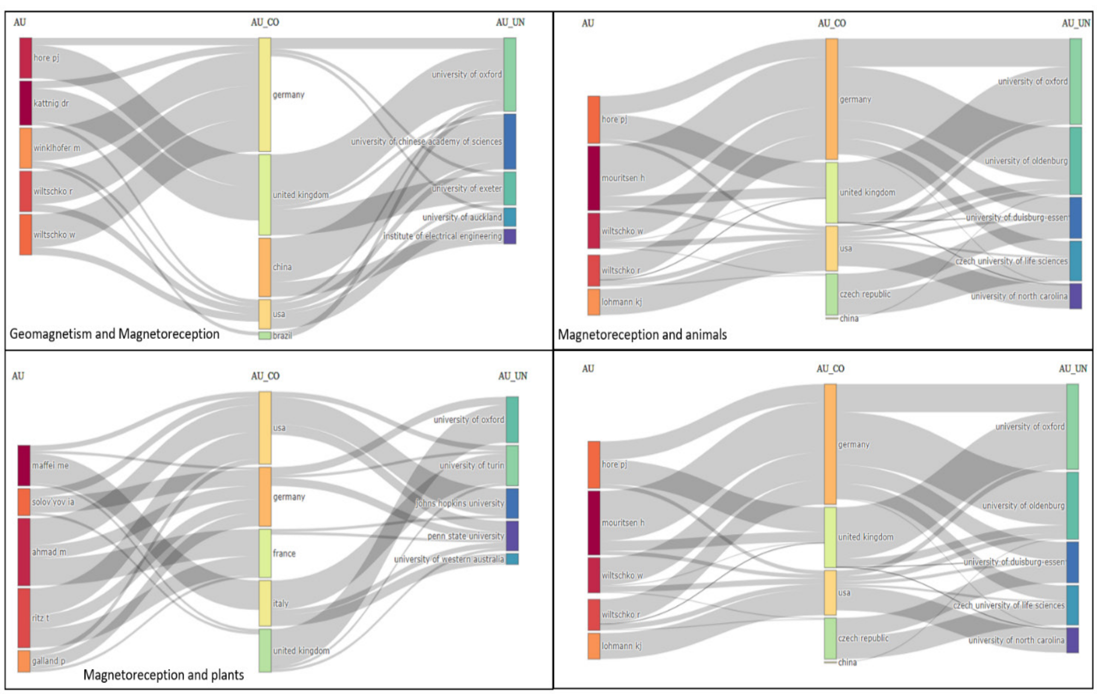

Fig. 6 (A-D): Three Field Plot with researchers (AU) on the left field, Author's Country (AU_CO) as the middle field, and Author University (AU_UN) as the right field for: (A) 'Geomagnetism and Magnetoreception' (B) 'Magnetoreception and Animals' (C) 'Magnetoreception and Plants', and (D) 'Cryptochrome and Magnetism'.

author who has worked in the same countries is Ritz T, and has 22 publications in this three-field plot. 'Cryptochrome and Magnetism' search fields revealed that the country with the greatest research output is Germany, followed by United Kingdom, USA, China and France. Hore PJ, Mouritsen H, Solov'yov IA, Wiltschko W, and Wiltschko R are the top publishing authors in this field of research (Fig. 6D). Interestingly, Hore PJ, Wiltschko W, and Wiltschko R occur as the top publisher in all three fields viz. 'geomagnetism and magnetoreception', 'magnetoreception and animals', 'magnetoreception and plants. A comparison of three field plots (6a-6D) reveals that the authors that appear 6C do not appear in any other three-field plots.

Conclusion

The work of many laboratories across the world suggests different mechanisms for magnetoreception in the biological sphere. Though the radical pair mechanism associated with cryptochrome provided a possible explanation for the perception of the geomagnetic field in some organisms, more work is required to unfold the still elusive mechanism operating in the organisms to perceive and then react accordingly to the geomagnetic field. Besides, some of the reports indicate differential mRNA transcripts at different magnetic flux densities and the fact that there is a 7-8-fold increase in the mRNA transcripts at some flux densities potentially provides an opportunity for increasing the yields of biotechnological products, simply by growing the transgenic organisms under the influence of certain magnetic flux densities. The idea needs to be explored in the future and can add another dimension to the research of static magnetic fields.

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Conflict of Interest

The authors declare no competing interests.

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