Review

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Review

Microbes and Sustainable Living: Focus on Electric and Magnetic Fields

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Abstract: Among earth's microbial populations are the genes, functional capacities, generational memory and sentient cognition that enable microorganisms to adapt and thrive in the full range of ecological conditions found on planet earth. In prior sequential publications, we considered fundamental properties (*e.g.,* use of and responses to sound, light, vibrations) and features of microorganisms that cause them to be critical co-partners of human and other holobionts as well as the potential benefits for humanity that can be gained by fully applying quantum-related and novel capacities of microbial life. In this narrative review we: 1) discuss key concepts concerning a microbially-enhanced and sustainable future, and 2) focus on electric- and magnetic-based features of microorganisms that make them pivotal for myriad benefits ranging from beyond pharma-based health and wellness to free- and/or renewable energy and restorative agriculture to improved human networking. While the benefits are many, the risks posed by hazardous electric or magnetic field exposures to both holobionts and microbial communities are significant. This review concludes that microbes and their remarkable capacities offer both humanity and the planet a much brighter future if we reverse the demonization of microbes and wanton microbiome degradation that has predominated much of the past century.

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1. Introduction

Life on earth is dominated by microorganisms existing both as communities living in even the harshest conditions and as co-partners for more complex lifeforms (holobionts). The relationships of microbes partnering with holobionts have existed for millennia [1], and are essential for the wellbeing of higher eukaryotic organisms including humans [2]. Microbes associated with the human microbiome have many roles, some of which are: 1) They drive key developmental changes during critical windows of human developmental vulnerability [3]. 2) They provide key vitamins and metabolites [4]. 3) They regulate fear and risk of mental health issues [5]. 4) They affect circadian rhythm and sleep [6]. 5) They have the capacity to facilitate longevity [7]. and 6) They have the capacity to reduce the risk of both infectious (via colonization resistance) and chronic diseases [8,9].

The critical role of microbes in holobiont health and survival extends well beyond humans to affect animal, plant and insect life. An example is the significant role of the microbiome of honeybees in their health [10], social group membership [11], behavior [12] and queen bee ovarian metabolism [13]. For humans to have a sustainable future, we must ensure that the symbiotic relationship with microbes continues and thrives. For healthy human and other holobionts, we need health and protection for microbial populations [14].

The fundamental yet novel properties exhibited by microbes, such as the capacity to capture, transfer, communicate with and generate electricity [15,16] as well as magnetism [17] makes them prime candidates for restoring ecological environments as well as improving human, animal, and plant holobiont health [18,19]. However, the same features also make microbes potentially sensitive targets for adverse effects of electric, magnetic, and electromagnetic fields (EMFs) and/or transmissions. When unintended consequences arise from exposure to a physical field among microbial ecological communities or holobiont microbiomes, the outcomes can be devastating. If we are to have a sustainable life here on earth, we will need to be effective stewards of earth's microbial life within and beyond holobionts.

In a series of recent articles, we reviewed the effects of various overt and subtle physical fields [20] on microbes including the key factors of sound, light, and vibrations [21]. In this present narrative review, we extend this consideration to examine two of the most fundamental features of microbes that are critical for the functioning of society, earth's ecology, and human holobiont wellness: the electrical and magnetic properties of microbes and their responses to changes in electric and magnetic fields. In this paper, we explore 1) fundamental concepts important for microbial communications and a microbially-enhanced, sustainable future, 2) the electric and magnetic nature of microorganisms and 3) the potentially beneficial and detrimental effects of electric and magnetic fields on microorganisms.

While we stress the wide range of electric and magnetic field applications that can benefit the environment and society, we also caution that the misapplication of these magnetic fields can be devastating. Beyond electric and magnetic fields, the topic of EMFs is massive in scope covering the entirety of ionizing and non-ionizing radiation. We introduce this subject but do not attempt to comprehensively review EMF within the present narrative review.

2. Microbial-Driven Capacities and a More Sustainable Future

We begin this review with a glimpse of key microbe-driven concepts and interactions that drive a microbially-enhanced, sustainable future. If part of human holobiont history on Earth was one where separation from Earth's most predominant lifeforms, microorganisms, was encouraged [22,23] and microbes could be seen as evil [24], then the key concepts shown in Table 1 [25–51] reverse this pattern and envision a future where microbial life is an integral part of future, sustainable living. This Table sets a broader microbial landscape for the subsequent consideration of electric, magnetic effects.

Table 1. Key Concepts for a Microbially-Driven, Sustainable Future.

Inherent Microbial Properties for a Sustainble Future [Citations]	Description
The Microbiome Commons [25–27]	The extensive diversity of Earth's prokaryotes has presented challenges particularly as emerging technologies have afforded different ways of exchanging, researching, analyzing and classifying microbes. Numerous investigators stressed the significance of a microbial commons approach to future microbiology and the need for greater attention and focus to protect our microbial resources.
Moving Beyond the Antibiocene [28]	The researcher draws upon the microbial commons concepts and eight decades of antimicrobial-fueled living (the Antibiocene) to avocate for a strategies to: 1) preserve the microbial commons and 2) envision "eubiotic governance."
Electrified Micobial Communities [29,30]	The researchers describe how specific microbes can use their inherent electrical and magenetic capabilities to both create and then share

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	electricity among different microbial species. In effect, electrified communities relying on minerals and fundamental microbial properties are sufficient for naturally electrified communities.
Living Electronics [31,32]	The researchers review the ultilization of and importance of microbes in bioelectronics, synthetic biology and electromicrobiology to produce biohybrid devices. Researchers also suggest that bacteria can power all sensing displays with sustainability.
Regenerative Architecture [33]	The researcher extends the “microbial commons“ concept to argue the importance of moving beyond controlling microbes for new technology and, instead, restoring microbial ecology within sustainable cities and architechture.
Restorative Ecology [34]	This review stresses that soil microbial community health is both a driver of and a critical indicator of ecological community status. The take home message is that a focus on microbial communities and their metabolism and interaction with plants is necessary to repair degraded ecosystems.
Regenerative Agriculture [35]	This review posits that microbial function is critical to increase soil biodiversity as a key component of regenerative agriculture. The author also cites the benefits of microbial diversity as a driver of increased soil resistance and resiliency to disturbances.
The Internet of Microbes [36,37]	Researchers have focused on the novel communication and sharing functions of microbes spread across virtually all of Earth’s ecological niches to illustrate that human and other holobionts tap this network to gain information originating from not only inside but also outside of the human body. Capacities such as communicating at-a-distance is connected to the internet of microbes.
Embodying the Microbiome [38–40]	Various researchers explored the embodiment of the human microbiome via the practice of dance, meditation, and other contemplative exercises. A variety of outcomes were seen

	among the studies: shifts in awareness including informational insights, shifts in psychological/ emotional states, and specific physical experiences. These contemplative and other practices can serve as tools to connect with the microbial part of the human holobiont.
Microbes Provide Our Social Brain [41]	These researchers describe the fundamental significance of microbes as the conduit through which human and other holobionts embody a social brain and display social behaviors.
Microbes and Spirituality [42–46]	Several researchers have emphasized the importance of microbes in a wide range of spiritual practices. Human holobiont spirituality is microbe-inclusive and sometimes, microbe-centered.
Promotion of Peace [47]	These researchers describe the benefits when microbes are used for the promotion of goods and services contributing to peace as opposed to bioweapons contributing to war.
Food Revolution [48]	These researchers present a comprehensive view of how and why microbes are the solution to converting unsustainable food production to a fully-sustainble future.
Biocivilizations [49]	The "Biocivilizations" view of lifeforms on Earth turns many historic views on their head. It presents compelling evidence that humans were preceeded by and will long be followed by micobes. It also argues that as communicators, we have thus far functioned primarily as "supporting actors"across the theater of life.
Magnetotactic Bacteria (MTB)-Based Micromotors [50]	Drug delivery including cancer therapy using magnetic bacteria is one of the many technologies drawing upon the array of special bacterial functions to benefit precision medicine.
Biochar as an Ecological Asset [51]	Beneficial circular economy and sustainable environment are discussed as major benefits arising from microbial fuel cell waste known as biochar. Biochar offers significant opportunities for restorative ecology as a result of energy production.

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The examples shown in Table 1 emphasize the importance of adopting a core view of humans not as a single species, but rather as a composite, human holobiont form. The key concepts of Table 1 illustrate the importance of discarding the dogma where microbes are seen predominately as germ theory-based threats to our existence. It is important to replace germ theory misapplication with a holobiont-centric view where microbiomes are embraced as the facilitators of maximized human holobiont consciousness, functional capacities, improved healthcare and wellness, sustainable living, and being better prepared to fully engage the biocivilizations described by Slijepcevic [49]. Part of this process is to retire the idea that we are on a mission to destroy life via the Antibiocene [28].

Increased sustainability is gained when the boundary between microbes associated with the human holobiont and other holobionts as well as environmental communities is softened and interconnectivity is fully embraced. For example, benefits can be found within precision medicine where bacterial motors offer new avenues in treatments and healthcare [50]. Similarly, in the environment, microbes represent ready solutions for both the restoration of damaged, polluted ecosystems [34] and sustainable food production systems [48].

Finally, aspects such as the social brain, microbial interactions aiding peace, and enlarged views of the "human image" and spirituality can offer us new pathways to a more holistic way of living. One of the intriguing aspects of the social brain and the question of where the human mind begins and ends concerns the role of the Internet of Microbes. Microbial networks are within but not bounded by the human body. While we go within to tap the mind, we are unlikely to remain solely within as we process information. Relatively recent findings that the bioelectric and biomagnetic state of microbes is significant in communication across the Internet of Microbes and that bacteria, themselves, respond to neurotransmitters with their own bacteria signaling is shifting our understanding of human-microbial connectivity [52].

From the foundation provided in Table 1, the remainder of this review examines the electric and magnetic nature of microbes, their holobionts and importantly, the sensitive responses of microbes to electric and magnetic fields. Holobiont integrity, health wellness and safety are all important considerations when it comes to the exposure to and various applications of these fields.

3. Bioelectrical and Biomagnetic Processes in Human Cellular Life

The human body itself generates electricity and research has suggested that human electricity/energy can be harvested when useful [53]. Depending upon frequency, strength, duration, and the nature of the externally applied fields (e.g., static. vs. pulsed), these factors can lead to beneficial or detrimental effects on holobionts and their microbial partners [54,55]. These factors have been used to increase the efficiency of medical and industrial applications such as bacterial fuel cells [56], bacteria-driven bioremediation [57] and wound healing [58].

4. Early Examples of Electrical and Magnetic Applications in Human Medicine

According to Luderitz [59] and Ma et al. [60], ideas around electrotherapy (antiarrhythmic) date back at least to the 280 BCE China where a series of ten texts titled "The Pulse Classic" and authored by Wang Shuhe discuss the significance of the pulse forming what would later become core to traditional Chinese medicine [60]. Modern applications of electrotherapy to treat arrhythmia can be found in the 1950s with major developments since that time [reviewed in 59]. As described by Markov [61] magnetic therapeutic centers began to emerge in Europe during the 1960s, while clinical applications in the U.S. can be found in the mid-1970s. One of the major applications of magnetic field therapy pertains to the reduction of inflammation. This specific medical application can be traced back to the 1980s [62,63]. Rumbaut and Mirkovic [64] also discuss earlier historic references concerning the use of magnetism to reduce edema.

6. Electric Microbes and Electrical Field Effects

While this narrative review focuses on electrical field effects on microorganisms, it is important to recognize that many microorganisms are electrically active in nature and large groups of microorganisms have the capacity to produce electrical current [65]. They have the capacity to transfer electrons to anodes within various electrochemical systems and have been termed "Living Electronics" by Thomasy [66]. Observations of bacteria as electrical beings date back to at least 1911 via the research of Potter [67]. Additionally, the application of generating electricity through microbial action was reviewed more than sixty years ago [68]. Additional recent research into the prevalence of microorganisms as electrical beings able to carry out the capacity of many prokaryotes to interact with charged electrodes led to a new field of study called Electromicrobiology [69]. As described by Nealson [69], bacteria are inherently electrically-powered organisms in which electron transport within bacteria lead to electrochemical gradients that power many processes via what has been termed proton motive force (an electrochemical gradient of protons across a membrane). This "force" can drive energy requiring processes and allows the bacterial cell to act much like a micro-battery.

Another group of bacteria go beyond comparatively weak electrical generation constituting a category known as Extracellular Electron Transport (EET) microorgansims. These have the capability to interact with a variety of insoluble electron acceptors and donors. EET microorganisms have opened a vast array of electrically-based technical applications and contributed to new ideas surrounding sustainability (e.g., biobatteries, pollution remediation, electrosynthesis and water reclamation) [69,70].

A final significant aspect of the inherently electrical nature of bacteria is the fact that EET organisms like *Geobacter* and *Shewanella* have created a natural global electrical grid via the production of nanowires [71,72]. Metabolic cross-feeding among microbial species is a process known as syntrophy or mutualistic symbiosis [73]. But microbes like EETs can go through a form of electrical syntrophy as recently reviewed by Rotaru et el. [74]. These researchers discuss the direct interspecies electron transfers between alcohol-utilizing *Geobacter metallireducens* and *Methanosarcinales* [74]. Remarkably, *Geobacter* EETs can even draw upon remnant activity in illuminated dead microalgae to boost their own electrical activity [75]. Hence, even dead microorganisms can contribute to what constitutes microbial electrical grids. As a result, the Internet of Microbes is not just about information exchange across a grid but also involves the flow of electrical current.

As with sound, light and magnetism, electrical fields can have divergent effects on microbial populations depending upon the nature and strength of the field and the specific responding microbial populations. Pulsed electrical fields and a rapidly-acting variation of this called locally enhanced electrical fields are used for microbial inactivation/germicidal outcomes [76,77]. Pulsed electrical fields have also been used to extract desirable compounds from disrupted microorganisms [78].

In contrast to the cell disruptive/germicidal effects of pulsed electric fields, other forms of electric field exposures can aid microbial growth, movement, and/or functional activity. Electric field effects on microorganisms include alteration of microbial populations within holobionts and among environmental microbial populations. Examples of these are illustrated in Table 2 [77,79–92].

Table 2. Examples of Electrical Fields, Bioelectric States, and Functions of Microbes.

Experimental Studies and Reviews [Citations(s)]	Experimental Approach [not applicable (NA) for Reviews]	Key Experimental Findings/ Review Conclusions
Studies on Kombucha mats as electronic and/or computing devices [79,80]	The researchers demonstrated that Kombucha mats have special properties that allow them to be converted into wearable electronics by exploring different technologies for manufacturing kombucha based PCBs: aerosol jet	The researchers demonstrated the feasibility of constructing electrical circuits within cured mats. They concluded that the Kombucha-based approaches offered advantages in being lighter, less expensive, and more flexible than conventional electronic systems. They also discussed the benefits regarding sustainability, biocompatibility,

	printing of PODOT:PSS as well as 3D printing of TPU and metal-polymer composite, adding ink with conductive filler and laser cutting.	customizability, breathability and moisture management.
Study of electrical resistivity as a measure of effective bacterial self-healing concrete [Esaker et al. 2023 81]	To find effective in situ measures of effectiveness of bacterial self-healing concrete	Concrete status beneath soil can be challenging to easily evaluate. Electrical resistivity was found to be a useful measure of the effectiveness of bacterial (*Bacillus subtilis*) driven self-healing in concrete beneath soil level.
Gut-brain axis regulation [82]	Bioelectric state alterations of specific microbiota during response to neurotransmitters were examined in *Bacillus subtilis* Marburg ATCC 6051 and *Limosilactobacillus reuteri* F275 ATCC 23272. Glutamate and GABA were used as neurotransmitters with growth rate, depolarization, and Vmem (a fluorescent reporter gene) evaluated during the exponential growth phase.	The study found that: 1) when cells are less energized (membrane depolarization), cell proliferation can increase and 2) bidirectional communication occurs between the bacteria and the brain. Using *B. subtilis*, depolarization (quantitated with the Vmem reporter gene) increased as did cell proliferation. Both bacteria responded to the two neurotransmitters with Vmem changes. Since *L. reuteri* is a psychoactive bacteria, this could have functional gut-brain implications.
Review of the impact of technologies including electrical fields on lactic acid bacteria [83]	NA	An emphasis is placed on the capacity of the technology to either enhance growth and/or functions of the bacteria or destroy the bacteria depending upon field strength/conditions.
Review of GABA and bacterial signaling [52]	NA	This review covers the range of GABA-driven signaling not only connecting bacteria within their own communities but also the regulation of neurological function in humans via interkingdom signaling.
Investigation of the	*Lactobacillus plantarum* from Mongolian	Key findings were: 1) electrical activity of *L. plantarum* MA was

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electrogenic mechanisms through which *Lactobacillus plantarum* affects intestinal epithelium and promotes intestinal adhesion [84]	fermented Airag (designated *L. planetarium* MA) was investigated for gene expression changes, electrical generation, and cecal adhesion properties.	dependent on type II NADH-quinone oxidoreductase and 2) was found to be conducted through flavin mononucleotide (FMN)-based extracellular electron transfer. 3) A significant effect was increased adherence by causing increased type 1 collagen expression among intestinal epithelial cells.
Study using a 3-D bioelectric platform (the e-transmembrane) to model host intestine-microbe cross-talk [85]	A 3-D stratified tissue human intestine model was used in conjunction with electrochemical impedance spectroscopy to monitor the effects of various postbiotics and live bacteria on integrity of the intestinal barrier. The electrical readout was an effective measure of gut barrier status.	The electronic transmembrane model facilitated real-time, in-line sensing of microbe-host barrier interactions. Impedance data could provide a clear evaluation of tissue integrity and changes in barrier function in response to postbiotics and live bacteria with different pro- or anti-inflammation-promoting properties.
Chemically-elevated bioelectric production from bacteria [86]	The phenoxazine electron-shuttling mediator, resazurin, was evaluated for its capacity to enhance electron transport at the anode electrode of a microbial fuel cell.	The major findings were that resazurin: 1) increased the microbial fuel cell power density fourfold, 2) increased electron conduction with a reduction in electrode resistance and 3) favored growth of electro-active microbial biofilm through increased biocompatibility.
Study using electric fields and highly aligned bacterial cellulose/gelatin membranes to guide cell migration. [87]	The focus was on establishing a highly-aligned bacterial cellulose/gelatin membrane that was combined with electrical stimulation to better recruit cells to an area in need of wound healing. In vivo wound healing was examined in mice.	A key finding was that wound healing was facilitated by accelerating wound closure, increasing granulation tissue thickness, collagen deposition, angiogenesis, and by upregulating specific gene expression.
Study of electric field stimulation of bacterial	Enhancing bacterial electrical	Key finding: electrical stimulation of biofilms under

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production of cytochrome OmcZ nanowires with higher conductivity [88]	conductivity of *Geobacter sulfurreducens* via nanowires was studied using a protocol to evaluate the difference in nanowire type, confirmation changes and electrical carrying capacity under different conditions.	specific pH ranges resulted in a change in nanowires (OmcZ instead of OmcS nanowires) with a 1,000 fold greater conductivity and increased nanowire stiffness than are generally found in nature.
Three bacteria consortium plug-and-play biobatteries [89]	Comparisons of single, double and tripled multilayer consortiums of biobatteries were constructed using *Shewanella oneidensis MR1*, *Bacillus subtilis,* and Synechocystis sp. PCC 6803)	The 3-D consortium of bacteria had excellent self-sustaining properties and was able to power supply for real-world wireless sensor network applications such as powering a telemetry system.
Optimization of an electrical field methodology to eliminate bacterial biofilm inhibition of wound healing. [90]	The study examined the effects of a new high-intensity current application (hydrogel circuit related) compared to conventional devices targeting methicillin-resistant *S. aureus* (MRSA) in a diabetic mice wound healing model.	The safer high intensity current produced two primary beneficial effects: enhanced bacterial debridement and greater antibiotic effectiveness.
The study examined more effective removal of biofilms on titanium structures as an orthopedic application. [91]	The study examined the effects of multiple short range, one-minute duration electrical fields on *Staphylococcus aureus* biofilms on titanium rings.	Multiple short duration electric applications proved effective in biofilm removal and would help to avoid what previously was necessary prolonged electrical field exposures.
Study using local electric fields to treat bacterial contamination of drinking water [77]	The researchers used *Staphylococcus epidermidis* as a model to test the effectiveness of locally enhanced electric field treatment employing nanosecond electric	The study found that one 20 nanosecond pulse at 55 kV cm^{-1} resulted in a 26.6% inactivation of bacteria by electroporation while ten pulses at 40 kV cm−1 produced 95.1% inactivation of bacteria. The study has

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	pulses. Different intensities and number of pulses were compared for effectiveness.	relevance for drinking water safety
Study demonstrating the utility of using pulsed electric field treatments for the eradication of *Saccharomyces cerevisia* [92]	The study examined the effects of up to four cycles of pulsed electric field (PEF) treatments under a variety of conditions such as with different media and with or without preservatives. Cell eradication and membrane resealing were the major endpoints evaluated.	Major findings were that: 1) the type of media and its electrical conductivity influenced yeast destruction vs. recovery and 2) specific preservatives affected the relationship between media electrical conductivity and yeast total destruction (damage without membrane repair).

Electrical technological applications using microbes have shown significant progress in recent years. Examples of these are the use of microbes in renewable fuel cells [93], conversion of waste organic material into sustainable energy [94], microbial environmental remediation [95], enhanced energy and functionality via nanowire technologies [96], and microbial sensing technologies [97].

Electroculture is an applied agricultural use to enhance plant growth via, at least in part, low electric fields producing rhizosphere microbe-plant enhancement. Not surprisingly, the “technology” associated with directed low level electric field into soil existed well before the delineation of soil-plant rhizosphere. Recent studies have demonstrated that electric field applications affect the status of rhizosphere microbe communities [98]. The history of electroculture dates back at least to the 18th century and was revisited/extended during the intervening years [99–101]. Nineteenth century scientific reports were presented [102]. By the 20th century, it was sufficiently vested in agricultural history that a publication titled “New Methods in Electro-Culture” appeared in a 1934 issue of the Journal of the Royal Society of Arts [103].

7. Microbes and Various Types of Magnetic Fields

Microorganisms and particularly certain kinds of bacteria and archaea have a variety of ways in which they interact with magnetism, both natural and artificial magnetic fields. These interactions can range for the capacity to: 1) acquire magnetism themselves through their own gene expression capability (e.g., MTB) and to use this to their functional advantage, 2) detect existing magnetic fields with great precision and sensitivity, 3) thrive or be killed by exposure to certain types and strengths of natural or artificial magnetic fields. In fact, magnetosomes have been described as a form of prokaryotic organelle that in conjunction with magnetosome-associated proteins control bacterial geomagnetic sensing [104].

These properties of microbes have implications for both earth’s ecosystems as well as for holobionts. For example, the idea that symbiotic magnetic sensing as a collaboration between MTB and host adaptations has gained increasing support [105]. In fact, magnetoreceptive bacteria have been found to be capable of transferring their capacities by producing a collective magnetic field-assisted motility guided by a chemoaerotaxis system in the holobiont [106].

This same sensitivity of microbes to magnetic fields means that magnetic field interactions can alter the compositions and distribution of microbial populations affecting ecosystems and holobiont

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health. Therefore, different types and strengths of natural and artificial magnetic fields become a significant tool through which microbial populations can be managed for better outcomes. They also become a significant health risk for holobiont humans, plants, and animals when field-induced microbiome damage occurs.

Microbial populations are known to be affected by both natural and artificial magnetic fields [107,108]. This has implications not only for the Internet of Microbes across planetary media ecosystems but also the microbiome of holobionts including those connected to humans. Humans and other holobiont microbiomes contain groups of highly specialized and in some cases extremophile archaea and bacteria. MTB are one example of highly specialized bacteria. These bacteria appear to be important in several functions including magnetic field detection and navigation via the production of magnetosomes containing magnetite crystals [109]. Simon et al. [110] recently found that several different species of MTB present within the human gut microbiome and their presence appears to be related to the presence of magnetite crystals in brain regions connected with navigation and orientation functions. Are the presence of these specialized bacteria in the human gut microbiome mere happenstance? If not, are they contributing to a much-underutilized human holobiont capacity?

Table 3 provides select examples of reviews and research studies focused on the importance of magnetic fields and microbes. Rather than being a comprehensive survey, these examples are presented to illustrate 1) unanticipated effects of magnetic fields on microbial populations producing potential hazards, 2) designed magnetic field alterations to enhance microbial functions, and 3) the potential origins and significance of magnetoreceptive microbes. Examples of the effects of magnetic fields on microbial populations via review articles and research studies are provided in Table 3 [105,110–119].

Table 3. Examples of Magnetic Field, Detection, States, and Effects Among Microbes.

Experimental Studies and Reviews [Citation]	**Experimental Approach [not applicable (NA) for Reviews]**	**Key Experimental Findings/ Review Conclusions**
Review article considering the likely origins of magnetoreception among microbes [111]	NA	The researchers present an exaptation model (where features acquire new functions) for early life magnetosome (MTB) development. They conclude that production of magnetosomes was a response for the need of an iron-oxide nanozyme with peroxidase activity to protect against oxidative damage.
Research study on the extent of MTB distribution [112]	The study used metagenomic analysis plus the reconstruction of metagenome-assembled MTB genomes from across highly divergent environments to examine the extent of MTB occurrence among bacteria.	The study found that MTBs were far more common among bacterial phyla than previously thought. Thirteen bacterial phyla were found to include MTB genomes with six phyla not previously known to possess MTBs.

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Research article on the effects of ultra strong static magnetic fields on human and mouse gut microbiota [113]	A 16 T static magnetic field was used to examine the changes in the structure and composition of human and mouse gut microbiota.	Exposure to the ultra strong magnetic field was found to significantly reduce the prevalence of six mouse gut microbiome bacterial genera and four human bacterial genera (*Bacteroides, Parabacteroides, Romboutsia, and Streptococcus*). Mice and humans differed in their response. Given the increasing prevalence of potential exposure to these fields, the researchers stressed the need to protect the microbiome.
Review article suggesting that magnetic fields can alter biochemical processes in microbial populations affecting a range of processes (e.g., nutrient transport across membranes, electron transfer during photosynthesis and respiration, enzyme activity and gene expression) and functions (*e.g.*, increased fermentation, growth rate, biomass) [114]	NA	The focus of this review is on magnetic field-assisted fermentation processes and the more efficient production of value-added products. A major finding was that device configuration could impact the magnetic field benefits and that needed to be part of the overall design considerations.
Review article emphasizing the impact of magnetic fields on microbial fuel cells and wastewater treatment application and the variables that can influence effective management [115]	NA	Magnetic fields affect the growth and functional activity of microbes in microbial fuel cells. These researchers focused on the mechanisms through which these effects occur. Changes in enzymatic activity and management of radical pairs were identified as key factors connected to functional status and potential benefits.
This review covers the germicidal capacities of pulsed magnetic fields. In this case, the applications are considered relative to food preservation.	NA	The review emphasizes the benefits of non-thermal pulsed magnetic field treatment of food as an effective sterilization

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[116]		technique while retaining food quality.
Research study involving the identification of specific genes and gene networks that are important for MTB crystal formation and biomineralization. [117]	The protocol involved the identification of specific genes encoding and/or regulating each step in MTB crystal formation and biomineralization among several phyla.	The research paper is important in associating genes with individual features such as crystal morphology, MTB chain assembly, and each step in the biomineralization process.
Research study showing that human gut microbiota include magnetotactic bacteria [110]	Metagenomic analysis of the gut microbiota from 34 healthy female adults was used to test for MTB. MRI was used for brain imaging in the subjects.	Researchers found seven MTB bacteria among the human gut microbiome (*Magnetococcus marinus*, *Magnetospira* sp. QH-2, *Magnetospirillum magneticum* , *Magnetospirillum* sp. ME-1, *Magnetospirillum* sp. XM-1, *Magnetospirillum gryphiswaldense* , and *Desulfovibrio magneticus*. The presence of the MTB in the gut was found to be associated with grey matter volume in magnetite-rich brain regions related to orientation and navigation.
Research study investigating the effects of external magnetic fields on MTB in China river sediments [118]	This research study examined the contribution of the external magnetostatic field to the diversity of MTB in various freshwater sediments in China.	Because MTB can rapidly relocate to optimal habitats by magnetotaxis, this can influence iron biogeochemical cycling. These researchers found significant changes in richness and diversity related to magnetic field intensity and/or duration of exposure. However, the changes in MTB populations were not necessarily the same across the three freshwater sampling locations.
Research study examining the effects of eternal magnetic fields on rhizosphere bacteria [119]	Popular seedling growth, the rhizosphere and soil microbes were evaluated under conditions of a static magnetic field. The field was created using framing ferrite permanent magnets	Magnetic field exposures had several reported beneficial effects. They increased dominant bacteria phyla (*Actinobacteria*, *Gemmatimonadetes*, and *Proteobacteria*), rhizosphere soil contents of extracellular polymeric substances, the ammonium

	Exposure was ~15 mT. Saline (3%) conditions were included in some trials.	nitrogen ($NH4^+$-N), amorphous iron oxide (Feo) and available phosphorus (AP) contents in the soil, as well as soil urease and acid phosphatase activity.
Review of the symbiotic magnetic sensing hypothesis [105]	NA	This review considers the pros and cons to the concept that MTB provide the underlying basis for magnetic sensing in animals.

8. Electromagnetic Waves and Microbes

The effects of electromagnetic (EMF) waves (the vibrational interactions of electric and magnetic fields) is a massive, complex subject of its own. While it is beyond the focus of the the current review, it is clearly related to both considerations of electric and maganetic fields and present day exposures. For this reason we: 1) introduce the significance of this topic, 2) indicate the massive range of environmental conditions that it encompasses, and 3) point to the differential sensitivities and responses among microbes to varying forms and strengths of electromagnetic waves. Electromagentic waves include infrared (IR) waves, radio frequency waves, ultraviolet, microwaves (MWs), visible light, X-rays, and gamma rays within the designations of both non-ionizing and ionizing radiation [120–122]. Electromagnetic waves have many industrial applications [123,124], and under certain circumstances they can be a source of potential health benefits via alterations in the gut microbiome and microbe-directed metabolism [125]. However, there is also evidence that they can be health hazards spanning cells, microbes, and holobionts [126,127]. For this reason, relevant exposure-outcome information is important. This is a topic that deserves both more attention in the literature and more research particularly when it comes to microbiomes, holobionts, and safety.

9. Perspectives on Sustainble Living and Conclusions

The consideration of sustainable living covers virtually every aspect of life on Earth running the gauntlet of levels from planetary to the biosphere and finally, to individual humans, plants, animals, insects, and microorganisms. At the planetary level, microbes are viewed as Earth's ancient lifeforms capable of residing in virtually every location and condition on the planet. Importantly, microbes have not only adapted to these various conditions but have also played a critical role in earth's biogeochemical cycles [128–130]. Obviously, this historic interconnection between microbial life and planetary level "health" leads to a conclusion that microbial life needs to be protected and sustained if other life on earth is to persist. It is intriguing to consider that ancient indigenous cultures emphasizing shamanic guidance and healing gave microbes a proper respect and role in their societies [43]. Much of the 20th century and its scientific dogmas emphasized the demonizing of microbes and the overkilling of bacteria [25,131–133]. Ancient wisdom is worth remembering.

At the level of the human holobiont, acceptance of humans as a composite of the human mammal and thousands of different microbial species has been slow to be reflected in medicine and public health. This has led to calls for microbiome first approaches to medicine and public health that approach the human body as majority microbial [134,135]. Most aspects of human development and function are significantly regulated by the human microbiomes [3,136,137]. Strategies of health maintenance, disease prevention, and disease treatment need to place our microbes first.

Another aspect of human sustainable life concerns the decades-long erosion of human health and functionality brought about by increasing disease burden. Rather than applauding a reasonable lifespan that is filled with ever increasely co-morbid chronic diseases and polypharmacy, we should be evaluating our progress toward sustainability with a different yardstick: by the length of our healthspan (days, week, months, or years spent in health) [6,138,139] not via a disease-ridden existence. An increasing number of prescription drugs consumed on a daily basis is not a sign of sustainable progress.

Finally, the focus of this paper is on microbes and particularly bacteria as premier producers, communicators, transferers, and collaborators when it comes to electricity and magnetism. Because electricity and magnetism are so important to microbes, natural and artificial electric and/or magnetic fields can either be beneficial or detrimental to microbial health and function. This extends not only to microbial communities in the environment but also to human, and other microbiomes. If electric and magnetic fields are particularly important for microbe community status, these are not the only physical fields to consider. In prior reviews, we considered the microbe-modifying effects of sound, light, and vibrations [21] as well as subtle energies associated with ancient and alternative health practices [20]. There is a broad spectrum of tools at our disposal to protect microbes as well as holobionts.

Beyond safety, the present narrative review illustrated examples of technological benefits by using electric and/or magnetic fields in conjunction with microbes. Advancement in medical applications and treatments as well as industrial applications (e.g., microbial fuel cells, bioremediation) will be a major part of our sustainable living. In this way, our progress to a sustainable future should be bright and it should be microbial.

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