

REVIEW

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Polyphenolic compounds as electron shuttles for sustainable energy utilization

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Abstract

For renewable and sustainable bioenergy utilization with cost-effectiveness, electron-shuttles (ESs) (or redox mediators (RMs)) act as electrochemical “catalysts” to enhance rates of redox reactions, catalytically accelerating electron transport efficiency for abiotic and biotic electrochemical reactions. ESs are popularly used in cellular respiratory systems, metabolisms in organisms, and widely applied to support global lives. Apparently, they are applicable to increase power-generating capabilities for energy utilization and/or fuel storage (i.e., dye-sensitized solar cell, batteries, and microbial fuel cells (MFCs)). This first-attempt review specifically deciphers the chemical structure association with characteristics of ESs, and discloses redox-mediating potentials of polyphenolics-abundant ESs via MFC modules. Moreover, to effectively convert electron-shuttling capabilities from non-sustainable antioxidant activities, environmental conditions to induce electrochemical mediation apparently play critical roles of great significance for bioenergy stimulation. For example, pH levels would significantly affect electrochemical potentials to be exhibited (e.g., alkaline pHs are electrochemically favorable for expression of such electron-shuttling characteristics). Regarding chemical structure effect, chemicals with *ortho*- and *para*-dihydroxyl substituents-bearing aromatics own convertible characteristics of non-renewable antioxidants and electrochemically catalytic ESs; however, ES capabilities of *meta*-dihydroxyl substituents can be evidently repressed due to lack of resonance effect in the structure for intermediate radical(s) during redox reaction. Moreover, this review provides conclusive remarks to elucidate the promising feasibility to identify whether such characteristics are non-renewable antioxidants or reversible ESs from natural polyphenols via cyclic voltammetry and MFC evaluation. Evidently, considering sustainable development, such electrochemically convertible polyphenolic species in plant extracts can be reversibly expressed for bioenergy-stimulating capabilities in MFCs under electrochemically favorable conditions.

Keywords: Electron shuttles, Polyphenolics, Microbial fuel cells, Antioxidants

Background

In this review, we aim to clarify some of the mysteries of the electron shuttles (ESs) used in sustainable bioenergy applications (e.g., electro-fermentation and electrochemical biorefining). In particular, increasing energy, and resource scarcity and ecological destruction have encouraged for bioremediation techniques and the use of renewable material and energy sources. Thus, the creation of innovative, practical “green” sustainable bioenergy applications is inevitably required.

One example of this technology is the exploitation of the bioelectrochemical potential of electroactive microorganisms. Bioelectrochemical devices, such as microbial fuel cells (MFCs), can use synergistic/cooperative consortia of microbes as biocatalysts, and the electric current produced by the oxidation of organic compounds can be used for simultaneous bioelectricity generation and wastewater treatment [1–5]. In fact, MFCs are a promising platform to explore the electrochemical potential of bioresources for bioenergy and biorefinery uses. In an MFC, an anodic biofilm of bacteria is used to oxidize organic matter, which acts as nutrient source (i.e., the primary substrate), thus degrading pollutants or detoxifying inorganic contaminants co-metabolically. The protons generated in this

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process migrate through a proton exchange membrane toward the cathode in a double-chamber MFC, and the electrons overcome the interfacial mass transfer resistance on the anodic biofilm and pass through an external circuit to the cathode (e.g., air cathode), simultaneously generating bioelectricity. Therefore, bioelectricity generation occurs at the (bio)cathode along with water formation (i.e., $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$). There are several mechanisms for biofilm formation, direct electron transfer, mediator electron transport, and direct interspecies electron transfer that affect the operating efficiencies of MFCs [6]. To decrease the internal electron transfer resistance between electron acceptors and donors significantly, exogenous bioelectrochemical catalysts are commonly used; this allows the power-generating performance of MFCs to be increased. Moreover, electron transfer between microbes and from microbes to electron-accepting compounds can be facilitated using ESs. This is a promising way to decline the activation energy and increase efficient electron between the intracellular compartment and extracellular medium during microbial energy metabolism [7, 8]. That is, ESs are “electrochemical catalysts” that increase the reaction rate under appropriate environmental conditions. Because electrochemical catalysts (e.g., ESs) are not consumed during the catalytic reaction, they function reversibly, stably, and persistently. In particular, oxygen is a strong electron acceptor; anaerobic conditions are necessary to guarantee the effective redox-mediating behavior of ESs during electrochemical reactions. In the presence of ESs and the absence of strong electron acceptors (e.g., O_2), electrochemically driven reactions and reductive biodegradation occur faster because such electrochemical catalyst provides an alternative reaction pathway with lower activation energy than that of the non-catalyzed mechanism. That is, ESs can speed up redox reactions by providing “a set of elementary steps” with more (bio)electrochemically favorable kinetics than those that exist in their absence. Thus, supplementing an ES to a MFC or bioreactor system that is not in steady state or equilibrium will speed up both the forward and reverse rates, allowing an equilibrium mixture to be achieved much faster than anticipated. Thus, ESs play a crucial role in increasing the electron transfer efficiency between electron donors and acceptors for sustainable bioenergy extraction. The electrochemical characteristics of ESs can be determined from cyclic voltammetry (CV) profiles, and the difference (ΔE) between the cathodic (reduction) potential (E_{pc}) and anodic (oxidation) potential (E_{pa}) is given by the Butler–Volmer equation and Cottrell equations: $i = \frac{nFAC_0\sqrt{D}}{\sqrt{\pi t}}$ and $E_{pa} - E_{pc} = \frac{56.5 \text{ mV}}{n}$, for an “ n ” electron

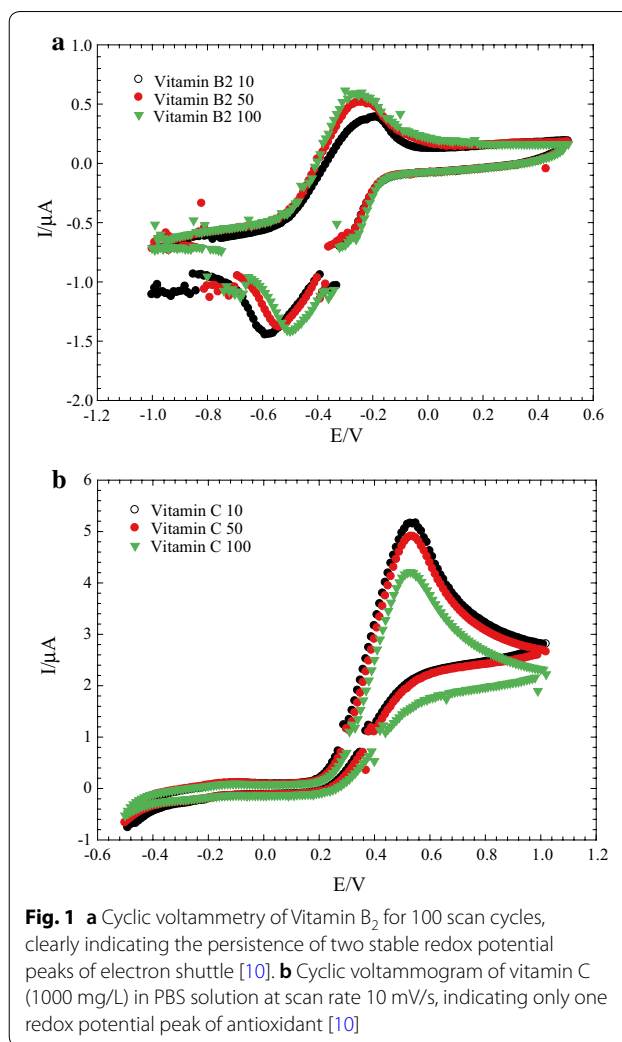


Fig. 1 **a** Cyclic voltammetry of Vitamin B₂ for 100 scan cycles, clearly indicating the persistence of two stable redox potential peaks of electron shuttle [10]. **b** Cyclic voltammogram of vitamin C (1000 mg/L) in PBS solution at scan rate 10 mV/s, indicating only one redox potential peak of antioxidant [10]

process [9]. The observed redox potential peaks of vitamin B₂ (riboflavin), a well-known ES, can be maintained over 100 CV cycles (Fig. 1a) [10]. In contrast, 100 CV cycles of the well-characterized antioxidant vitamin C only yielded an oxidation peak, as shown in Fig. 1b [10]. Furthermore, if the ratio of the peak currents of a test chemical approaches unity (i.e., $i_{pc}/i_{pa} \approx 1$ or the reduction and oxidation potentials are symmetric, where i_{pc} and i_{pa} are the cathodic and anodic peak currents for a reversible reaction, respectively), the chemical could be an ES with semi-reversible redox characteristics and electrochemical use (e.g., biorefinery and bioenergy uses) [11–13].

ESs can be either inorganic or organic compounds, such as iodide/triiodide [14] and Fe^{3+} [15], quinones [7], and vitamin B₂ [16, 17]. Considering the need for environmental friendliness for sustainable development, organic compounds, both natural and synthetic, with low biotoxicities (e.g., polyphenols or

polyhydroxyphenols) are favorable and promising for use as ESs compared to other inorganic species. In the following sections, we clarify several aspects of ESs not previously reported and suggest an optimal strategy for maximizing bioenergy extraction for sustainable development.

Chemical characteristics of organic ESs

The chemical structure of an ES strongly affected whether electrons and radicals are stable and delocalized for bioenergy extraction. The chemical structures significantly influence chemical or physical characteristics (e.g., polar or non-polar) and functions (e.g., Lewis acids/electrophiles/oxidants or Lewis bases/nucleophiles/reductants) and reactivities. That is, the chemical structure directly determines the reactions and reactivity of an organic compound (e.g., strong or weak reducing or oxidizing activities). In particular, ESs can be used to stimulate the biodegradation of various pollutants and bioelectricity generation in MFCs [18, 19]. Therefore, it is important to disclose that chemical structure of organic ESs can be used as essential prerequisite to determine whether they can own the capabilities of ESs or not.

Aromaticity

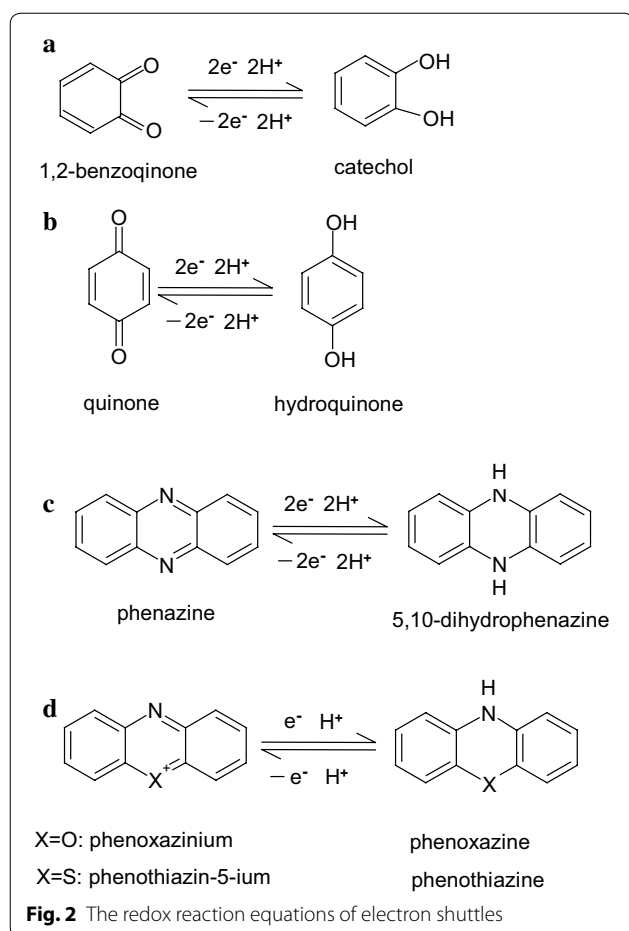
Table 1 lists several different ESs (e.g., phenazine, riboflavin, phenoxazine, thionine, viologen, quinone, naphthoquinone, anthraquinone, and aminophenol); these compounds have been used as ESs in MFCs to enhance the biodecolorization of azo dyes, as well as bioelectricity generation [7, 16, 17, 20–27]. Because pollutant degradation (e.g., reductive biodegradation) and bioelectricity generation are both associated with electron transfer, the formation or addition of an appropriate ES species can enhance the reductive and oxidative capabilities of an MFC. Therefore, the supplementation of ESs can be a valuable strategy to enhance the efficiency for diverse redox-mediated treatments (e.g., electro-fermentation and reductive biodegradation). From the perspective of molecular structures, ESs must be able to form the structures that can delocalize electrons and radicals during the redox reactions, for example, by resonance effect owing to aromaticity. That is, ESs must be able to form stable intermediates/complexes rapidly to allow further electrochemical reactions to be initiated. Therefore, the activation energies of the redox reactions can be decreased, and the reaction rates will be increased significantly. As shown in Fig. 2 for the redox reactions of ESs, the radicals (i.e., unpaired electrons) formed on the aromatic rings of ESs during redox reactions

Table 1 Some compounds used as electron shuttles (ESs) in microbial fuel cells (MFCs) or biological anaerobic decolorization (BD)

Redox mediators ^a (ESs)	Applied condition ^b	References
Phenazine	MFC	[7]
	BD	[16]
Neutral red	BD	[16]
Phenazine ethosulphate	MFC	[20]
Safranine-O	MFC	[20]
Riboflavin	BD	[16]
	MFC	[17]
Phenoxazine		
Brilliant cresyl blue(s)	MFC	[20]
Gallocyanine	MFC	[20]
Resorufin	MFC	[20]
Azure A	MFC and BD	[21]
Azure C	MFC and BD	[21]
Methylene blue	MFC	[20]
New methylene blue	MFC	[20]
<i>N,N</i> -dimethyl-disulphonated thionine	MFC	[20]
Phenothiazinone	MFC	[20]
Thionine	MFC	[20]
	MFC and BD	[21, 22]
Toluidine blue-O	MFC	[20]
Benzyl viologen	BD	[16]
	MFC	[20]
Methyl viologen	BD	[16]
Viologen	MFC	[7]
Malachite green	MFC	[22]
2,6-Dichlorophenolindophenol	MFC	[20]
Cobalamine	MFC	[7]
	BD	[16]
Quinones series		
1,2-Benzoquinone	MFC and BD	[23]
Dopamine	MFC	[17]
Epinephrine	MFC	[17]
1,4-Benzoquinone	BD	[16]
	MFC	[24]
Naphthoquinone	MFC	[7]
	BD	[16]
	BD	[24]
	BD	[25]
Alizarin brilliant blue	MFC	[20]
Anthraquinone	MFC	[7]
	BD	[16]
	BD	[24]
	BD	[25]
2-Aminophenol	MFC and BD	[26]
1-Amino-2-naphthol	MFC and BD	[27]
4-Amino-1-naphthol	MFC and BD	[27]
Humic acid	MFC	[7]

^a Redox mediator (RM) is also electron-shuttle (ES)

^b BD and MFC denoted bio-decolorization and microbial fuel cell, respectively



are delocalized by significant resonance effects (e.g., RD1A \leftrightarrow RD1B as shown in Fig. 3a, b [26]), resulting in redox reversibility. However, the ability to delocalize electrons results in greater electrochemical stability, enhancing the reversible redox-mediating capabilities of these compounds [28, 29]. This delocalization of electrons, radicals, and charge in intermediates or “transition complexes” of the ESs with aromatic rings ensures their stable reversible electrochemical reactions. Due to the formation of radicals or the effective delocalization of charge in intermediate species, ESs are kinetically and electrochemically favorable electron mediators between oxidants and reductants [29]. Thus, aromaticity seems to be a critical characteristic of most ESs. Furthermore, the redox characteristics of aromatic ESs are affected by the electron withdrawing or donating nature of substituents, as well as their orientations, which strongly affect the reactivity and catalytic power [7].

Substituent effects

As benzenes/polybenzenes contain a wide range of derivatives, easily obtained, and relatively inexpensive, they can be candidate sources of the practical ES species. Chen et al. [26] screened some model benzene derivatives with hydroxyl/amino and other substituents as possible ESs via CV analysis. The redox potential peaks of these benzene-based chemicals with different auxochromes (i.e., color-generating functional groups) were intentionally screened for possible electrochemical activity (e.g., antioxidant or ES). Such chemical with functional groups hydroxyl (–OH), amino (–NH₂), sulfhydryl (–SH), and methoxy (–OCH₃) carboxyl (–COOH) and sulfo (–SO₃H) groups was tested via CV analysis from –0.8 to 0.6 V (Table 2). Thus, compounds such as 2-aminophenol (2-AP) and 4-aminophenol (4-AP) bearing these substituents are characterized as ESs (i.e., displayed $i_{pa}/i_{pc} \approx 1$). The CV results revealed that suitably placed hydroxyl and amino substituents (e.g., *ortho*- and *para*-) resulted in typical reduction and oxidation peaks characteristic of ESs [26]. As a matter of fact, because atoms O and N are more electronegative (3.44 and 3.04, respectively) than carbon, organic compounds containing these atoms could favorably act as oxidants (i.e., EAs) during the formation of oxidized forms (i.e., intermediates with low electron densities). However, when these atoms are bounded on the aromatic rings, the lone pair electrons on O/N can act as electron donors via resonance effects in the reduced forms (i.e., higher electron densities) [29]. That is, some polyphenolics or aromatic heterocyclic rings containing N or O are electrochemically active ESs (Table 1). In particular, if strongly activating electron donating substituents (e.g., –OH and –NH₂) are present on an aromatic ring, radicals or charged ES intermediates located on O/N atom or on the carbon atoms attached O/N atom via resonance are electrochemically stabilized (Fig. 3a–d [26]), resulting in a decrease in the activation energy and a significant increase in the reaction rate.

In fact, it was found that ESs with hydroxyl substituents are more stable than amino groups with respect to their electrochemical redox behaviors. For instance, compared to 1,2-diaminobenzene (also known as benzene-1,2-diamine), benzene-1,2-diol (catechol) shows superior redox reversibility during repeated CV cycling [23]. Moreover, if hydroxyl-bearing ES compounds are obtained from natural polyphenols (or polyhydroxyphenols), the ESs could be less toxic and more biocompatible than compounds containing amino groups, making them green and sustainable compounds for practical uses. For example, 4-AP is toxic to electroactive bacteria, and the bioelectricity-generating capability of an MFC inoculated with *Proteus hauseri* ZMd44 was significantly repressed by this compound [8, 30]; thus, the biotoxicities of the

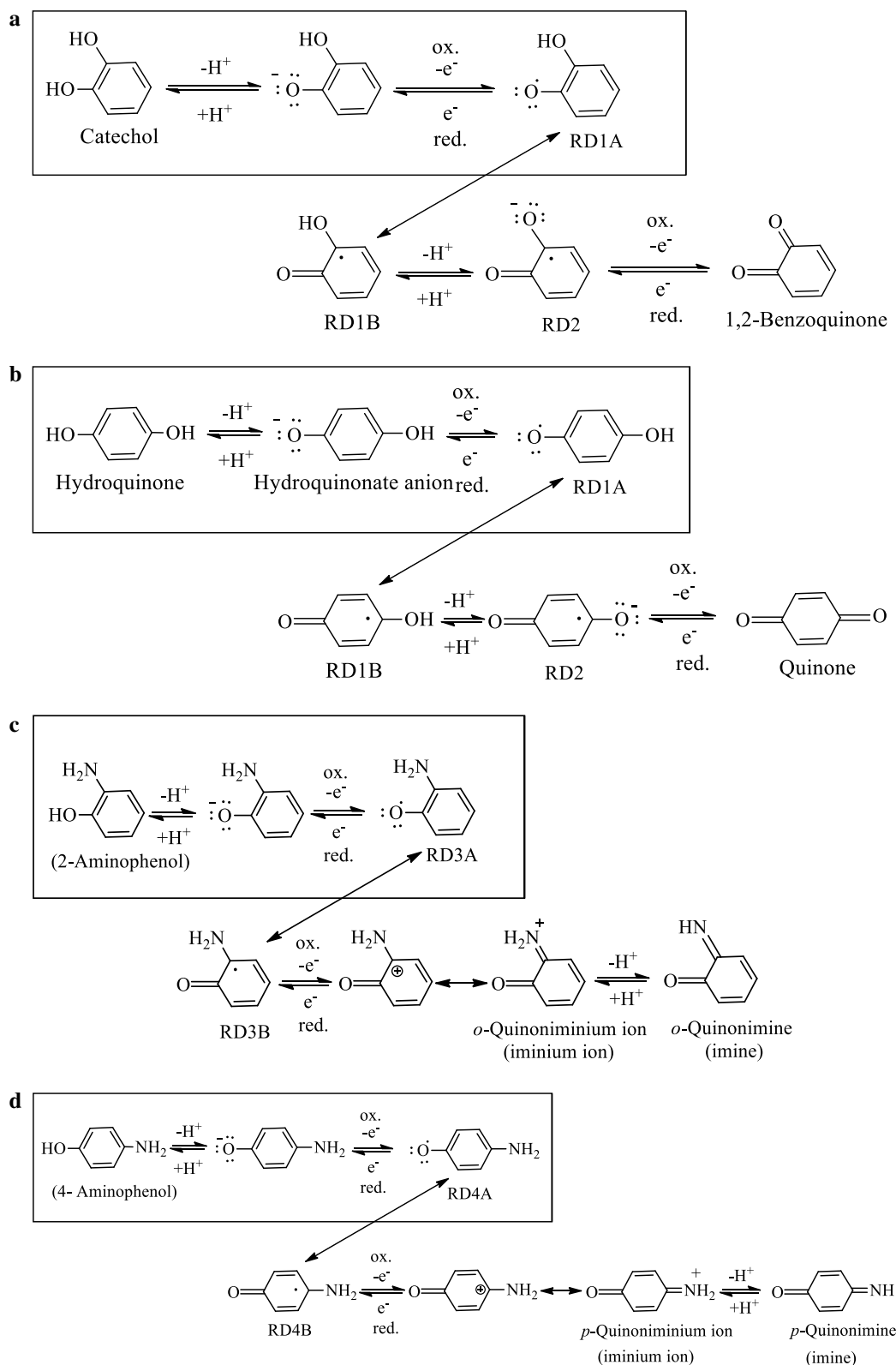


Fig. 3 a–d proposed pathways of inter-conversion of hydroquinone/quinone and catechol/1,2-benzoquinone, 2-aminophenol/*o*-quinonimine, and 4-aminophenol/*p*-quinonimine, respectively (cited from [26]) (RD denoted resonance forms of intermediates)

Table 2 Different auxochromes on benzenes whether owning the capabilities to be electron shuttles

Auxochrome	Electron-mediating capabilities ^a
Hydroxyl group, -OH	+
Amino group, -NH ₂	+
Sulfhydryl group, -SH	-
Methoxy group, -OCH ₃	-
Carboxyl group, -COOH	-
Sulfo group, -SO ₃ H	-

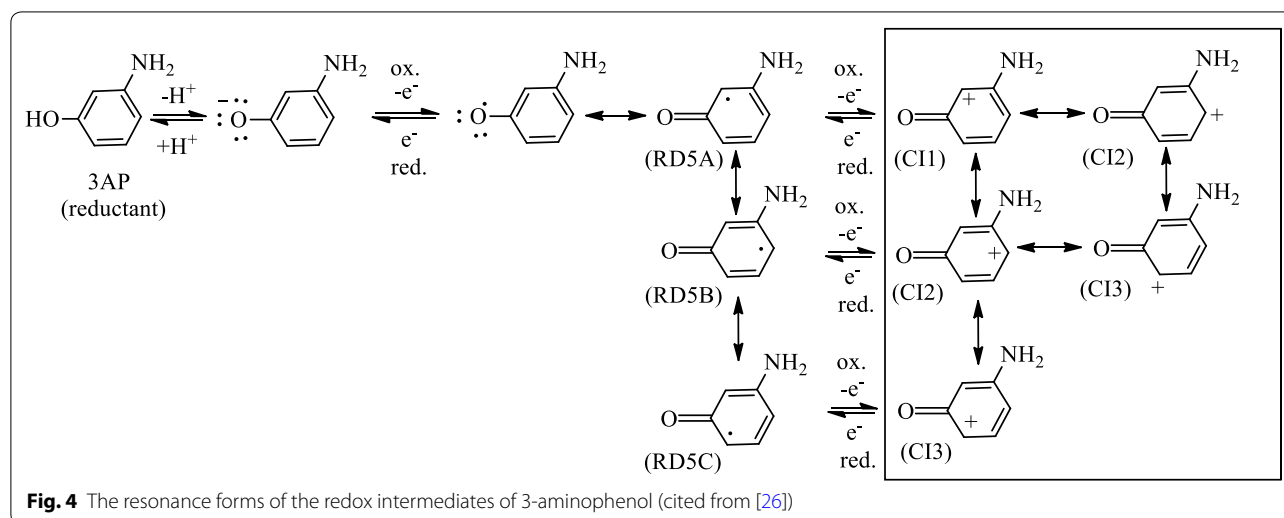
^a +: with redox peaks on CV profile; -: without redox peaks on CV profile (cited from [26])

compounds must be assessed before use for biotechnological applications. That is, as hydroxyl groups are more electrochemically stable and reversible, and less toxic than amino groups, polyhydroxy derivatives of benzenes/polybenzenes (e.g., benzoquinone, naphthoquinones, anthraquinones, and other polyphenolic compounds) are good candidate ESs for sustainable applications [23]. Therefore, if polyphenolic compounds are obtained from natural sources to be ESs, they can be environmentally friendly and bioelectrochemically appropriate for diverse purposes (e.g., bioenergy and biofuel uses).

Effect of substituent position

The substitutional patterns (e.g., *meta*, *ortho*, or *para*) of functional groups on an aromatic ring affect both the reactivity and regioselectivity of electrophilic/nucleophilic aromatic substitutions via inductive and resonance effects [29]. Similar concepts may also be applicable to affect ES capabilities. For example, significant redox peaks were only observed in the CV profiles when the

hydroxyl or amino groups were arranged at *ortho*- and *para*-positions on benzene-based redox mediators such as 2-AP, 4-AP, 1,2-diaminobenzene [23, 26], dopamine [17, 31], catechol, hydroquinone, caffeic acid, and paracetamol [31]. These compounds can show strong ES characteristics. Chen et al. [23, 26] employed 1,2-benzoquinone, 2-AP, and 1,2-diaminobenzene as ESs to improve the biodecolorization efficiency and increase the bioelectricity-generating capabilities of an MFC. In fact, Van der Zee et al. [16] and Bradley et al. [24] also used 1,4-benzoquinone to stimulate color removal and bioelectricity-generating capabilities in MFCs. Moreover, Guo et al. [17] recently reported that epinephrine and dopamine, which own *ortho*-dihydroxyl substituents, significantly enhance the bioelectricity production in MFCs. Possibly, the *ortho*- and *para*-positioned hydroxyl/amino groups in these compounds stabilize the radicals and charges in the intermediates (or transition states) of the ESs via resonance effects, thus mediating or accelerating redox reactions. That is, the radicals or charges could be delocalized on carbon atoms attached to hydroxyl or amino groups via resonance effects aided by the presence of the lone pairs on oxygen and nitrogen [26, 28, 29] (Fig. 3a–d modified from [26]). However, some compounds with hydroxyl or amino groups at the *meta*-position on phenyl rings can not exhibit redox potential peaks in their CV profiles, for example, 3-AP [26], resorcinol, and resveratrol [31]. Of course, these compounds are not ESs and only act as antioxidants because the hydroxyl or amino groups at the *meta*-position cannot stabilize radicals or charges in the redox intermediates (Fig. 4, cited from Ref. [26]). That is, the radicals or charges of the redox intermediates cannot be stabilized by delocalization on the O/N atom or the carbon attached to the O/N



atom [29]. Although *meta*-dihydroxy aromatics (e.g., morin, resveratrol, and 3,5-dihydroxybenzoic acid, refer to Table 1 in [32]) are not ES compounds, they can still act as antioxidants for use as reductants in redox reactions. In summary, aromatic compounds with two or more hydroxyl or amino groups *ortho* or *para* to each other can provide a conjugated system for electron delocalization by resonance effect, making these species suitable mediators to shuttle electrons for further electron transport between electron donors and acceptors for electrochemical catalysis. As mentioned, hydroxyl-bearing compounds (e.g., polyphenols) are common antioxidants used in the treatment of pathogenic bacteria and environmental free radicals to increase cell survival and health. Natural polyphenolic compounds from edible and medicinal plants are appropriate sustainable ESs or reductants for use as redox enhancers in bioenergy and biofuel applications. Therefore, if ES compounds are obtained from natural sources, they can be environmentally friendly and bioelectrochemically appropriate for a range of purposes (e.g., bioenergy and biofuel uses).

Natural polyphenolics as ESs

Antioxidants as reductants or ESs

Phenolic compounds are widely distributed in plants as secondary metabolites and, as antioxidants, can be used to scavenge free radicals and prevent oxidative stress. For many phenolic antioxidants [32], their reactions can be formulated as, $R \rightleftharpoons O + nH^+ + ne^-$, where R is the reductant (antioxidant) and O is the intermediate/product of oxidation. These phenolic antioxidants are necessary to sustain the normal metabolic functioning of plants. In addition, although many natural substances (e.g., edible flora and medicinal herbs) contain polyphenolic compounds, their ES and antioxidant capabilities can often be either synergistically or antagonistically affected and, sometimes, completely repressed by each other due to interactive complexity of the mixtures of these compounds. Consequently, it is difficult to distinguish the ES activity from antioxidant capability. For example, oxidation usually results in the generation of free radicals, which triggers further chain reactions that may damage individual cells or the whole organism. Antioxidants react with oxidants or radicals and, thus, inhibit or repress the oxidation of other more important species, such as biochemicals, nutrients, and cells. Antioxidants scavenge free radicals to prevent harmful reactions to be taken place. Thus, in this review, we discuss pure ES species to enable a comparison of ES and antioxidant behavior and exclude possible confounding effects of other chemical species. Moreover, whether an electroactive substance or chemical can act as either an ES or antioxidant strongly

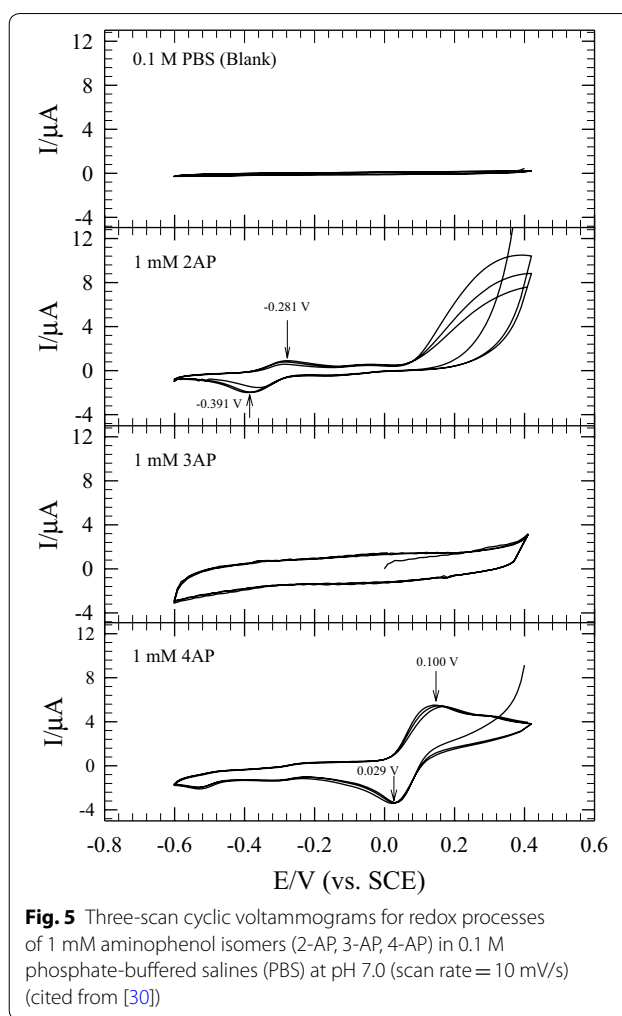


Fig. 5 Three-scan cyclic voltammograms for redox processes of 1 mM aminophenol isomers (2-AP, 3-AP, 4-AP) in 0.1 M phosphate-buffered saline (PBS) at pH 7.0 (scan rate = 10 mV/s) (cited from [30])

depends on the reversible electrochemical characteristics over multiple CV scans under specific conditions (e.g., the unstable and decaying profiles of 2-AP versus the stable reversible profiles of 4-AP in Fig. 5; [30]), even though both aminophenols may be ESs on the basis of their structure. As shown by the CV profiles (Fig. 5), the repeated oxidation and reduction of amino-bearing compounds (e.g., 2-AP) results in the gradual loss of electrochemical stability because of the repeated electrochemical oxidation and reduction, whereas hydroxyl substituents are more electrochemically stable [23, 26]. The reversible electrochemical behavior of ESs, as shown by their stable and reversible CV profiles, is characteristic of these “catalysts” crucial for their redox-mediating activity in pollutant biodegradation and power generation in MFCs. For example, catechol, an *ortho*-dihydroxy compound, is a typical biological redox mediator, and the compounds with catechol moieties are also found widely

in the natural world. The redox stability of hydroxyl-containing compounds may explain why similar compounds (e.g., dopamine, epinephrine, norepinephrine, caffeic acid, and chlorogenic acid) are present in diverse organisms for bioenergy utilization. Catechol can be produced by the reversible two-electron, two-proton reduction of 1,2-benzoquinone ($E^\circ = +795$ mV versus (SHE), E_m (pH 7) = +380 mV vs. SHE) (also see the CV profile of catechol in [23]). Thus, catechol is an ES with a suitable standard electrode potential (E°) for redox reactions, explaining its frequent presence in many organisms (Table 3, Fig. 3a). In addition, 100 repeated CV

cycles on catechol at neutral pH show its reversible redox behavior and stable ES characteristics [23]. In contrast, antioxidants such as vitamin C (Fig. 1b) and vitamin E scavenge free radicals and form unstable intermediates, leading to gradual “decomposition” by electrooxidation, making antioxidants non-renewable reductants. In contrast, riboflavin (also known as vitamin B₂) is a typical ES chemical species, remaining stable over multiple redox cycles (Fig. 1a). The oxidation of antioxidants under atmospheric conditions is unlikely to be reversed (i.e., to the original chemical species). That is, the loss of electrochemical characteristics cannot be prevented, resulting in gradually decaying redox peaks over repeated CV scans, as seen for 2-AP (Fig. 5).

Table 3 Typical standard reduction potentials of electron transfer carriers in organisms

Half-reaction	E° (mV)
$\text{NAD}^+ + \text{H}^+ + 2\text{e}^- \rightarrow \text{NADH}$	-320
$\text{FAD} + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{FADH}_2$ (free coenzyme)	-220
$\text{FAD} + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{FADH}_2$ (in flavoproteins)	~0
Coenzyme Q10	+100
Cytochrome C (Fe^{3+}) + $\text{e}^- \rightarrow$ Cytochrome C (Fe^{2+})	+220

Polyphenolics are ubiquitous natural compounds, and these polyphenol/polyhydroxyphenol species have diverse chemical structures, and frequently show promise as antioxidants or reductants with cell-protecting effects [33–35]. In addition, although polyphenolics contain several hydroxyl groups, not all of the hydroxyl groups can be fully utilized for antioxidant or ES activity. For example, as reported by Lemanska et al. [36] and Firuzi et al. [37], hydroxyflavone isomers (see Fig. 6) have different antioxidant capabilities. For instance, the 3-OH

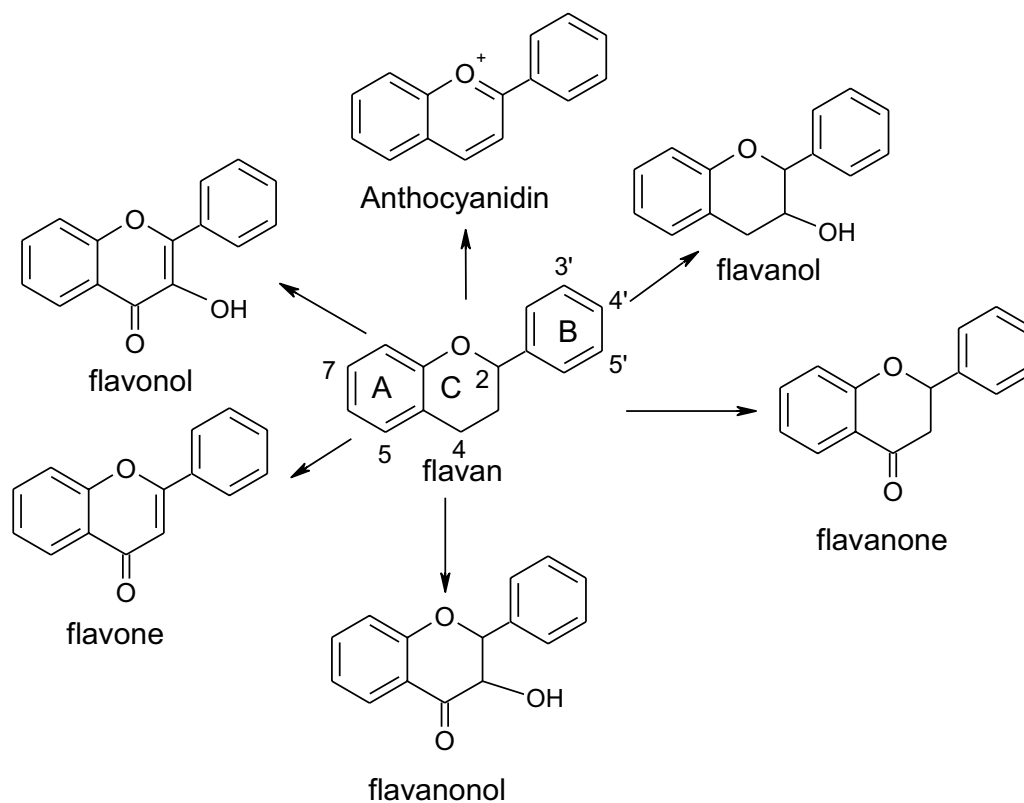
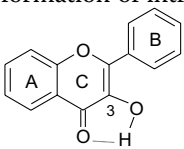
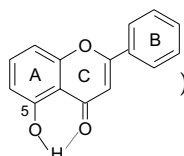


Fig. 6 Classification of flavonoid subclasses

(on the C ring) and 5-OH (on the A ring) isomers electrochemically favor high antioxidant activity, possibly because these hydroxyl groups are near the carbonyl group (C=O on C-4) allowing the formation of intramo-

lecular hydrogen bonds (e.g.,  and

) [38] to result in easier oxidation. In con-

trast, the 7-OH (on the A ring) and 4'-OH (on the B ring) isomers, where the hydroxyl groups are far from the carbonyl group, do not show antioxidant activities. Thus, despite having the same functional groups, these compounds have different electrochemical activities arising from orientation effects. These effects of the chemical structure on reactivity and catalysis can be analyzed by structure–activity relationships (SARs) [28, 39]. However, 1,2,3-trihydroxyl or 1,3,5-trihydroxyl arrangements are electrochemically favorable for high antioxidant activity; i.e., these compounds are good reductants [40]. That is, trihydroxyl-bearing flavonoids act as strong antioxidants, but simply function as reductants in MFCs for simultaneous pollutant degradation and bioelectricity generation [18, 41]. For example, the main polyphenolics in *Camellia* green tea, epicatechin gallate (ECG), epigallocatechin gallate (EGCG), and gallic acid (GA), have CV profiles that show significant oxidative potential peaks [41]; yet, the lack of significant reductive potential peaks (see Kilmartin and Hsu [42]) indicates that these compounds are not electrochemically viable as electron shuttles. However, they can still be as reductants to enhance the power density in MFCs [41]. Compared to the antioxidants GA and vitamin C, dopamine and epinephrine as ESs result in significant increases in power generation in MFCs [17]. Moreover, baicalins having 5,6-dihydroxy groups on the A ring display more significant reductive and oxidative potential peaks (i.e., E_{pc} and E_{pa}) in their CV profiles than those bearing 5,6,7-trihydroxyl groups on the A ring [43]; however, baicaleins have higher free-radical-scavenging capabilities than baicalins [44]. In addition, when the CV profiles of test chemicals do not show reversible redox potential peaks, these chemicals can not maintain their chemical properties after redox cycling. This explains why CV analyses on medicinal herbal extracts usually showed gradually decaying redox potentials [41, 45]. That is, as CV profiles show an irreversible response curves, the compounds under study are easily converted to different chemical species after such

repeated redox reactions. Furthermore, as reported by Danilewicz [46], catechol (H_2Q) can undergo redox reactions under acidic conditions (pH 3.6) and an ideal CV profile showing distinct reduction and oxidation potential peaks is obtained. In addition, polyphenolics with *ortho*-dihydroxyl groups (e.g., epicatechin, catechin, 5-*O*-caffeoylquinic acid, caffeic acid, chlorogenic acid, rutin, and quercetin) also exhibited significant redox potential peaks on CV scanning [42, 47]. Of course, these polyphenolic compounds could not only be antioxidants but also ESs if appropriate environmental conditions are electrochemically satisfied. For example, at slightly alkaline pH, *Camellia* green tea and medicinal herbal extracts, which contain high antioxidant polyphenolic contents, could be converted as sustainable ES “catalysts” for renewable energy extraction [41, 45]. In contrast, polyphenolics having *meta*-dihydroxyl substituents on the phenyl rings (e.g., resorcinol and resveratrol) can only function electrochemically as antioxidants due to a lack of reductive potential peaks in their CV profiles [31]. Moreover, compared to baicalins, which contain 5,6-dihydroxy groups on the A ring, the redox potential peaks of wogonins and chrysin with 5,7-dihydroxy (i.e., *meta*-dihydroxy) groups on the A ring were almost absent because of the lack of the resonance structure required for ES behavior [43, 48, 49]. Evidently, the *meta*-dihydroxyl substituents are not electrochemically suitable for use as ES in cyclic bioenergy applications.

Natural polyphenolics as ES species

On the basis of the CV profiles of the polyphenolics discussed above, polyphenolic compounds with dihydroxyl groups *ortho*- or *para*- to each other could act as ESs. For example, humic acids (or humic substances) are well-known ESs in bioelectrochemical systems [7, 50–52]. As mentioned, phenolic compounds play crucial roles in plant development (e.g., lignin and pigment biosynthesis), and these compounds can be categorized as (A) polyhydroxyl derivatives of phenylpropanoids, (B) derivatives of quinones/naphthoquinones/anthraquinones or catechols, (C) polyhydroxyl derivatives of flavonoids, (D) polyhydroxyl derivatives of anthocyanidins, and (E) tannins (Table 4) [53–126]. Due to the earth's species biodiversity, the levels of ESs vary significantly from plant to plant. However, some plant species contain abundant in ES chemicals (e.g., chlorogenic acid, rosmarinic acid, and verbascoside (acteoside)). For example, *Cynara scolymus* [58] and *Lonicera japonica* [62] contain 4.713% and 6.14% chlorogenic acid, respectively, and *Origanum majorana* L. and *Salvia officinalis* L. contain 15.15% and 17.85% rosmarinic acid, respectively [56]. In addition, *Orobancha rapum-genistae* [71] and *Plantago lanceolata* [85] contain 6% and 3–8% verbascoside

Table 4 Polyhydroxyphenols (polyphenols) as electron shuttles in plants

Model polyphenols	Contents in plant species	Refs.
A. Derivatives of phenylpropanoids		
		
Caffeic acid	1.05–62.84 mg in 100 g dry samples of <i>Echinacea purpurea</i>	[53]
	773 mg phenolics (as caffeic acid) in 5 g sample of <i>Ilex paraguariensis</i>	[54]
	0.62 mg/g of <i>Monarda fistulosa</i> L.	[55]
	7.99–19.75 mg in 100 g dry samples of <i>Salvia apiana</i>	[53]
	1.98% in <i>Salvia officinalis</i> L.	[56]
	1.4% in <i>Thymus vulgaris</i> L.	[56]
Caffeoylquinic acid	~ 11 mg/g dry sample of <i>Akebia quinata</i>	[57]
	0.740% in dry sample of <i>Cynara scolymus</i>	[58]
	773 mg phenolics (as caffeoylquinic acid)/5 g sample of <i>Ilex paraguariensis</i>	[54]
	723 mg/100 g fresh samples of <i>Vallis glabra</i>	[59]
Monocaffeoyl tartaric acid	223 µg caffeic acid (as monocaffeoyl tartaric acid)/g in fresh leaves of <i>Cichorium intybus</i> L.	[60]
Calceolarioside	~1 mg/g dry sample of <i>Akebia quinata</i>	[57]
Chlorogenic acid	566.5 µg of caffeic acid (as chlorogenic acid)/g fresh leaves of <i>Cichorium intybus</i>	[60]
	4.713% in dry sample of <i>Cynara scolymus</i>	[58]
	2.60% in dry samples of <i>Eucommia ulmoides</i>	[61]
	6.14% in dried plant samples of <i>Lonicera japonica</i>	[62]
	1.22% in <i>Salvia officinalis</i> L.	[56]
	0.22% in dry leaves weight of <i>Taraxacum officinale</i> Wigg	[63]
	1.02% in dry leaves weight of <i>Vaccinium arctostaphylos</i> L.	[63]
Chichoric acid (chicoric acid)	1535 µg/g fresh leaves of <i>Cichorium intybus</i>	[60]
	0.41% in dry aerial parts weight of <i>Chicorium intybus</i>	[63]
	42.37–258.70 mg caffeic acid (as chicoric acid)/100 g dry samples of <i>Echinacea purpurea</i>	[53]
	88.5 mg in 100 g fresh weight of <i>Ocimum basilicum</i> L.	[64]
	0.77% in dry leaves weight of <i>Taraxacum officinale</i> Wigg	[63]
Cynarin	1.689% in dry sample of <i>Cynara scolymus</i>	[58]
Danshensu	24.8% in crude aqueous extract of <i>Salvia miltiorrhiza</i>	[65]
Echinacoside	42.71% in 210 g crude phenyl ethanol glycosides extract from dried and sliced rhizomes of <i>Cistanche tubulosa</i> (6.0 kg)	[66]
Forsythiaside	16.7 mg from 500 g <i>Forsythia suspense</i>	[67]
Gravolenic acid	<i>Ruta graveolens</i>	[68, 69]
Nordihydroguaiaretic acid (NDGA)	0.0898% in the dried weight of <i>Larrea divaricata</i>	[70]
Orobanchoside	3% from <i>Orobancha rapum-genistae</i>	[71]
Pedicularioside	70 mg from 13.5 kg <i>Buddleia lindleyana</i>	[72]
Rosmarinic acid	9.30 mg/g <i>S. africana-lutea</i>	[55]
	3.68% from dry weight basis in 40 <i>Mentha × piperita</i> Clones	[73]
	622.28 mg caffeic acid (as rosmarinic acid)/100 g dry samples of <i>Melissa officinalis</i>	[53]
	15.15% in <i>Origanum majorana</i> L.	[56]
	8% of rosemary extract from 50 g dried leaves of <i>Rosmarinus officinalis</i> L.	[74]
	4.8 g from dried roots of <i>Salvia miltiorrhiza</i> (32 kg)	[75]
	17.85% in <i>Salvia officinalis</i> L.	[56]
Salvianolic acid A	0.7 g from the dried roots of <i>Salvia miltiorrhiza</i> (32 kg)	[75]
	11.96 g residue from the dried roots of <i>Salvia miltiorrhiza</i> (30 kg)	[76]

Table 4 (continued)

Model polyphenols	Contents in plant species	Refs.
Salvianolic acid B (lithospermic acid B)	2.06 g from the dried roots of <i>Salvia miltiorrhiza</i> (32 kg)	[75]
	33.93 mg/g in <i>Salvia miltiorrhiza</i> (<i>Danshen</i>)	[77]
Salvianolic acid C	0.4 g from dried roots of <i>Salvia miltiorrhiza</i> (<i>Danshen</i>) (32 kg)	[75]
Tubuloside (A, B, C, D)	Tubuloside A (II) 200 mg; Tubuloside B (VI) 100 mg; Tubuloside C (VII) 60 mg; Tubuloside D (VIII) 65 mg from fresh whole plants of <i>Cistanche tubulosa</i> (Schrenk) (22 kg)	[78]
Verbascoside (acteoside)	0.009% (pure compound) from dried leaves (1 kg) of <i>Buddleja globosa</i>	[79]
	16 g isolated from dried and ground leaves of <i>Buddleja cordata</i> (2.3 kg)	[80]
	361.2 mg from the fresh whole plants (246 g) of <i>Byblis liniflora</i> <i>Salisb.</i>	[81]
	14.27% in 210 g crude phenyl ethanol glycosides extract from dried and sliced rhizomes of <i>Cistanche tubulosa</i> (6.0 kg)	[66]
	0.50 g from 35 g <i>Lantana camara</i>	[82]
	0.43 g from 35 g dry <i>Lippia javanica</i>	[82]
	1.7% from dry weight of <i>Olea europaea</i>	[83]
	6% from the dried plant (<i>Orobancha rapum-genistae</i>)	[71]
	11.3 mg/mL (<i>n</i> -butanol extracts from dried and powdered leaves of <i>Phlomis</i> species (100 g))	[84]
	3–8% in <i>Plantago lanceolata</i>	[85]
	0.612 mg/g dry extract of <i>Verbascum mallophorum</i>	[86]
	0.18–3.03% of the dry weight <i>Verbascum</i> leaves	[87]
	30.31 mg/g dry weight of <i>Verbascum nigrum</i>	[87]
	~ 3.7% in MeOH extract from ground aerial parts (1.3 kg) of <i>Verbena officinalis</i>	[88]
	13.28 mg/g dry weight of <i>Verbascum phoeniceum</i> species	[87]
	15.79 mg/g dry weight of <i>Verbascum xanthophoeniceum</i>	[87]
B-1. Quinones and derivatives		
		
Hydroxyechinofuran B	Hydroxyechinofuran B (15 mg) from 1 g of fresh hairy roots of <i>Lithospermum erythrorhizon</i>	[89]
6-(4,7-Hydroxy-heptyl) cyclohex-2,5-diene-ene-1,4-dione (6-(4,7-hydroxy-heptyl) quinone)	the new quinone isolated from ten grams of crude ethyl acetate extract of 500 g <i>Pergularia daemia</i> leaves	[90]
Scabequinone	~ 7 × 10 ⁻³ % from fresh <i>Cyperus distans</i> weight	[91]
2,6-Dimethoxyquinone	~ 0.002% based on root of <i>Rauwolfia vomitoria</i>	[92]
	1.1% of aqueous methanol fraction from 15 g dried stems of <i>Tibouchina pulchra</i>	[93]
2,5-Dihydroxy-3-undecyl-para-benzoquinone (Embelin)	1.9 g embelin from 100 g of <i>Embelia ribes</i> extracted using hexane	[94]
B-2. Catechol and derivatives		
		
Catechol (1,2-dihydroxybenzene).	0.1–0.2 g of crude catechol from 100 g of dry scales of pigmented onion scales (<i>Allium cepa</i>)	[95]
Protocatechuic acid (3,4-dihydroxybenzoic acid)	~ 0.1 g/100 g dry scales of pigmented onion scales (<i>Allium cepa</i>)	[96]
Carnosic acid	3.77% in <i>Salvia officinalis</i> L.	[56]
	7.57% in <i>Thymus vulgaris</i> L.	[56]
Dopaol beta-D-glucoside (2-(3,4-dihydroxyphenyl) ethyl beta-D-glucopyranoside)	~ 3 mg/g dry sample of <i>Akebia quinata</i>	[57]
Horminone	0.4 g from about 1 kg of the dried whole plant (aerial parts and roots of <i>Salvia lanata</i>)	[97]

Table 4 (continued)

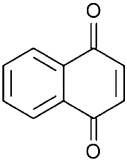
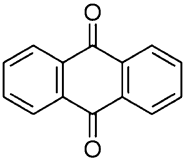
Model polyphenols	Contents in plant species	Refs.
B-3. Naphthoquinones and derivatives		
		
3',3'-Biplumbagin	~ 10% from the n-hexane extracts of stem bark (20 g) of <i>Diospyros anisandra</i>	[98]
Diosquinone	120 µg from 5 kg of the dried root of <i>Diospyros mespiliformis</i>	[99]
Droserone	~ 70% from the n-hexane extracts of stem bark (20 g) of <i>Diospyros anisandra</i>	[98]
Maritinone	~ 5% from the n-hexane extracts of stem bark (20 g) <i>Diospyros anisandra</i>	[98]
Plumbagin	~ 30% from the n-hexanic extracts obtained from Powdered stem bark (20 g) <i>Diospyros anisandra</i>	[98]
	34 mg from 5 kg of the dried root of <i>Diospyros mespiliformis</i>	[99]
Shikonin (derivatives)	12.4% shikonin derivatives in cells corresponding to 3 g dry wt. inoculated on 1 L of the medium of <i>Lithospermum erythrorhizon</i>	[100]
Vitamin K	Spinach, swiss chard, lettuce and <i>Brassica</i> vegetables (such as cabbage, kale, cauliflower, broccoli, and brussels sprouts), avocados, kiwifruit and grapes	[101]
B-4. Anthraquinones and derivatives		
		
	1.9% free and 4.5% total anthraquinones in <i>Cassia occidentalis</i> roots	[102]
	hydroxyanthraquinones indicated in <i>Cassia angustifolia</i> Vahl, <i>Cassia senna</i> Linn. and <i>Cassia tora</i>	[103]
	0.04 to 3.8, 5.9 and 36 mg total anthraquinones per kg fresh weight in peas, cabbage, lettuce and beans, respectively	[103]
Alizarin (1,2-dihydroxyanthraquinone)	39 mg from <i>Rubia cordifolia</i> L. root powder (3 kg)	[104]
	147.9 and 216.8 µg/g dry weight of <i>Rubia peregrina</i> in roots and callus, respectively	[105]
	939.6 and 335.2 µg/g dry weight of <i>Rubia tinctorum</i> in roots and callus, respectively	[105]
Chrysophanol	140 mg from powdered roots of <i>Rumex nepalensis</i> (2 kg)	[106]
1,3,8-Trihydroxy-6-methylanthracene-9,10-dione (Emodin, Emodol, Schuttgelb)	0.1 g/8 kg (0.0012%) of <i>Aster tataricus</i>	[107]
	79 mg from <i>Cassia obtusifolia</i> seeds (4.9 kg)	[108]
	2.03 mg/g in <i>Fragula alnus</i> bark	[109]
	16.2 mg from 928 g of the ethanol extract (9% (g/g)) of the dried stem and roots of <i>Polygonum hypoleucum</i> Ohwi	[110]
	105 mg from powdered roots of <i>Rumex nepalensis</i> (2 kg)	[106]
	0.31% (w/w) from shade-dried plant samples of <i>Ventilago madraspatana</i> (500 g)	[111]
Emodin-8-O-β-D-glucopyranoside	17.4 mg from 928 g of the ethanol extract (9% (g/g)) of <i>Polygonum hypoleucum</i> Ohwi)	[110]
	35 mg from powdered roots of <i>Rumex nepalensis</i> (2 kg)	[106]
Endocrocin	7 mg from powdered roots of <i>Rumex nepalensis</i> (2 kg)	[106]
Isomangiferin	15 mg/g in <i>Anemarrhena asphodeloides</i> Bunge	[112]
	2 mg/g in <i>Anemarrhena Rhizoma</i>)	[112]
Mangiferin	31 mg/g in <i>Anemarrhena asphodeloides</i> Bunge	[112]
	16 mg/g in <i>Anemarrhena Rhizoma</i>	[112]
Neomangiferin	16 mg/g in <i>Anemarrhena asphodeloides</i> Bunge	[112]
	8 mg/g in <i>Anemarrhena Rhizoma</i>	[112]

Table 4 (continued)

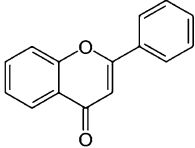
Model polyphenols	Contents in plant species	Refs.
Munjistin	Two major anthraquinones (munjistin and purpurin) representing 90% of the total anthraquinone yield from <i>Rubia cordifolia</i> L.calluses	[113]
Physcion	0.11 mg/g in <i>Frangula rupestris</i> bark (Scop.)	[109]
	8 mg from powdered roots of <i>Rumex nepalensis</i> (2 kg)	[106]
	0.22% (w/w) from shade-dried plant samples of <i>Ventilago madraspatana</i> (500 g)	[111]
Purpurin	Two major anthraquinones (munjistin and purpurin) representing 90% of the total anthraquinone yield from <i>Rubia cordifolia</i> L.calluses	[113]
C. Derivatives of flavonoids		
		
Azaleatin	2×10^{-3} % from <i>Plumbago indica</i>	[114]
Catechin	10.9 (mg/g) catechin from <i>Abies pindrow</i>	[115]
	75 (mg/g) in catechu resin chunks (<i>Acacia catechu</i>)	[116]
	2.67 (mg/g) from <i>Cedrus deodara</i>	[115]
	358 mg from 100 g dry matter in Chardonnay seeds	[117]
	127 mg from 100 g dry matter in Merlot seeds,	[117]
	12 mg from 100 g dry matter in Muscadine seeds	[117]
	the total catechins content in green tea ranges from 9 to 117 mg/g of dry weight of green tea leaves	[118]
	6.15(mg/g) from <i>Pinus gerardiana</i>	[115]
	13.3 (mg/g) from <i>Pinus roxburghii</i>	[115]
	5.78 (mg/g) from <i>Pinus wallichiana</i>	[115]
	12.7 mg isolated from 928 g of the ethanol extract (9% (g/g)) of <i>Polygonum hypoleucum</i> Ohwi	[110]
	21.8 (mg/g) from <i>Taxus fuana</i>	[115]
	3.6 mg/g (dry weight) of red wine wastes from <i>Vitis vinifera</i>	[119]
	56 mg/g (dry weight) of white wine wastes from <i>Vitis vinifera</i>	[119]
	total catechins, including EGCG, ECG, EC and EGC, accounted for 10.1 g/100 g dry longjing tea leaves	[120]
Cedeodarin	3.23 (mg/g) from <i>Cedrus deodara</i>	[115]
Epicatechin	15 (mg/g) in catechu resin chunks (<i>Acacia catechu</i>)	[116]
	421 mg in 100 g dry matter in Chardonnay seeds	[117]
	115 mg in 100 g dry matter in Merlot seeds	[117]
	96 mg in 100 g dry matter of Muscadine seeds	[117]
	3.1 mg/g dry weight of red wine wastes from <i>Vitis Vinifera</i>	[119]
	100 mg/g dry weight of white wine wastes from <i>Vitis Vinifera</i>	[119]
	7.5 mg isolated from 928 g of EP the ethanol extract (9% (g/g)) of <i>Polygonum hypoleucum</i> Ohwi)	[110]
	Epicatechin < 11 mg/g tea	[121]
Epicatechin-3-O-gallate	21 (mg/g) in catechu leaves (<i>Acacia catechu</i>)	[116]
Eriocitrin	14.98% (with a concentration range of 6.6–15.0%) in <i>Mentha × piperita</i>	[73]
Isomangiferin	15 mg/g in <i>Anemarrhena asphodeloides</i> Bunge	[112]
	2 mg/g in <i>Anemarrhena rhizoma</i>	[112]

Table 4 (continued)

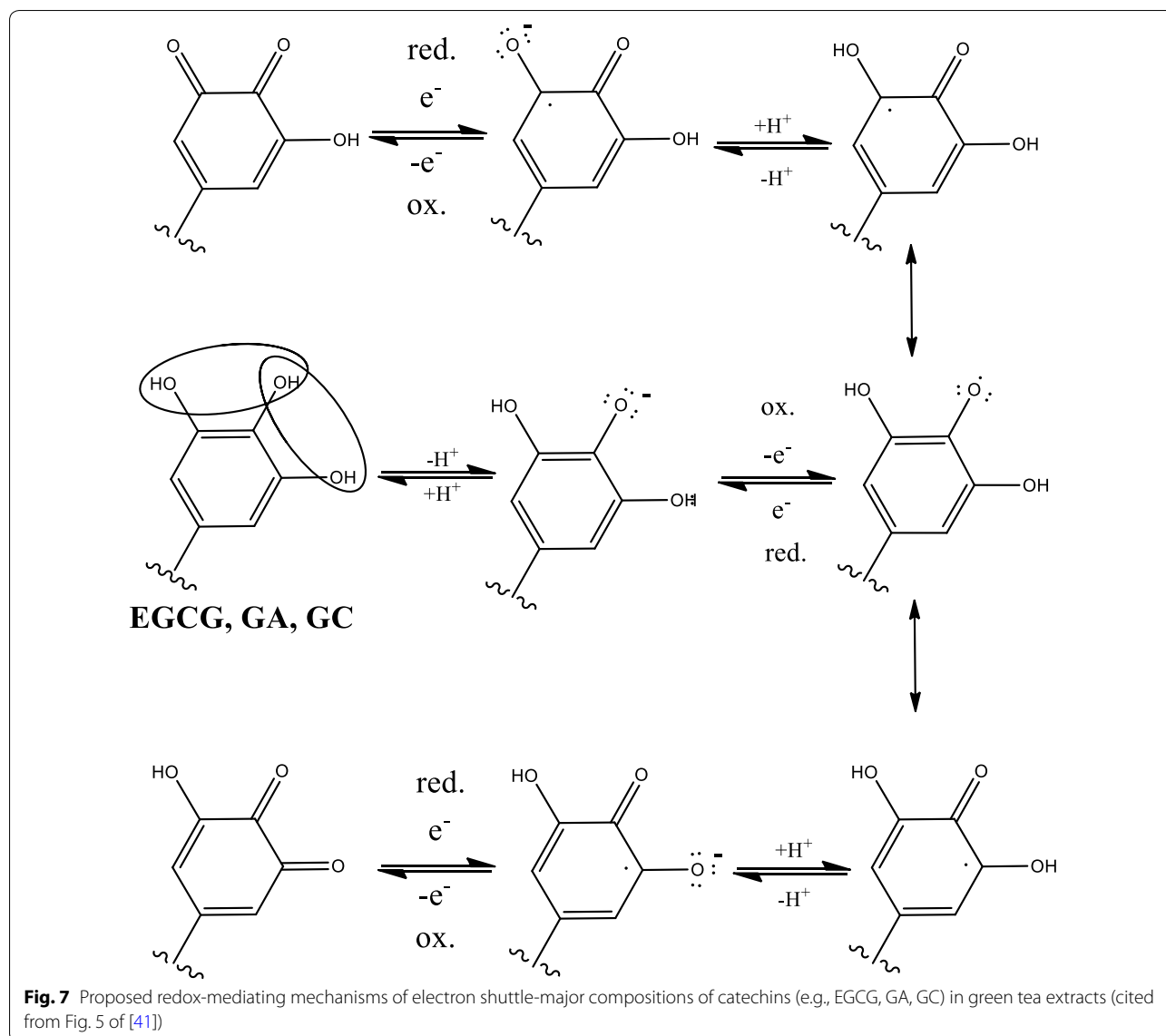
Model polyphenols	Contents in plant species	Refs.
Mangiferin	31 mg/g in <i>Anemarrhena asphodeloides</i> Bunge)	[112]
	16 mg/g in <i>Anemarrhena Rhizoma</i>	[112]
Luteolin-7- <i>O</i> -glucuronide	1650 µg rutin (as luteolin-7- <i>O</i> -glucuronide)/g fresh leaves of <i>Cichorium intybus</i>	[60]
	Quercetin and luteolin glycosides up to 21% and 38% for radicchio di Chioggia and radicchio di Treviso respectively	[60]
Luteolin-7- <i>O</i> -rutinose	0.420% in dry sample of <i>Cynara scolymus</i> L.	[58]
	9.38% in <i>Origanum majorana</i> L.	[56]
	8.61% in <i>Salvia officinalis</i> L.	[56]
	7.65% in <i>Thymus vulgaris</i> L.	[56]
Quercetin	2.32% (dry Weight Basis) in 40 <i>Mentha × piperita</i> Clones	[73]
	9.3 mg from the air-dried and powdered rhizomes of <i>Alpinia officinarum</i> (3.2 kg)	[123]
	Quercetin (1.6 g/8 kg) (0.02%) in <i>Aster tataricus</i>	[107]
	Quercetin and luteolin glycosides up to 21% and 38% for radicchio di Chioggia and radicchio di Treviso, respectively	[60]
Quercetin 3- <i>O</i> -glucuronide	Rutin ~ 190 mg/g) and quercetin ~ 14 mg/g) from <i>Sophora japonica</i> L. buds	[122]
Quercetin 7- <i>O</i> -glucoside	1055 µg as rutin/g in fresh leaves of <i>Cichorium intybus</i>	[60]
Dihydroquercetin (taxifolin)	2.52% in <i>Salvia officinalis</i> L.	[56]
	1.72% in <i>Thymus vulgaris</i> L.	[56]
Theaflavin	5.98 (mg/g) in <i>Cedrus deodara</i>	[115]
	2.65 (mg/g) in <i>Pinus roxburghii</i>	[115]
D. Anthocyanidin	1.58 g/100 g dry leaves of qimen black tea	[124]
Cyanidin	Cyanidin and peonidin glycoside representing 37.1% of total anthocyanins in bilberries, and 17.6% in blueberries	[125]
	Cyanidin and peonidin glycoside representing 37.1% of total anthocyanins in bilberries, and 17.6% in blueberries	[125]
Cyanidin 3- <i>O</i> -glucoside	536 µg keracyanin (as cyanidin 3- <i>O</i> -glucoside)/g in fresh leaves of <i>Cichorium intybus</i>	[60]
	Red grapes, bilberry, blackberry, blueberry, cherry, cranberry, elderberry, hawthorn, loganberry, açai berry and raspberry	[125]
Cyanidin 3- <i>O</i> -(6''malonyl)-glucoside	4790 µg keracyanin (as cyanidin 3- <i>O</i> -(6''malonyl)-glucoside)/g in fresh leaves of <i>Cichorium intybus</i>	[60]
Petunidin (Petunidol; Myrtillidin)	red grapes, bilberry, blackberry, blueberry, cherry, chokeberries, cranberry, elderberry, hawthorn, loganberry, açai berry and raspberry	[125]
E. Tannin; ellagic acid	Strawberries (630 µg/g dry wt), raspberries (1500 µg/g dry wt), blackberries (1500 µg/g dry wt), walnuts (590 µg/g dry wt), pecans (330 µg/g dry wt), cranberries (120 µg/g dry wt)	[126]

(acteoside), respectively. *Salvia officinalis* L. and *Thymus vulgaris* L. contain different redox-mediating compounds. For example, they contain 1.98% and 1.40% caffeic acid, 3.77% and 7.57% carnosic acid, 8.61% and 7.65% luteolin-7-*O*-rutinose, and 2.52% and 1.72% quercetin 7-*O*-glucoside, respectively [56]. In particular, *Salvia officinalis* L. also possesses 1.22% chlorogenic acid and high levels of rosmarinic acid [56]. Moreover, *Salvia miltiorrhiza* contains 24.8% danshensu in its aqueous extracts [65]. Furthermore, 1.9% embelin could be extracted from *Embelia ribes* using hexane [94], and 12.4% shikonin derivatives could be extracted from a

culture of *Lithospermum erythrorhizon* [100]. There are other cases of herbal plants containing hydrophobic (lipophilic) ESs that can be extracted by *n*-hexane. For example, high contents of naphthoquinone derivatives (e.g., 3',3'-biplobagin, droserone, and plumbagin) could be obtained by extracting *Diospyros anisandra* [98] with *n*-hexane. In addition, 1.9% free and 4.5% total anthraquinones could be extracted from *Cassia occidentalis* roots [102], and *Rubia cordifolia* L. calluses produced two major anthraquinone: munjistin and purpurin, having a total anthraquinone yield of ca. 90% [113]. *Anemarrhena asphodeloides* Bunge contains plentiful isomangiferin,

mangiferin, and neomangiferin [112]. Regarding flavonoid derivatives in plants, luteolin, quercetin, and their glycosides are also widely distributed in many plants. In fact, some plants contain very high quantities of flavonoids (e.g., quercetin and luteolin glycosides up to 21% and 38% for radicchio di Chioggia and radicchio di Treviso (both *Cichorium intybus*), respectively [60], and 9.38% luteolin-7-*O*-rutinose in *Origanum majorana* L. [56]). In addition, *Mentha × piperita* [73] contains 14.98% eriocitrin and 2.32% luteolin 7-*O*-rutinoside on a dry weight basis. Moreover, catechin and epicatechin were also widely distributed in many plants, such as tea plants, in high levels [118, 120]. In addition, wine-producing waste of *Vitis vinifera* [119] is also feasible to obtain ESs for MFCs. Similarly, because of the abundance of catechin and epicatechin, *Camellia* green tea could also have high antioxidant contents [127]. In addition, anthocyanidins (e.g., cyanidin and peonidin and their glycosides) are often present in red grapes, bilberries, blackberries, blueberries, cherries, cranberries, elderberries, hawberries, loganberries, açai berries, and raspberries. A relatively high percentage of total anthocyanins are found in bilberries (37.1%) compared to that of blueberries (17.6%) [125]. Further, ellagic acid is often found in nuts, berries, pears, peaches, plums, grapes, apples, and kiwi [126]. Thus, these polyphenolics-rich plants contain many electroactive chemical species that could serve as natural sources of electrochemically active species for biofuel applications. For example, the addition of ca. 2.5 g dry weight L⁻¹ *Camellia* green tea extract as an ES considerably enhances power generation in MFCs [41, 45]. In fact, the bioelectricity-generating performance of supplemented MFCs has been increased by 143–167% compared to a supplement-free MFC (from 11.40–12.56 to 30.51 mW/m² for *Camellia* green tea extract supplementation [127]). This increase in bioelectricity generation is promising for bioelectrochemical biofuel utilization. For example, the serial brewing of *Camellia* tea extracts at different degrees of fermentation (e.g., green, oolong, and black tea) by a comparative assessment of the DPPH free radical-scavenging activities showed the outstanding benefit of using *Camellia* tea waste for cost-effective bioenergy applications [127]. As Chen et al. revealed [41], for many different types of *Camellia* tea extracts, the antioxidant activity, total polyphenolics contents (e.g., EGCG, GA, and GC), and ES capabilities are strongly interrelated. As a matter of fact, *Camellia* tea has been shown to have an effect on human health, especially concerning to age-related deterioration of the brain [128]. Thus, *Camellia* tea extracts are promising for enhancing bioenergy generation over several cycles, and 47% and 45% activity remained after 5 and 4 cycles when using unfermented *Camellia* green tea and partially fermented

oolong tea, respectively [127]. In contrast, because black tea (e.g., Pu'er tea) is a completely fermented tea, its DPPH free radical-scavenging activity is significantly lower, <10% after three cycles of tea brewing. Thus, *Camellia* green tea extract is the most bioelectrochemically favorable ES extract for bioenergy applications. As mentioned, extracts of these polyphenolics-rich plants can act as either antioxidants or ESs under appropriate conditions. For instance, catechins (i.e., the main components of *Camellia* tea extracts) can be either antioxidants (i.e., oxidation peak dominant) or ESs (i.e., nearly symmetric oxidation and reduction potentials), as shown in the CV profiles of some catechins [42] and various *Camellia* tea extracts [45]. Because of the condition dependence of the ES and antioxidant behavior of catechins (e.g., EGCG, GA, and GC), both the electron-mediating mechanism of an ES (e.g., Fig. 7 obtained from [41]) and that of an antioxidant [129] are feasible. For example, catechin has been shown to act as an ES at pH > 8 and an antioxidant at pH < 6 [41]. In addition, Xu et al. [130] reported that the power density of an MFC was considerably enhanced by the addition of extracts of the anthocyanin abundant *Lycium ruthenicum* Murr. As shown by the ES mechanism (Figs. 2, 3), ES or antioxidant behavior is dependent on the ability to form stable phenolic radicals. Thus, the environmental conditions are crucial in determining whether an ES or antioxidant undergoes stable redox reactions. Moreover, a recent literature [131] revealed that the interactions of bacterial consortia in the hot springs of the Yellowstone National Park resulted in the synergistic evolution of a microbial community under hostile conditions (e.g., sulfur-containing hot springs), resulting in the ability to utilize formaldehyde as an ES. Consequently, control of the biotic or abiotic environment can convert an ES to an antioxidant and vice versa. Although some criteria of obtaining an electrochemically favorable environment for ES activity have been reported [7], the understanding of the change between ES and antioxidant behavior still remains limited. It has been proposed that the environmental conditions for the conversion of an ES to an antioxidant are strongly dependent on the redox reversibility of the derived intermediate radical species. However, the typical characteristics of antioxidants can be easily expressed because antioxidants can be gradually oxidized, leading to progressive attenuation in CV profiles, as discussed earlier. Thus, some polyphenolic compounds could function as reversible ESs under specific controlled abiotic or biotic conditions. Considering the practicality of using plant polyphenolics, natural polyphenolics are usually less biotoxic to receptor microbes and show higher electrochemical activities as ESs to stimulate the bioelectricity generation of electrochemically active microorganisms. For example, 3 to 5



times serially brewed extracts of *Camellia* green tea still exhibited significant antioxidant activity [127] because of its abundant antioxidant chemical species with low biotoxicity. This indicates that, with toxicity attenuation, even waste medicinal herbs have sufficient potential reuse in practical and sustainable bioenergy applications. Although the environmental conditions required for reversible ES characteristics are not always satisfied [7, 15], these natural polyphenolic compounds can function as antioxidants (i.e., reductants) for non-sustainable use (e.g., the enhancement of the rates and efficiencies of redox reactions in reductive biodegradation and bioelectricity generation). However, for the environmentally friendly and sustainable use of polyphenolic compounds, the electrochemical activities of ESs are still favorable if

such polyphenolics have the capability to switch roles between antioxidant and ES (e.g., *ortho* or *para* dihydroxyl-bearing aromatic compounds).

Feasible ES flavonoids

Many natural polyphenolics, in particular the flavonoids in edible flora, are ubiquitous, relatively inexpensive, highly biocompatible, and generated in large quantities. Thus, under appropriate conditions (e.g., alkaline pH), these compounds could be highly environmentally friendly ESs for sustainable applications. The skeleton of flavonoids contains three six-membered rings (i.e., A, B and C rings; Fig. 6). As mentioned above, dihydroxyl groups are located at different positions in different rings, the antioxidant and ES capabilities vary

significantly, because of synergistic effects or noncooperative structural effects, *ortho*-dihydroxy compounds, such as flavonoids, show different reactivities when the functional groups are arranged on different rings (i.e., the A, B, or C rings in Fig. 6), as reported by Lemanska et al. [36]. Moreover, 6,7-dihydroxy and 7,8-dihydroxy substitution on the A ring results in much stronger antioxidant capabilities than 3',4'-dihydroxy substitution on the B ring. In addition, as Makhotkina and Kilmartin reported the strong oxidation potential of a catechin having 5,7-dihydroxyl groups on the A ring at ca. 850 mV, whereas reversible redox peaks corresponding to the *ortho*-dihydroxy groups on the B ring were observed at about 380 and 400 mV [12]. Firuzi et al. [37] also revealed that redox peaks on CV profiles of taxifolin, rutin, catechin, baicalein, quercetin, fisetin, and myricetin with redox peaks corresponding to the *ortho*-dihydroxy groups on the B rings appearing at ca. 300–460 mV in the CV profile. These results suggest that 3',4'-dihydroxy groups on the B ring result in reversible redox behavior. Therefore, flavonoids with *ortho*-dihydroxy groups on the B ring are potential electrochemically favorable ESs. Obviously, the chemical compounds bearing at least one *ortho*-dihydroxy group on the benzene ring could be ESs. Some common flavonoids with *ortho*-dihydroxy or *para*-dihydroxy groups that are potential ESs are listed in Table 5 [56, 132–136]. In addition, glycosides or oligomeric flavonoids could also be used as ESs under the appropriate conditions to trigger ES activity [7, 15]. In particular, by changing the operating variables to convert non-sustainable antioxidants to renewable ES catalysts for sustainable applications, the productivities of bioenergy processes (e.g., electro-fermentation, biorefining, and bioremediation) can be maximized, especially if the structural criteria for ESs are satisfied.

Methods to extract ESs from natural bioresources

One crucial question is how to effectively extract electroactive natural polyphenolics from their source. The extraction method and parameters (e.g., temperature) affect the compounds obtained (e.g., relative ratios of antioxidants and ESs) [45]. For instance, among the various tea extracts, aqueous extracts are more electroactive than ethanol extracts for bioenergy applications (Fig. 8) [43], possibly because of the more favorable ES extraction. This is shown by a comparison of the enhancement in the power generated (units: mW/m²) when using different tea extracts in MFCs: *Camellia sinensis* (L.) Kuntze (green tea) (30.51) > Oolong tea (21.10) > *Camellia boreali-yunnanica* (17.31) > *Camellia assamica* (Mast.) Chang (16.28) > blank (11.40). In contrast, the use of ethanol extracts resulted in the

following ranking: *Camellia sinensis* (L.) Kuntze (green tea) (22.91) > Oolong tea (17.88) > *Camellia boreali-yunnanica* (Dianhong) (15.77) \approx *Camellia assamica* (Mast.) Chang (Pu'er) (15.24) > blank (11.40) [43]. This comparison clearly shows that the use of different solvents extracts distinct electrochemically functioning species in different amounts from *Camellia* tea leaves. Thus, appropriate solvent selection for the extraction of electroactive ESs and electrochemical components is of course crucial. Furthermore, if the selected solvent is “generally recognized as safe” (e.g., water or ethanol), the harvested herbal extracts should be more biocompatible, inevitably increasing their potential range of applications. Regarding the condition-dependent electroactive characteristics (i.e., antioxidant or ES behavior), aqueous extracts of *Camellia* green tea seems to be more electrochemically promising for ES function than ethanol extracts [45], although some reports [137] have mentioned that 100% ethanol extraction resulted in the most abundant antioxidant polyphenolic content. That is, water extraction might be feasible to effectively harvest the most abundant ES polyphenolics in *Camellia* green tea. That is, an optimal temperature to extract maximal amounts and the most electrochemically functioning ES compounds could be expected for herbal extracts. However, the use of an excessively high temperature may decompose such electroactive compounds, leading to a significant attenuation in the electrochemical activities. For example, as Chen et al. [45] indicated, the optimal temperature to extract the maximum electrochemically active components from *Syzygium aromaticum* and *Camellia* green tea was ca. 65 °C, and temperatures higher than 65 °C hampered the extraction of electroactive compounds, possibly because of thermal decomposition.

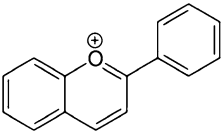
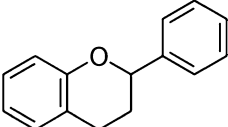
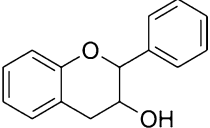
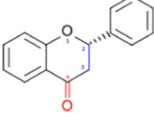
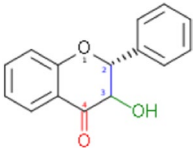
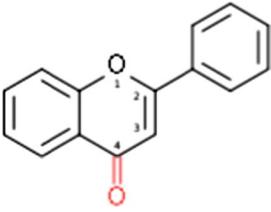
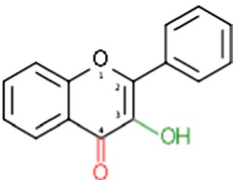
Environmental conditions to convert natural polyphenolic compounds to ESs

Regarding the convertible nature or natural polyphenolics, several factors influence the conversion of natural polyphenolics to ESs within living organisms: (1) range of reduction potentials, (2) pH, (3) water solubility, (4) biotoxicity to electrochemically active bacteria, and (5) possible biodegradability to utilize carbon as an energy source.

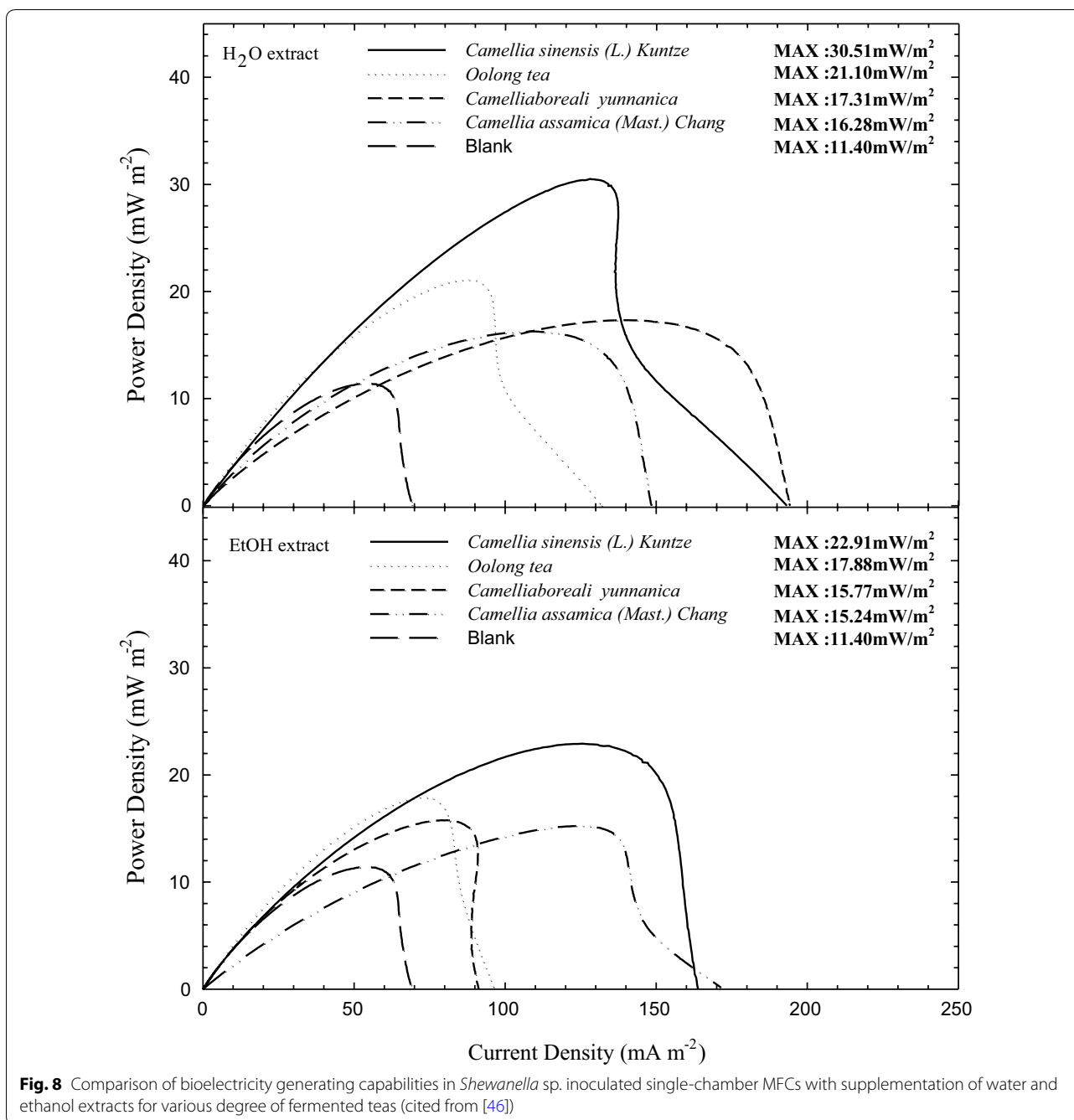
Potential of polyphenolic compounds as ESs for MFCs

Crucially, the redox potentials of these compounds are between those of the electron donor (ED) and electron acceptor (EA) (e.g., $E_{ES}^0 = \frac{1}{2}(E_{ED}^0 + E_{EA}^0)$), making these ESs electrochemically favorable for mediating electron transfer. To mediate electron transfer between electron donors and acceptors, the reduction potentials (E_{ES}) of the candidate ES should be lower than the potential (E_{EA})

Table 5 Comparative list of typical feasible ES-behaved flavonoids

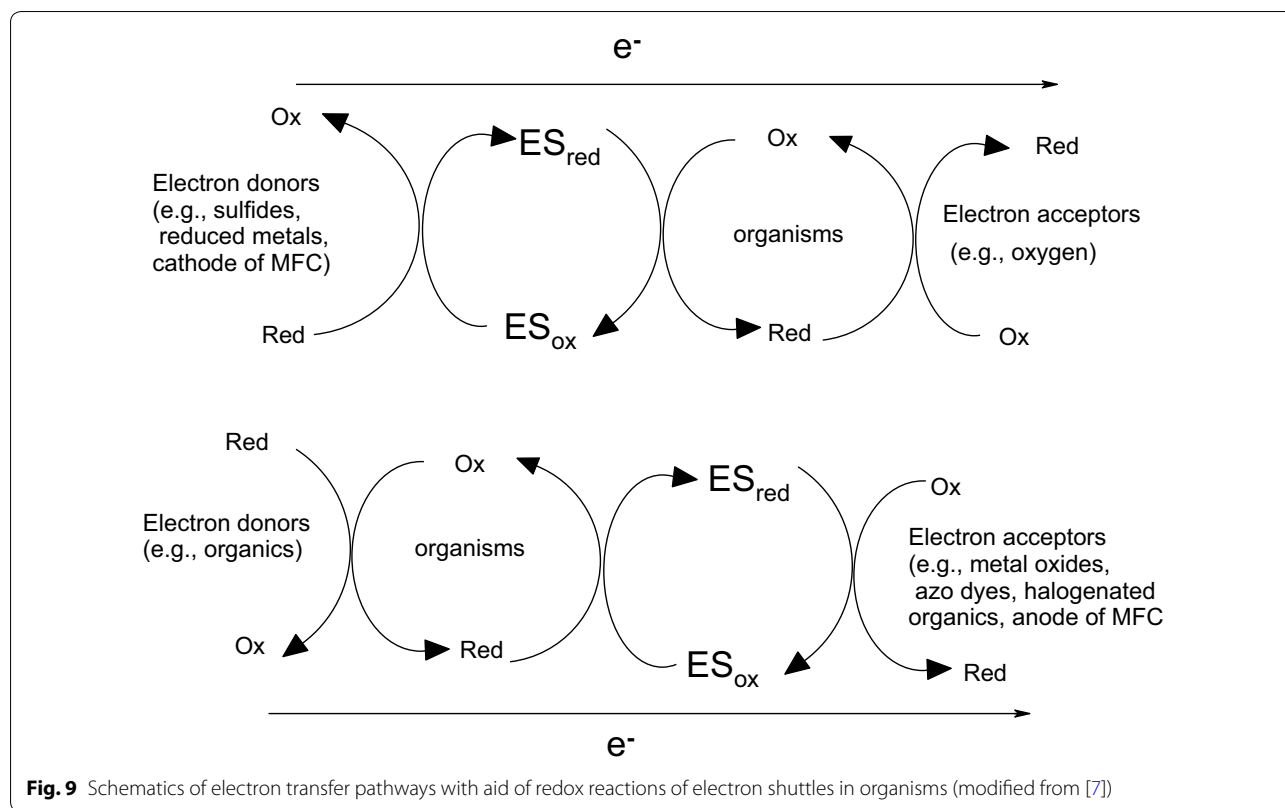
Classify	Feasible ES-behaved flavonoids
Anthocyanidins 	Arrabidin ^e , 3'-hydroxyarrabidin ^e , carajurin ^e , cyanidin ^b , 5-methylcyanidin ^e , cyanidin-3-O-glucoside (chrysanthemins), cyanidin-3-O-rutinoside, cyanidin-3-O-malonylglucoside, cyanidin-3-O-galactoside-5-O-glucoside, cyanin ^b , europinidin ^e , kuromanin ^b , petunidin ^e , petunidin-3-glucoside, riccionidin A ^e
Flavans 	Butiniflavan ^d , luteoliflavan ^d
Flavanol (flavan-3,4-diols) 	Catechin ^b , epicatechin ^b , epicatechin gallate ^b , epicatechin-5- or -7-O-xylofuranoside ^c , epigallocatechin gallate ^b , fisetinidol ^c , epifisetinidol ^c , mesquitol ^d , gleditsin (fisetinidol-4β-ol) ^c , theaflavin, 4β-carboxymethylepicatechin (dryopteris acid) ^d
Flavanones 	Carthamidin ^a , carthamidin-7-O-D-glucuronide ^a , dihydrobaicalin ^a , dihydronorwogonin ^a , dihydroreherianin I ^a , eriodictyol ^b , isocarthamidin-7-O-D-glucuronide ^a , naringenin ^b ,
Flavanonols 	3,6,7,2',6'-pentahydroxyflavanone ^a , taxifolin (dihydroquercetin) ^b
Flavone 	Amentoflavone ^a , baicalin ^a , baicalein-7-O-D-glucopyranside ^a , baicalein-7-O-L-rhamnoside ^a , cirsilineol ^a , 5,6-dihydroxy-7-O-glucosideflavone ^a , 5,8-dihydroxy-6,7-dimethoxyflavone ^a , ganhuangenin ^a , 6-hydroxyflavone ^a , ikonnikoside I ^a , luteolin ^b , orientin ^b , norwogonin ^a , norwogonin-7-O-D-glucuronopyranside ^a , scutellaprostin C ^a , scutellaprostin F ^a , scutellarin ^a , scutellarein-7-O-D-glucopyranside ^a , 5,6,2',6'-tetrahydroxy-7,8-dimethoxyflavone ^a , (2S)5,7,3',4'-tetrahydroxyflavone (eriodictyol) ^a , 5,6,2'-trihydroxy-7,8-dimethoxyflavone ^a , 5,8,2'-trihydroxy-7-methoxyflavone ^a , 5,8,2'-trihydroxy-7-O-D-glucopyranside ^a , 5,8,2'-trihydroxy-6,7-dimethoxyflavone ^a , 5,6,2'-trihydroxy-7,8,6'-trimethoxyflavone ^a , 5,7,2',3'-tetrahydroxyflavone ^a
Flavonol 	Fisetin ^b , isorhamnetin ^b , quercetin ^b , quercetin 3-O-glucuronide (miquelianin), quercetin-7-O-glucoside, quercetin-3-O-malonylglucoside, rutin ^b , quercetrin ^b , rhamnetin ^b , Quercetin-7-o-glucoside ^f ,
Proanthocyanidin or dimeric flavonoids ^c	Probutinidin ^d , procyanidins B1-B4 ^d , profisetinidins ^c ,
Others or glycosides or esters, or oligomeric flavonoids ^d	Epimopan ^e , mopanin ^c , mopanol ^c , peltogynin ^c , peltogynol ^c , trimeric profisetinidins ^c

^a [131], ^b [132], ^c [133], ^d [134], ^e [135], ^f [56]



of the oxidant (EA) and higher than the potential (E_{ED}) of the reductants (ED). That is, if $\Delta E = E_{EA} - E_{ES} > 0$, it is electrochemically favorable for the reduced form of the ES to reduce the oxidant (EA). Similarly, if $\Delta E = E_{ES} - E_{ED} > 0$ [7, 16, 50], the reductant (ED) will reduce the oxidized ES (Fig. 9; [7]). If the oxidized electron shuttle (ES_{ox}) is considered to be reduced by biological reduction systems, then the standard reduction potential (E_{ES}) of the ES should not be lower than that of

the biological reduction system (Table 3). That is, ES_{ox} can be reduced by the biological systems. Because of this specific reductive potential, an ES can electrochemically function only under appropriate environmental conditions. Polyphenolic compounds are usually weakly acidic compounds, so the reduction potential can be affected by the concentration and pH, as indicated by the Nernst equation. For example, quinone (Q) + 2H⁺ + 2e⁻ → hydroquinone (H₂Q), and the reduction potential

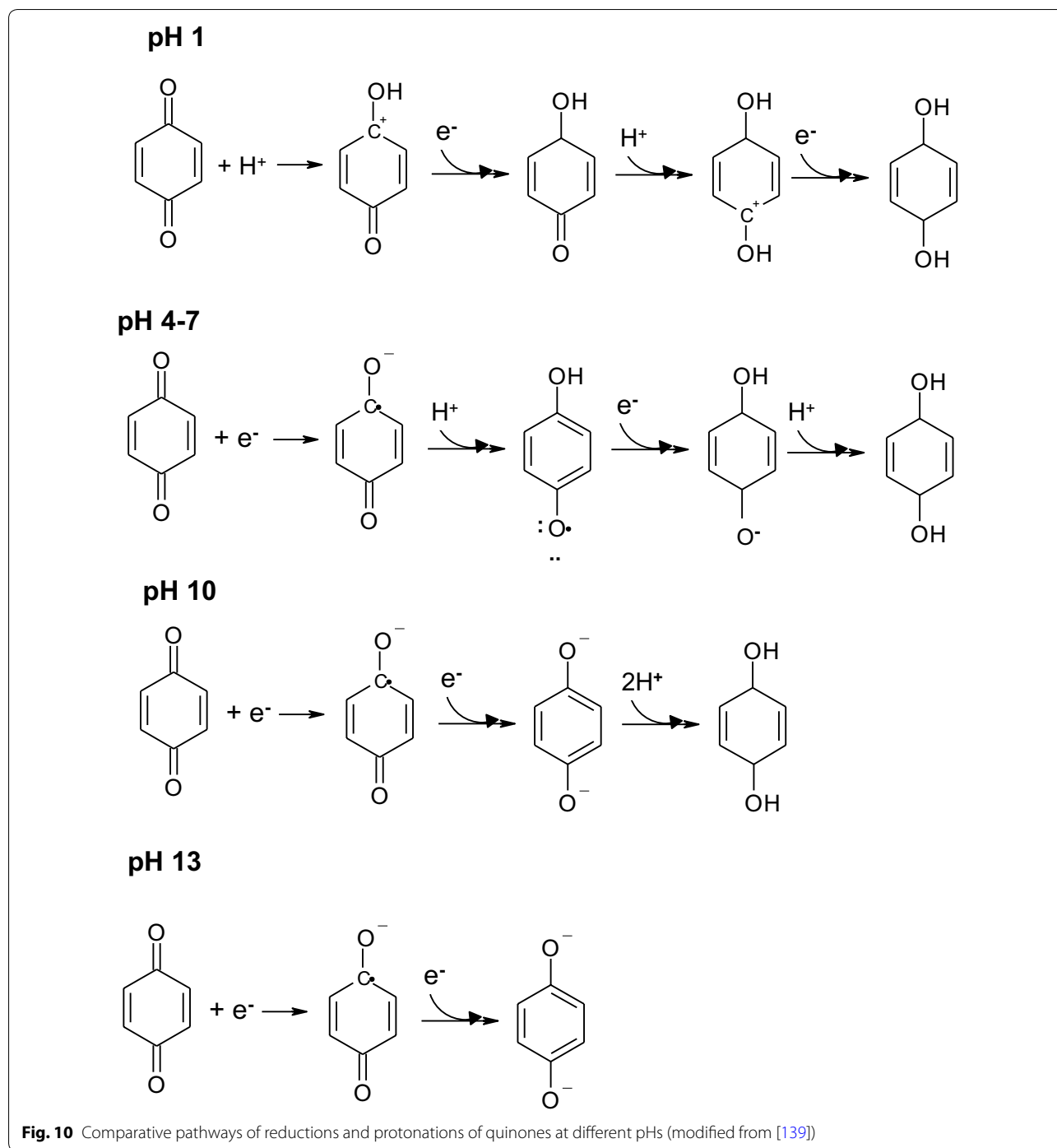


$(E = E^0 - \frac{RT}{2F} \ln \left(\frac{[H_2Q]}{[Q][H^+]^2} \right))$ of quinones varies with the concentration of chemical species and pH [138]. Similarly, the oxidation potential, as shown by the Nernst equation, is also affected by the chemical and proton concentrations. As a matter of fact, the first E_{pa1} (measured by cyclic voltammetry and listed in Table 2 of [133]) of some polyphenolic compounds ranged from 0.30 to 0.72 V at pH 3.6–4.0 [133], whereas the first E_{pa1} of other polyphenolic compounds ranged from 0.087 to 0.236 V at concentrations of 0.01–0.05 mM and nearly neutral pH [42]. Thus, the redox potentials of these polyphenolics could be adjusted by varying the proton and chemical concentrations to achieve the correct electrochemical activity over the threshold for bioenergy stimulation before use in MFCs. With appropriate supplementation of chemical species, the electrochemical activities of polyphenolic compounds could be significantly promoted for efficient bioenergy extraction (e.g., increased the electrochemical content and conversion of antioxidants to ESS).

Effect of pH on the redox potentials of polyphenolic compounds

As discussed, the redox potentials of polyphenolic compounds are strongly influenced by the pH and

concentrations of chemical species. For example, alternative redox reactions can also occur at different pH values, as shown in Fig. 10 (modified from [139]). For an example of a pH-dependent electrochemical reaction, at highly acidic pH (e.g., pH 1.0), quinones are first protonated and then reduced, as reported by Wedege et al. [139]. In contrast, at slightly acidic or neutral pHs (e.g., pH 4.0–7.0), quinones are reduced first and then protonated, and repeated reduction and protonation can occur sequentially. At alkaline pH (e.g., pH = 10), quinones are reduced twice in sequence of deprotonation, resulting in different electrochemical characteristics. Thus, pH is a feasible control variable affecting the conversion of antioxidant to ES “catalysts” in bioenergy applications. As revealed by the Nernst equation, the pH-dependent reduction potentials of some polyphenolic compounds (e.g., caffeic acid, catechin, and chlorogenic acid) are slightly decreased as the pH increases from 7.0 to 10.0 [140]. Moreover, as observed in their CV profiles, the E_{pa} and E_{pc} values of catechin, chlorogenic acid, epicatechin, epigallocatechin gallate, and gallic acid can shift toward lower values as the pH increases from 5.0 to 6.0 [141] according to Le Chatelier’s principle and the Nernst equation. It has also been reported that the reduction potentials of some polyphenolics (i.e., luteolin and catechol) linearly decrease with increasing pH [142, 143].



In addition, Chen et al. [45] studied extracts of *Camellia sinensis* (L.) Kuntze (green tea) and *Syzygium aromaticum* at a slightly alkaline pH (approximately 10) and found that this pH is more appropriate to augment bioenergy expression. That is, the appropriate manipulation of the pH and ES concentrations can result in polyphenolic compounds with electrochemically favorable redox

potentials and low biotoxicities for renewable bioenergy extraction in bioelectrochemical reactors (e.g., MFCs).

Solubilities of polyphenolic compounds as ESs in MFCs

Because MFCs are usually operated in an aqueous phases, ESs should be highly water soluble to attenuate the electron transfer resistance. Thus, slightly water-soluble anthraquinones (e.g., water solubility < 1 g/L

at 23 °C) can be sulfonated to be anthraquinone-2-sulfonates (AQS) or anthraquinone-2-sulfonic acids to increase the water solubility. In fact, these modifications increase the water solubility; they can remarkably decrease the mass transfer resistance to enhance electron transport efficiency in wastewater bioremediation and bioelectricity generation in MFCs [25, 144, 145]. Furthermore, these modified ESs could be biotoxic and environmentally unfriendly. However, because natural polyphenolic and flavonoid ESs with low toxicity are often weakly acidic, they can be dissolved easily in alkaline aqueous solution or with initial addition of small volume of ethanol. Moreover, monosaccharides can be bound to polyphenolics or flavonoids to form glycosides, significantly increasing their water solubilities [146].

Toxicity of polyphenolic compounds in MFCs

Although polyphenol and flavonoid-containing herbal extracts (e.g., *Camellia* green tea) usually have low biotoxicity, a few natural polyphenols and flavonoids may be still toxic. Thus, any antibacterial characteristics must be attenuated prior to bioenergy applications. In fact, the antibacterial activity of these compounds is often the reason to be considered for uses in medicine. For example, of the compounds extracted from *Scutellaria baicalensis*, the biotoxicities of baicaleins were higher than those of baicalins; thus, baicaleins are not suitable for direct applications to MFCs [43]. In addition, the toxicity of aqueous *Camellia* tea extracts to microorganisms is possibly lower than that of methanol extracts, even if the methanol is completely removed via freeze-drying (i.e., lyophilization), resulting in a high-quality tea extract (data not shown). In fact, the biotoxicity of *Camellia* or medicinal herbs (e.g., *Lonicera japonica*, *Citrus reticulata*, and *Scutellaria baicalensis*) extracts can be declined by electrochemical treatment (e.g., serial CV scans); thus, the power-generating capabilities of MFCs could be increased by the use of processed or CV-treated herbal extracts [45].

Biodegradability and use as possible energy sources in MFCs

Regarding natural polyphenolic compounds, for example, the main components of *Camellia* green tea (EGCG, ECG, GA, and GC) could act as nutrient sources for microorganisms, as well as ESs and antioxidants, indicating that it is not only the ES activity that stimulates bioelectricity generation in MFCs [41, 45]. However, the conversion efficiency of nutrient source to be electrochemical catalyst for energy generation is not known, and further research is still required.

Overall performance assessment

In summary, some suggestions of significance are provided for further exploration of natural ESs for renewable bioenergy utilization. As Chen et al. [45] reported, although *Camellia* green tea extract contains 10-times the total polyphenolic contents of other promising electroactive edible flora and medicinal herbs, only a three-fold increase in power density is achieved when *Camellia* extracts are used in MFCs. That is, the maximal increase in bioenergy extraction is only ca. 30%. Detailed studies to enhance bioenergy mining and conversion are inevitably required from an engineering perspective. (a) The biotoxicity potency: medicinal herb extracts could have biotoxic/inhibitory effects upon bioreceptors (e.g., electroactive bacteria), thereby repressing the bioelectricity-generating performance of MFCs. (b) Electron transport limitation: the efficiency of bioelectricity generation is affected not only by the characteristics and concentrations of electroactive bacteria but also by the electrode characteristics and other factors affecting mass transfer (e.g., liquid–solid interface electron transport resistance) (c) Antioxidant/redox mediator conversion: The repeated CV responses revealed that the electroactive components of herbal extracts are gradually attenuated, indicating that these compounds are antioxidants rather than ES and revealing the relatively low ES contents of herbal plants. (d) CV and MFC conditions: Cyclic voltammetry is an abiotic redox process, but these redox reactions may not be directly related to the metabolic functions of bacteria. That is, the bioelectricity generating characteristics of MFCs may place a metabolic burden on electroactive bacteria, limiting MFC performance. (e) Inconsistency of redox activity: due to the different components in herbal extracts, there is a lack in consistency in the redox potentials required for effective, reversible electrochemical activity. The unbalanced electrochemical characteristics of the existing antioxidant species reflect irreversible redox characteristics, i.e., free radical scavenging as functioning reductants, and the reversible electron transfer activities of ES species may be not fully expressed or may be even masked. (f) Biodegradation: Some compounds may be consumed by the bacteria as nutrients rather than used as ESs, resulting in lower power generation performance than anticipated. Furthermore, if the electrochemical conditions are appropriate, ESs could behave as antioxidants. However, many antioxidants might not be capable of becoming ES species because of inadequate (electro)-chemical reactivity or orientation for such redox-mediating behavior. These all state that antioxidant and ES polyphenolics may be present; however, specific environmental conditions to maximize their bioenergy extracting efficiency still require further exploration.

Conclusion

Under electrochemically suitable conditions, *ortho*- or *para*-dihydroxy-bearing polyphenolics are potential electroactive ESs for increasing the electron transfer rates of pollutant biodegradation and bioelectricity generation in MFCs. In particular, plant polyphenolics are abundant renewable bioresource for bioenergy applications. Because polyhydroxy flavonoids are ubiquitous, highly diverse, relatively nontoxic, and biocompatible, they are ecologically promising ESs for bioenergy technology. Because of the weakly acidic nature of polyphenolics, electrochemical manipulations can control the relative contents of chemical species or pH levels of polyphenolics, altering the redox potentials of polyphenolics for bioenergy generation or pollutant biodegradation. In addition, water solubility (i.e., a basic criterion to decrease electron transfer resistance in aqueous media for organisms and MFCs) can be increased at slightly alkaline pH conditions. These points provide a guide to create environmentally friendly and renewable bioenergy extraction processes.

Abbreviations

2-AP: 2-aminophenol; 4-AP: 4-aminophenol; AQS: anthraquinone-2-sulfonates; CV: cyclic voltammetry; EA: electron acceptor (i.e., oxidant); ED: electron donor (i.e., reductant); ES: electron shuttle; ESox: oxidized ES; E_{ES}^0 : standard reduction potential of ES; E_{ES}^- : reduction potential of ES; E_{EA}^0 : standard reduction potential of EA; E_{EA}^- : reduction potential of EA; E_{ED}^0 : standard reduction potential of ED; E_{ED}^- : reduction potential of ED; E_{pa} : anodic (oxidative) potential; E_{pc} : cathodic (reductive) potential; ECG: epicatechin gallate; EGCG: epigallocatechin gallate; GA: gallic acid; H₂Q: catechol or hydroquinone; Q: quinone; MFC: microbial fuel cell; RM: redox mediator.

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Research involving human participants and/or animals

The authors declare that this research does not involve human participants and animals.

Authors' contributions

CCH completed the preparation of major content in the manuscript. CCW participated in collecting herbal details of this work. As the corresponding author, BYC revised and improved the content regarding significance of the antioxidants and electron shuttles and finally submitted the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors consented to the publication of the work.

Competing interests

The authors declare that they have no competing interests.

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