Extracellular electron transfer explained

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Arpita Bose, PhD from Washington University in St. Louis, guides us through host-associated impacts and biotechnological applications of extracellular electron transfer in electrochemically active bacteria

Electron flow and oxidative and reductive reactions, referred to as "redox reactions," collectively impact the outcomes of biochemical pathways essential for cell growth, energy conservation, and stress response throughout various organisms. An example of these organisms is electrochemically active bacteria (EAB), which can link internal redox reactions with external electron acceptors or donors via a process known as extracellular electron transfer (EET).

EET is a bioelectrochemical process fundamental to the existence of EAB, where it often utilizes EET to enhance its ecological fitness and leaves an impact on its host environment. EET can occur through direct electron transfer (DET) or mediated electron transfer (MET), where MET utilizes electron shuttles to effectively transfer electrons from inside the cells to terminal electron acceptors. The prevalence of the EET process across several domains of microorganisms creates the need to evaluate its significant impacts and potential applications across host-associated environments.

Extracellular electron transfer and its impacts in the rhizosphere

The rhizosphere is a region of soil around plant tissue influenced mainly by root secretions and their associated microorganisms. The high content of humic acids (HA) often present in plant rhizospheres makes this region particularly suited for the occurrence of EET, as HAs are redox-active organic molecules. In these regions, these HAs serve as the electron shuttle for MET systems occurring in EAB, which help facilitate the electron transfer process necessary for plant and microbial growth.

Specifically, iron is essential in plant development, and its bioavailability can be enhanced through EET. Since iron(III) is far less accessible to plants than iron(II), bacteria capable of EET often utilize HAs to transfer electrons, ultimately reducing iron(III) to iron(II), helping plants by making the metals more readily absorbable. EABs, such as the *Geobacter metallireducens* have demonstrated their existing potential in the rhizosphere.

In recent studies, *Geobacter metallireducens* placed in chemically optimal conditions within the rhizosphere of cattail plants resulted in a two-fold increase in the reduction of iron(III) to iron(II) for plant absorption, proving its potential as a way to significantly enhance the availability of vital nutrients and biochemicals needed for plant survival.

Additionally, the presence of EET within the rhizosphere of bacteria is not only limited to the microbiomes of land plants, as another example includes the workings of cable bacteria found in the rhizosphere microbiomes of aquatic plants deep underwater. Often, these bacteria like to perform DET, helping transfer electrons directly to electron acceptors such as nitrate, nitrite, and iron, facilitating essential biogeochemical processes. The electron transfer aids in trapping heavy metals such as arsenic in sediment layers, ultimately being able to prevent the release of toxic metals into the water column and aquatic environment.

EET and its effects on human and animal microbiomes

Similar to how EET is seen as an active process in the rhizosphere, EET also influences human and animal microbiomes, particularly in environments where redox-active metals interact with mucosal surfaces. Some of these environments, including the oral cavity, gut, and lungs, create conducive environments for EET, impacting the behavior and composition of microbes within these systems.

In the oral cavity, EET-conductive conditions have been observed to facilitate the formation of electroactive bacterial biofilms created by oral opportunistic pathogens on titanium dental implants for the patients who received this form of treatment.

As a result, the biofilms caused by pathogens such as *Streptococcus mutans* pose a great degree of biocorrosion of these dental plants, which leads to significant problems such as perimplantitis, soft tissue inflammation, bone loss, and implant failure down the line.

Research on EET activity in the human gut microbiome is still minimal, as there is potential for both positive and negative health impacts. However, soil-dwelling EABs such as *Clostridium*, *Desulfovibrio, Pseudomonas, and Bacillus* have all been previously observed in insects such as beetles and earthworms where the bacteria facilitate nutrient cycling via EET.

In termites, EABs aid in lignin degradation, helping these insects break down complex plant materials into simple compounds that can be better utilized and absorbed by the host for nutrition. Based on these existing organism studies, it may be possible for opportunistic pathogens such as *Enterococcus faecalis* to form persistent biofilms that complicate gut health. However, this also leaves the possibility for probiotic bacterial strains to potentially enhance adhesion and metabolic activity in intestinal cells via EET pathways.

The human lung microbiome is rather nutrient-poor when compared to the gastrointestinal tract and oral cavity. Although not rich in redox-active organic molecules, the lung microbiome can still support EET activities. Bacteria such as *Pseudomonas aeruginosa* already utilize EET for energy conservation, redox homeostasis, and biofilm production. These processes have already led to observations of increased persistent infections in cystic fibrosis patients that are hard to treat and suppress. More research can be conducted into the potential positive applications of EET in medical treatments.

Alternative extracellular electron transfer uses

EET has significant applications in biotechnology, not just in host-associated habitats but also beyond these environments.

Within host-associated habitats, one application involves utilizing EAB in host-associated microbiomes to facilitate the production of fermented foods. Often, *lactic acid bacteria* (LAB), which is commonly found in fermented foods, utilize EET to control and influence its fermentation outcomes. Both the *Lactiplantibacillus plantarum* and *Lactococcus lactis* strains generate electrical currents during their fermentation process, which helps with the acidification of food. Moreover, EET is often utilized by LAB to lower the oxidation-reduction potential, helping inhibit the growth of undesirable microorganisms and thereby improving the flavor and safety of fermented products such as dairy, wine, sourdough, and poultry.

Outside of these host-associated habitats, EET's applications in biotechnology are exceptionally promising, particularly employed in bioelectrochemical systems like microbial fuel cells (MFC), microbial electrolysis cells (MEC), and microbial electrosynthesis (MES).

In MFCs, EABs transfer electrons generated during metabolic processes to an anode via EET, which then flows through a cathode and creates a current. This process converts chemical energy into electrical energy by harnessing electrons from organic substrates, allowing for the potential to generate electricity while treating wastewater or pollutants. MEC systems operate similarly to MFCs, but instead require a small voltage to drive the electrochemical reactions occurring at the cathode. In the process of doing so, hydrogen gas is derived as a valuable fuel from organic waste, which can be harvested and utilized through a wide variety of applications.

In MES, the system leverages EET to drive the conversion of CO^2 into valuable biofuels also by utilizing electrons taken up from a cathode. Applications of MES include temperature-dependent CO^2 reduction by thermophilic acetogens, sulfide oxidation and electron transfer in co-culture, electromethanogenesis using methanogens, and photoautotrophic growth by directly using the electrons harvested from the uptake using electrodes.

Extracellular electron transfer summary

In conclusion, EET is a valuable and widespread bioelectrochemical process that impacts host-associated environments and biotechnological applications and can be further studied and understood. Harnessing EET in these respective applications can lead to advancements in environmental sustainability, human health, and, most importantly, energy production, as it offers a new way to derive energy from a cleaner and more efficient source.

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