APPLIED PHYCOLOGY
2025, VOL. 6, NO. 1, 9–20
https://doi.org/10.1080/26388081.2024.2434476

Algal biomusic generation

Joshua M. Lawrence[a], Emma Albertini[b], Alberto Scarampi[c,d], Paolo Bombelli[d], Lucia B. Giron[d], Lena Kuzmich[e] and Christopher J. Howe[d]

[a]Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge, UK; [b]Department of Physics, Imperial College London, London, UK; [c]School of Life Sciences, University of Warwick, Coventry, UK; [d]Department of Biochemistry, University of Cambridge, Cambridge, UK; [e]Hybrid Forms Lab, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

ABSTRACT
Technologies which can generate music with limited human intervention are a longstanding area of investigation for musicians and musicologists, with particular interest in how these technologies can be harnessed for ecocentric forms of musical expression. To date, most of these efforts have focused on the use of computational algorithms to compose music. Biomusic – music created using biological data – provides an alternative paradigm for the creation of non-human music which can be truly ecocentric. Photosynthetic organisms in particular offer the ability to create music which responds to changes in their environment, such as changes in light conditions and temperature. Herein, we propose how the ubiquitous bioelectrical activities of algae (which are correlated with their photosynthetic activity) can be utilized for biomusic generation. In addition to describing the scientific principles underpinning these algal biomusic systems, we also provide tutorial descriptions of the bioelectrochemical devices and signal processing pipelines which can be used to engineer them. In addition, we provide an overview of the many musical applications that can be accessed with this technology, highlighting a few pioneering examples of algal biomusic generation.

ARTICLE HISTORY
Received 16 August 2024
Accepted 18 November 2024

KEYWORDS
Algae; bioelectricity; biophotovoltaic; biomusic; sonification; electronic music; biodesign; bioart

Introduction

Technological advancements in electronics and computing have revolutionized music, including creating new and modifying existing forms of musical composition, production, and performance. Despite the ever-increasing use of digital technologies, the creation of music remains largely guided by human-defined inputs (Collins et al., 2010). As such, many have proposed that music is inherently anthropocentric (Allen & Dawe, 2017; Allen & Titon, 2019), with musicians seeking to identify new methods of 'Musicking' (Small, 1999) which are less reliant on human direction. The musical methods employed for this, such as the use of field recordings and noise, have long histories of use in experimental, classical, and popular music; with their use being espoused by Luigi Russolo, not long after the advent of recorded music (Russolo, 1986). Some musicians have embraced algorithmic composition to introduce separation between themselves and *their* music (Collins et al., 2010; McLean & Dean, 2018). Various forms of music composition algorithms have been developed, including ones using mathematical (McAlpine et al., 1999), evolutionary (Horowitz, 1994), and machine learning models (Sturm et al., 2016). However, these algorithms still retain an anthropocentric bias due to their use of artificial models or (especially for machine learning models) large datasets of human-made music.

Biomusic is a loose term used to describe music composed or modulated using biological inputs. Whilst the term has been used to describe environmental field recordings, it is more closely aligned with the conversion of biological signals into sound (Eaton, 1974). This establishes biomusic as a form of sonification, which is the conversion of data into an auditory form for human perception (Hermann et al., 2011). Historically, biomusic has largely been applied to biological phenomena from the human body, including neuronal signals (Knapp & Lusted, 1990) or human microbiome datasets (Larsen et al., 2013). These types of biomusic have been explored for their potential to enhance closeness between individuals (Chou-Ren et al., 2023), or as a form of musical therapy for individuals with learning disabilities or autism spectrum disorder

CONTACT Joshua M. Lawrence jml203@cam.ac.uk; Emma Albertini emma.albertini17@imperial.ac.uk; Alberto Scarampi as2945@cam.ac.uk; Christopher J. Howe ch26@cam.ac.uk
Supplemental data for this article can be accessed online at https://doi.org/10.1080/26388081.2024.2434476

(Grond et al., 2022). In recent years, there has been a growing interest in environmental biomusic created with non-human species, especially with plants and mushrooms (Dogane & Fujieda, 1994; Leudar, 2018; Matmos, 1997; Miranda et al., 2011; Nishida & Jo, 2020; Wai & Chao, 2023). This non-human (alternatively referred to as 'more-than-human' (Dixon, 2009)) music can be framed within a wider paradigm shift towards eco-art and bioart, ecocentric forms of expression which are in no doubt driven by the ever-growing climate crisis (Weintraub, 2012). This 'environmental biomusic' is not only an interesting artistic endeavour but can be leveraged to educate and communicate biological or ecological concepts to listeners (Larsen et al., 2013; Zanella et al., 2022). It can also be used to create environmental music which reflects rather than merely emulates a specific environment.

Environmental biomusic can be made from biological datasets (Larsen et al., 2013), or by directly processing biological signals (Eaton, 1974). The latter example is perhaps the most exciting, enabling the creation of systems which can continuously produce music with minimal human intervention. However, as highlighted in the previous research (Leudar, 2018), this requires accurate recordings of biological data in a computer-readable format. Due to these requirements, bioelectrical measurements have commonly been used because they can be easily interfaced with electronic musical equipment (Leudar, 2018; Miranda et al., 2011; Nishida & Jo, 2020). Examples of these bioelectrical musical systems include large 3D sound installations within a botanical garden (Leudar, 2018) and commercially available patches for modular synthesizers (Instruo Limited, 2017). However, the bioelectrical signals which have been used for biomusic generation often do not reflect biological processes within the organism(s) being used. For example, music created with plants and mushrooms utilizes the ability of their tissues to conduct electrical currents, although this conduction is largely dependent on water content and is observed in non-living materials, both biotic and abiotic in origin (Duursma et al., 2019; Miller & Cox, 2024; Tripaldi, 2022). Therefore, the music generated only superficially resembles the biological state of the organism and is largely insensitive to environmental conditions. Alternatively, biomusic has been created using microbial fuel cells, which utilize the ability of certain microorganisms to generate electrical currents (Castellanos et al., 2020). Whilst this electricity generation activity is altered by environmental conditions, the oftentimes heterotrophic organisms used in microbial fuel cells require a high-energy carbon source to drive electricity generation (Wey et al., 2019). This makes the use of microbial fuel cells in biomusic generation unsustainable and reliant on regular human intervention.

Herein, we propose an alternative avenue for biomusic generation, utilizing bioelectricity produced by algae. These systems promise a sustainable generation of biomusic which is shaped by the environment it is operated within. We provide an overview of the design and operations of bioelectrochemical devices and musical systems which are suitable for this task, including detailing the various signal processing methods which can be used to convert biological signals into music. Finally, we describe how this algal biomusic could be used for different forms of recorded and live music, highlighting some early examples of this technology. We have successfully used algal-based biomusical systems in public outreach events, generating a great deal of interest.

Harnessing photosynthetic bioelectricity

Photosynthetic organisms transduce light energy into electrical energy which can be harnessed using bioelectrochemical devices known as biophotovoltaics (BPVs). As discussed below, these devices can provide an electrical interface for biomusic generation.

Photosynthetic extracellular electron transport

Photosynthetic organisms (or phototrophs) perform the conversion of solar energy into electrical energy through the activity of their photosynthetic electron transport chain. In oxygenic phototrophs, which include cyanobacteria and chloroplast-containing plants and eukaryotic algae, the photosynthetic electron transport chain is located in the thylakoid membranes. The process begins with photosystem II, a protein complex which performs the light-catalysed oxidation of water, thereby obtaining high-energy electrons and generating oxygen (Blankenship, 2021). These high energy electrons are subsequently transferred between a series of different proteins and metabolites before eventually being stored within the electron carrier molecule NADPH. A comprehensive description of photosynthetic electron transport can be read elsewhere (Lawrence et al., 2023).

Extracellular electron transfer (EET) is the process by which cells secrete electrons to their extracellular environment (Logan et al., 2019). EET activity has been observed in various clades of algae, including both eukaryotic microalgae and prokaryotic cyanobacteria (Lawrence et al., 2023; Wey et al., 2019). The biological mechanism underpinning algal EET remains uncharacterized, although it has been demonstrated that EET is directly dependent on the photosynthetic electron transport activity of the cell (McCormick et al., 2015;

Wey et al., 2019). This means that the rate of EET is dependent on environmental conditions, such as light intensity and temperature, which alter the photosynthetic activity of the cells.

Biophotovoltaic devices

BPVs are bioelectrochemical devices which utilize the EET activity of photosynthetic microorganisms for light-driven electricity generation (Fig. 1a–c). In BPVs, electrodes are used to accept electrons from a surrounding biofilm or cell-suspension. The anode serves as the electron acceptor, with the captured electrons then being transferred via an external circuit to the cathode, completing the electrical circuit. The difference in potential between the anode and cathode facilitates the generation of a measurable electric current (Wey et al., 2019).

Electricity production by BPVs is several orders-of-magnitude below that of conventional photovoltaics, although theoretical predictions suggest they could achieve similar performances (Lawrence et al., 2023). Various approaches to improving BPV performance are being explored, as detailed elsewhere (Wey et al., 2019; Wroe et al., 2024). Already, BPVs are being utilized for applications with low-power electronic devices (Howe & Bombelli, 2023; Lawrence et al., 2023). The sustainability of BPVs, alongside their ability to generate computer-readable electrical signals which respond to environmental conditions, make them well suited as an interface between photosynthetic microorganisms and musical instruments.

Biomusical device design

Unlike traditional BPVs that are optimized for electricity production, devices used for biomusic generation must also accommodate the nuances of musical expression and interaction with environmental stimuli. BPVs

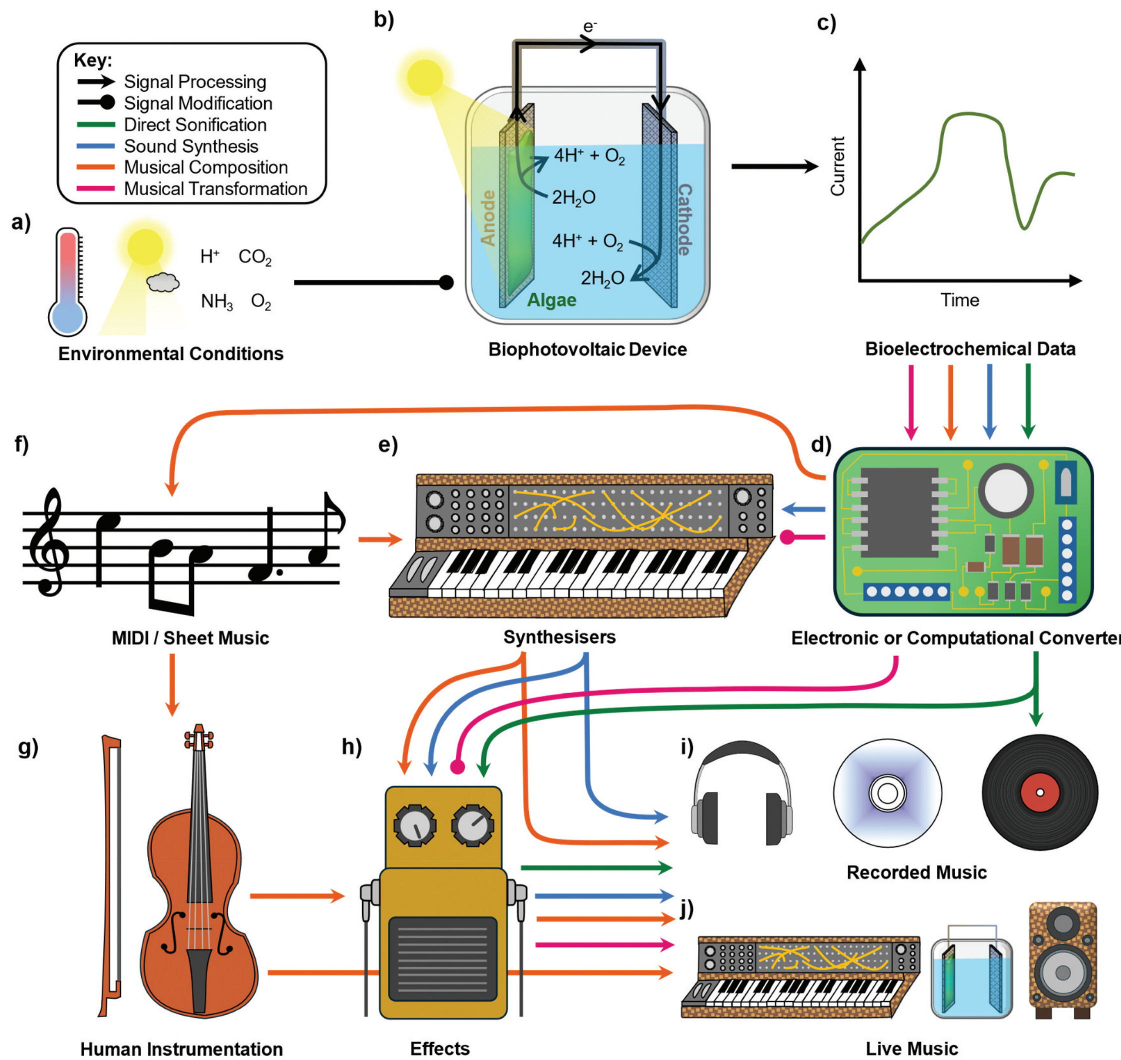

Fig. 1. Sonification methods for creating algal biomusic. Panels (a-j) are referred to throughout the main text.

for biomusic generation must act as transducers, in which environmental inputs are converted into electrical outputs via the photosynthetic activity of the algae within them (Fig. 1a–c). This necessitates the design of BPVs which balance functionality, sensitivity, and practicality.

Designing biophotovoltaics for biomusic generation

Inspiration for the design of BPVs for biomusic generation can be taken from existing BPVs developed for real-world applications, such as herbicide sensors, educational toolkits, wastewater remediation systems, or power sources for internet-of-things devices (Ahiahonu et al., 2022; Bateson et al., 2018; Bombelli et al., 2022; Elhadad & Choi, 2023; Sawa et al., 2017; Tucci et al., 2019). These BPVs utilize inexpensive, stable and readily available materials such as aluminium or carbon electrodes and plastic chambers (Howe & Bombelli, 2023; Wey et al., 2019), alongside cultures of model and abundant strains, including various substrains of the cyanobacterium *Synechocystis* sp. PCC 6803 or the green alga *Chlorella vulgaris*, for which robust protocols for growth and implementation in BPVs have been developed (Cereda et al., 2014; McCormick et al., 2011; Wey et al., 2021). Choice of organism is an important consideration, due to the large differences in both the magnitude and dynamics of electrical signals which have been observed from different algal species (McCormick et al., 2011; Pisciotta et al., 2010; Wenzel et al., 2018; Wey et al., 2021). Because no clear genetic predictors of algal EET activity have been identified, we recommend screening multiple strains in a given device to identify which are most suitable for the desired musical application. We recommend that BPVs developed for biomusic generation utilize a biofilm of algae on the surface of the anode as opposed to a suspension of planktonic cells, due to the previously reported longevity of the former (Bombelli et al., 2022; Zhang et al., 2018).

BPVs developed for real-world applications have previously utilized an initial inoculum of axenic algae which is exposed to a non-sterile environment within the BPV. Over time, this leads to the formation of a photosynthetic consortium, consisting of both the inoculated algal strain and various species of other microorganisms (both photosynthetic and non-photosynthetic). Consortia developed by this method have been shown to provide light-dependent electricity production over long time periods (Bombelli et al., 2022). Synthetic consortia created using a mixture of an algal species and a non-photosynthetic bacterium capable of high electricity production could also be used (Zhu et al., 2019). These synthetic consortia could provide more sensitive measurements of electrical activity and have been proposed to be more resistant to contamination than axenic cultures (Lawrence et al., 2023). The use of consortia can also impart complexity to the resulting electrical profile, causing it to be influenced by the ecological relationships between species, which will also change in response to environmental stimuli (Lawrence et al., 2023).

One important consideration when creating BPVs for biomusic generation is size. Larger BPVs can enable more sensitive electrical measurements and (via their larger surface area) an increased sensitivity to environmental inputs, both of which can enrich the musical output by capturing subtle changes in the surrounding environment. This poses new challenges in the maintenance and transportation of liquid-filled devices, especially when intended for mobile exhibitions or live performances. These challenges incentivize the creation of devices which can be easily assembled, disassembled and stored. Maintenance of the photosynthetic microorganisms is also a concern. Several of these problems could be solved using desiccation-resistant photosynthetic microorganisms (Douchi et al., 2024), enabling devices to be drained and cells dehydrated between periods of use.

Insulating the devices from leaks or potentially damaging external conditions (such as high or low temperatures) whilst still maintaining a sensitivity to ambient conditions will also prove a challenge. BPVs must be able to translate variations in light conditions effectively into variations in electricity production. Materials should therefore be chosen which allow for sufficient light transmission from across the visible spectrum, such as glass or clear plastic. Maintaining sensitivity to subtle fluctuations in temperature and humidity poses deeper design challenges. Proper ventilation will be necessary, as well as adequate airflow to regulate the concentration of gases such as carbon dioxide and oxygen.

Thinking beyond functionality and aesthetics will also play an important role in designing BPVs for biomusic generation. Biodesign and bioart more generally have provided a paradigm shift in artistic practices and design trends, with an increased emphasis on sustainability, interdisciplinarity, and the convergence of technology and biology. It is common to see design approaches that merge the functional minimalism of scientific innovation with embellishments that subvert our expectations of these types of instruments, oftentimes creating a futuristic sci-fi aesthetic (Weintraub, 2012). These design approaches can be used to challenge conventional notions of what constitutes artistic and scientific expression, exploring the aesthetic potential of living organisms and biological processes to engage both auditory and visual senses, contributing to a more immersive experience of biomusic. Inspiration can be taken from other biodesign projects which have utilized photosynthetic microorganisms, creating smart materials in which the artistic form and scientific function are intertwined. Examples include textiles (Aghighi, 2019), furniture (Douenias et al., 2016; Melchiorri, 2017), and building materials (Giron, 2023; Hanafi, 2021) which either utilize photosynthetic microorganisms in their assembly and/or incorporate them in order to perform carbon-capture.

Environmental and artificial inputs

Variation in biomusic produced with BPVs can be obtained via changes in electricity production caused by a variety of environmental inputs (Fig 1a), many of which are described above. These inputs can be left to evolve naturally or can be controlled via human intervention. Example inputs include physical conditions such as light intensity and colour, temperature and humidity. Electricity generation in BPVs is especially sensitive to light conditions, which could be artificially programmed using computer-controlled LED lighting systems. This could be used to impart musicality on the resulting signals, without compromising the biological nature of the music being produced. Chemical conditions such as pH, gas conditions or the concentration of electron shuttles in the BPV will naturally change over time but are more difficult to reliably change with human intervention. One rapid and easily programmable method of artificially altering electricity generation would be to change the applied electrode potential using a potentiostat, which can change the rate at which BPVs harvest electrons secreted via EET by altering the energetics of this process (Wey et al., 2019).

It is unclear if the sound produced by an algal musical system could influence the electricity production, thereby creating feedback. Previous research has demonstrated how audio, which is in the human-perceivable range, can provide enhancements in the cultivation of algal biomass (Cai et al., 2016), although the biological mechanism underlying this observation remains uncharacterized.

Electrical outputs

Various electrical outputs can be recorded from BPVs, including the current, the voltage or (their product) the power (Wey et al., 2019) (Fig. 1c). It is important to consider which of these parameters to use for biomusic generation. Parameters should be easy to measure with non-specialist hardware and should sufficiently reflect the biological systems to be suitable for downstream signal processing into musical signals. Electrical parameters can be measured using a potentiostat, or simpler devices such as ammeters, voltmeters and other sensors. However, it is important to choose measuring devices that are suited for measuring low currents or voltages, not only due to their lower noise and increased sensitivity but also because some devices can influence the current and voltage of the circuit, thereby distorting measurements. Of the electrical parameters that can be measured, the current is the most dependent on the biological activity, exhibiting the greatest response to environmental conditions (Bombelli et al., 2022) which in turn makes it the most suitable for biomusical applications. By comparison, whilst the voltage of BPVs varies, it is largely determined by the choice of electrode materials (Wey et al., 2019). However, it is important to note that current in BPVs can also be generated by abiotic processes, such as capacitance and electrode corrosion (Bombelli et al., 2022; Wey et al., 2019).

Electricity-sound conversion

Converters are required to convert the electrical signals from BPVs into auditory signals (Fig 1d). One method of this is to use electronic converters, such as voltage-to-frequency converters (VFCs) and current-to-frequency converters (CFCs) (Texas Instruments, 2013, 2015). These converters can accept analog electrical inputs from BPVs, using these signals to generate a single-frequency waveform, such as a sine wave. These waveforms can then be used in downstream signal-processing pathways (see Sonification of Biological Data) to generate music.

One challenge is to design electronic converters which are highly sensitive to changes in BPV outputs, thereby producing waveforms which provide an accurate and easily perceivable representation of the biological data. The frequency of the generated waveforms can be scaled linearly with the inputted electrical parameters, or logarithmically using op-amp diode circuits or trans-diode connections (Zumbahlen, 2008). External capacitors and resistors can also be used to change the sensitivity and measuring range of the converters to provide greater variation in the output frequencies (Texas Instruments, 2013, 2015). The use of CFCs is recommended due to the aforementioned sensitivity of BPV currents to environmental changes.

Alternatively, electricity-sound conversion can be performed entirely computationally by using software to convert electrical data to waveforms. As with electronic converters, this could be done with live or pre-recorded data, although it requires more programming experience and prevents the creation of a standalone BPV 'instrument'.

Sonification of biological data

Sonification is the process by which data is converted into sound. Several sonification methods are available, each of them utilizing different signal processing pipelines. These methods vary in the amount of human-input required, which in turn alters the extent to which the music will retain the biological information used to generate it.

Direct sonification

Direct sonification involves the creation of sound using waveforms directly generated from input data (Fig. 1). Sound provides a method of perceiving and interacting with the data that can be more accessible and inclusive than traditional graphical and mathematical representations (Hermann et al., 2011). Existing examples of direct sonification include NASA's interdisciplinary collaborative project to sonify observational data from telescopes like NASA's Chandra X-ray Observatory, Hubble Space Telescope and James Webb Space Telescope (NASA, 2024).

Coloured arrows show the signal processing pathways for different sonification methods.

Single-frequency waveforms obtained from the conversion of BPV data can be used to generate audio output, with the frequency of waveforms dictating the pitch and amplitude dictating the volume. This would provide an accurate auditory representation of the biological activity. However, the signals produced by an individual BPV would be inherently monophonic, and therefore likely monotonous and non-musical also. More complex sounds could be created using multiple BPVs, or multiple converters with the same BPV, to generate multiple frequencies simultaneously. However, if these frequencies are similar to one another, the interference between them will generate beats – an auditory phenomenon associated with dissonance (Heffernan, 1887). The musicality of the sounds could be improved using effects such as echo, reverb, distortion or chorus also.

Alternatively, pre-recorded data from BPVs could be computationally converted into waveforms in an asynchronous manner (likely faster than real-time) to obtain sounds with greater variation and musicality. For example, the sensitivity of high-performance BPVs allows them to record rapid changes in the current produced by cyanobacteria, which are known to depend on experimental conditions. Whilst these BPVs would be unsuitable for real-time music generation, this data could be used to create sound with a high degree of musicality, like the sonification of astronomical data.

Sound synthesis

Sound synthesis techniques can be used to sonify BPV data, in which the BPV is used as an oscillator unit which triggers a synthesizer (Fig 1e). Additive synthesis could be used to layer waveforms from multiple BPV signals whilst subtractive synthesis could be used to shape waveforms using filters (McGuire & Van Der Rest, 2015). The human-input provided from these synthesis techniques can be used to provide a greater musicality to the signal, whilst maintaining the biological information. Sound synthesis would be especially suited to the use of modular synthesizers, where BPVs could be constructed as a standalone oscillator module (Nishida & Jo, 2020). However, a variety of analog and digital synthesizers or digital audio workstations could be used.

Sound synthesis could be performed live, although the slow and aperiodic evolution of oscillations produced from a single BPV may not be especially musical. One solution to this would be to use frequency modulation synthesis, in which a carrier waveform produced by a traditional oscillator is modulated using the frequency from the BPV waveform (McGuire & Van Der Rest, 2015). Pre-recorded BPV data can instead make use of computational Fourier analysis to decompose a BPV signal into a series of single-frequency periodic waveforms (Attinger et al., 1966) which in turn can be used in sound synthesis (McGuire & Van Der Rest, 2015). Although Fourier decomposition could be used to generate various kinds of waveforms, sine waves would be the most useful for accurately reflecting biological activity (Attinger et al., 1966). Harmonic sine wave oscillators are widely used to model biological processes, such as the circadian clock of photosynthetic organisms (Kucho et al., 2005), which have been linked to electricity generation by BPVs (Lu et al., 2014; Nishio et al., 2015). The ability of wave decomposition techniques to extract biologically relevant single-frequency oscillations from BPV data has already been demonstrated (Okedi et al., 2022). Furthermore, such techniques could be used to denoise BPV data by excluding high-frequency information caused by electrical noise (Wahab et al., 2021).

Musical composition

Music could be composed by converting BPV signals into musical notation (Larsen et al., 2013) (Fig. 1f), imparting tonality to the signal which would not be present with direct sonification. The musical notation generated could be sheet music for traditional instrumentation or MIDI notation for electronic instrumentation. Conversion of frequency data to MIDI signals is already widely available both as standalone software (Nilson Ltd., 2022) or as plugins for digital audio workstations (Cycling '74, 2015).

Single-frequency waveforms from BPVs could be converted to musical notes, such that the frequency is relative to the pitch. The octave range or key of the resulting music would be determined by human-input. This would bound and bin the BPV data, such that waveforms with similar frequencies would produce the same note but waveforms with very different frequencies would produce different notes. Music composed with BPV signals is expected to be highly chromatic with limited rhythmic variability. This could be overcome with the use of arpeggiators to impart rhythm, melody and harmony on the resulting music whilst ensuring the pitch is still influenced by biological information.

Musical transformation

Instead of being used to generate new music, signals from BPVs could be used to transform music. For example, when creating music using a synthesizer, BPV signals could be used to control envelope generators, filters, gates and effects units (McGuire & Van Der Rest, 2015) (Fig. 1e & h). Interpretation of the underlying biological data is unlikely when using this method, although it would allow for environmental signals to perceptibly influence human-composed music.

Musical applications

Environmental biomusic generation has been hindered by the high level of technical expertise required to build systems capable of generating music which is influenced by biological signals in a non-superficial way. As such, its uptake beyond a small group of artists and scientists has been limited. BPVs provide a sustainable, affordable and easy-to-build technology which could not only improve environmental biomusic generation but make it accessible to a larger group of non-specialist artists and educators, greatly expanding its applications.

Music for listening

Algal biomusic could be used in various genres of recorded music (Fig. 1i). The environmental nature of the music would make it especially suitable for experimental and ambient music, in which it could be paired with field recordings or other naturally or stochastically generated sounds. The use of algal biomusic in popular music genres is possible but would require a greater degree of human-input (Fig. 2). For example, BPV signals lack an inherent rhythm or tempo, making it hard to use them to trigger percussive elements. As a result, these features of the music would rely on human composition.

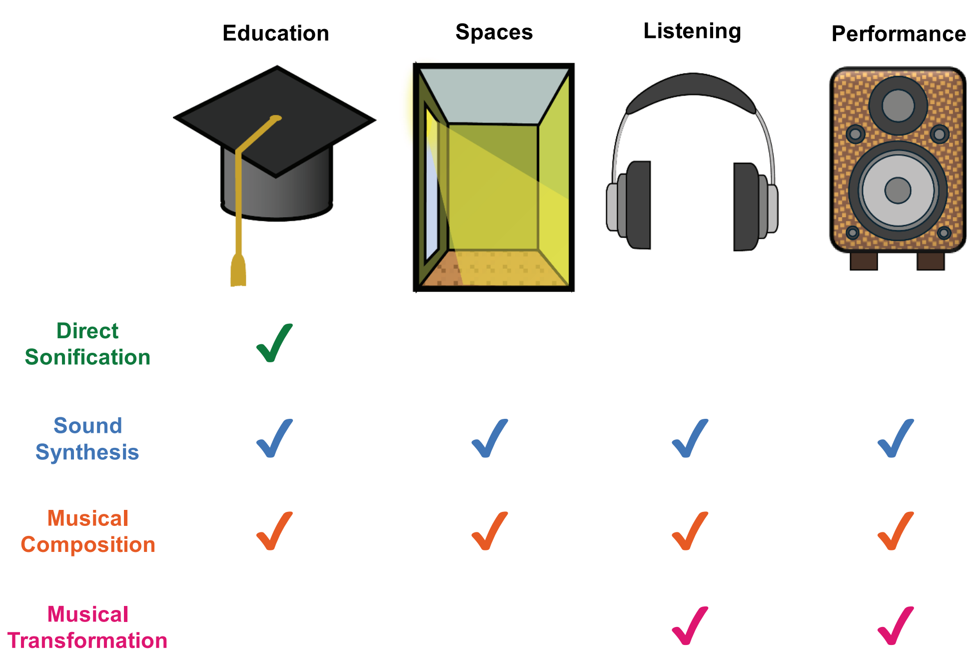

Fig. 2. Recommended sonification methods for different applications of algal biomusic.

Music for performance

Live musical performance of algal biomusic could be performed (Fig. 1j), albeit with significant human-intervention. The slow responses of BPVs within the sub-minute time scale (Bombelli et al., 2022) would make direct sonification unsuitable for this application, but sound synthesis methods could be used to enable live control of electronic instruments (Fig. 2). Performances could be done with individual BPVs, multiple BPVs acting as a chorus, or as part of an ensemble alongside human musicians. Alternatively, pre-composed music generated from BPV data could be played live on a variety of instruments (Fig. 1g).

Electricity generation by BPVs could be influenced by artificially imposed changes to environmental conditions, such as the light intensity. This human-intervention could not only be used to impart musicality but could contribute to a holistic audio-visual experience also. For such a performance to work, BPV devices must be designed to improve sensitivity to environmental conditions. In order to achieve this, state-of-the-art electrodes could be used which can measure rapid sub-second changes in electricity production (Chen et al., 2022; Wey et al., 2021; Zhang et al., 2018).

We are in the process of creating an algal musical instrument suited to live performance. An early prototype of this device performed alongside an ensemble of human instrumentalists as part of the installation *Choir of Kin* at Brut Nordwest, Vienna in 2024 (Transformative Narratives, 2024). The development and implementation of this device will be the subject of a future research publication.

Music for education

Biomusic could be used to communicate biological concepts to non-expert audiences, including in science communication, outreach and policy settings. Direct sonification and composition can provide the most accurate rendering of the biological data, which is perhaps more important for adult and professional audiences when trying to communicate biological concepts (Hermann et al., 2011; Larsen et al., 2013; Zanella et al., 2022) (Fig. 2).

For outreach exercises and environmental education, sound synthesis and musical composition are recommended. The user-input provided by these methods allows for greater engagement with the system, included in simple and tactile ways (such as turning knobs and pressing switches). This provides an intimacy with the subject which can impart inspiration in outreach settings or foster human-ecological ties in an environmental education setting (Monroe et al., 2008).

As part of the Cambridge Science Festival, an educational outreach event hosted by the University of Cambridge each year, we have created a prototype system for algal biomusic generation. This system utilized a musical composition approach, in which signals from a BPV were fed into a VFC (Texas Instruments, 2015), thresholded using capacitors and resistors, with the resulting frequencies being converted into MIDI notes (Nilson Ltd., 2022). These MIDI notes were subsequently fed into the Ableton Live digital audio workstation (Ableton, 2022) from which they were used to trigger various external synthesizers. This BPV-generated music was supplemented with a human-controlled drum machine and effects units. Attendees of the exhibit were able to connect the system to a variety of BPV devices, being able to perceive the change in their electricity generating capacity directly by changes in the pitch of the resultant music. Whilst simple, this prototype demonstrates the opportunities for algal biomusic in education and outreach. Further documentation of this system, including videos, can be downloaded from publicly available repositories (Supplemental Material).

Music for spaces

A major challenge for composers is creating music for public spaces which can integrate with, or even reflect, the environment in which it is played. Creating 'music for spaces' such as this was the original philosophy promulgated by Brian Eno for ambient music, which was designed to replace the 'background music' widely used in public spaces which rarely reflected the environments they are piped into (Eno, 1978). In recent years generative music, another term coined by Eno (Eno, 1996), has been explored for this purpose (Mazurowski, 2015). Generative music is created by a system, often algorithmic (Collins, 2008), enabling the generated music to be separated from the creator and even potentially to be guided by environmental inputs (Fig. 2).

Algal biomusic provides a new form of generative music which can be almost entirely free of human-input and which can directly reflect its environment. For example, changes in electricity generation by BPVs throughout the course of the day could give a clear change in the nature of the music being played. Before its use in more ordinary settings, algal biomusic could be used in art installations where the same biological data used for music generation is used to generate visual representations, creating synergy between the visual and auditory aspects of the installation.

Conclusion

Algal biomusic has the potential to communicate biological processes that govern life but are inaccessible to our sensory perception. In the process, we believe this technology could provide new avenues for ecocentric forms of artistic expression, in which music can directly reflect the environment it was made in.

In addition to our prototype algal biomusical systems used for outreach purposes (see Music for Education), other artists have developed BPV-style devices for musical applications. *Sonomatter* by Sabina Hyoju Ahn (2018) was a sound installation utilizing a bioelectrochemical device powered by a consortium of photosynthetic and non-photosynthetic bacteria. In this work, bioelectrical signals were used as control voltages for synthesizers in an example of musical transformation (Hyoju Ahn, 2018). Live performance was achieved using 10 devices in unison, with human-intervention achieved by connecting and disconnecting individual devices. *BioSoNot* by Gilberto Esparza (2017) used electrical signals from microbial fuel cells to generate music via sound synthesis (Esparza, 2017). Contaminated water was added to the device as an environmental input which produced a clear change in the outputted sound.

The use of BPVs to generate algal biomusic provides numerous advantages over other methods of generating environmental biomusic. The biological signals recorded from BPVs can be measured continuously in a computer readable format. Furthermore, unlike other biomusical devices measuring the conductivity of plant tissues (which is dependent on abiotic processes), BPVs provide a non-invasive method for measuring the purely biological photosynthetic activity of algae. An interesting alternative approach to generating algal biomusic without the use of BPVs is through directly recording the sounds generated by oxygen bubbles formed during photosynthesis (Berger, 2023; Freeman et al., 2018). In comparison to BPVs, the range of sounds which could be generated by this method is limited, although it could be used to create biomusic from large marine ecosystems such as coral reefs.

We urge researchers and artists who adopt this technology to adhere to the open-source principles and DIY culture which is prominent among other forms of bioart and biodesign (Delgado, 2013). Many academics, designers and artists share their methods, tools, and findings openly- encouraging collaboration, democratizing access to biotechnological tools, and empowering artists, educators, and non-specialist individuals to explore bio-related disciplines on their own terms. Taking on a design approach that prioritizes accessibility and affordability could pave the way for more inclusive and diverse explorations of eco-centric design.

Acknowledgements

The authors thank Peter Coppola, Ezra Kitson and Henry Lloyd-Laney for helpful discussions.

Disclosure statement

P. Bombelli and C. J. Howe are holders of Patent GB2466415 (Hydrogen and electrical current production from photosynthetically driven semibiological devices).

Funding

J. M. Lawrence thanks Trinity Hall, Cambridge, for financial support. We also thank the Biotechnology and Biological Sciences Research Council, the Engineering and Physical Sciences Research Council, and the Science and Technology Facilities Council for financial support [BB/X511092/1] and [EP/X525686/1] to C. J. Howe, P. Bombelli and L. B. Giron [BB/Y001370/1] to C. J. Howe [ST/W507519/1] to E. Albertini, and [BB/M011194/1] to A. Scarampi.

ORCID

Joshua M. Lawrence http://orcid.org/0000-0002-9250-8690
Emma Albertini http://orcid.org/0000-0003-3099-642X
Alberto Scarampi http://orcid.org/0000-0003-4177-8575
Paolo Bombelli http://orcid.org/0000-0001-5836-0218
Christopher J. Howe http://orcid.org/0000-0002-6975-8640

Authors contributions

J.M. Lawrence: the initial concept, first draft, research and writing of the manuscript; E. Albertini: the initial concept, research and writing of the manuscript; A. Scarampi: the initial concept, research and writing of the manuscript; P. Bombelli, expertise on biophotovoltaic device design, research and writing of the manuscript; L.B. Giron: expertise on biophotovoltaic device design, research and writing of the manuscript; L. Kuzmich: the initial concept, research and writing of the manuscript; C.J. Howe: research and writing of the manuscript.

References

Ableton. (2022). *Ableton live*. Ableton, AG.
Aghighi, R. (2019). Biogarmentry. https://designawards.core77.com/personal-accessory/83837/Biogarmentry-Living-and-Photosynthetic-Textile
Ahiahonu, E. K., Anku, W. W., Roopnarain, A., Green, E., Serepa-Dlamini, M. H., & Govender, P. P. (2022). Exploring indigenous freshwater chlorophytes in integrated biophotovoltaic system for simultaneous wastewater treatment, heavy metal biosorption, CO_2 biofixation and biodiesel generation. *Bioelectrochemistry*, *147*, 108208. https://doi.org/10.1016/j.bioelechem.2022.108208

Allen, A. S., & Dawe, K. (2017). *Current directions in Ecomusicology: Music, culture, nature*. Routledge.

Allen, A. S., & Titon, J. T. (2019). Introduction: Anthropocentric and ecocentric perspectives on music and environment. *MUSICultures*, *46*, 1–6. https://journals.lib.unb.ca/index.php/MC/article/view/30487

Attinger, E. O., Anné, A., & McDonald, D. A. (1966). Use of Fourier series for the analysis of biological systems. *Biophysical Journal*, *6*(3), 291–304. https://doi.org/10.1016/S0006-3495(66)86657-2

Bateson, P., Fleet, J. E. H., Riseley, A. S., Janeva, E., Marcella, A. S., Farinea, C., Kuptsova, M., Conde Pueyo, N., Howe, C. J., Bombelli, P., & Parker, B. M. (2018). Electrochemical characterisation of bio-bottle-voltaic (BBV) systems operated with algae and built with recycled materials. *Biology (Basel)*, *7*(2), 26. https://doi.org/10.3390/biology7020026

Berger, L. (2023). Photosynthetic beats. https://f-o-m.bandcamp.com/album/photosynthetic-beats-utricularia-vulgaris-marais-des-pontins

Blankenship, R. E. (2021). *Molecular mechanisms of photosynthesis* (3rd ed.). Wiley.

Bombelli, P., Savanth, A., Scarampi, A., Rowden, S. J. L., Green, D. H., Erbe, A., Årstøl, E., Jevremovic, I., Hohmann-Marriott, M. F., Trasatti, S. P., Ozer, E., & Howe, C. J. (2022). Powering a microprocessor by photosynthesis. *Energy Environment Science*, *15*(6), 2529–2536. https://doi.org/10.1039/D2EE00233G

Cai, W., Dunford, N. T., Wang, N., Zhu, S., & He, H. (2016). Audible sound treatment of the microalgae *picochlorum oklahomensis* for enhancing biomass productivity. *Bioresource Technology*, *202*, 226–230. https://doi.org/10.1016/j.biortech.2015.12.019

Castellanos, C., Bello, B., Lee, H., Lee, M., Lee, Y. S., & Chang, I. S. (2020). On creating multimedia interfaces for hybrid biological-digital art installations. In *International Conference on Multimedia Modeling*, Daejeon, South Korea (pp. 139–150). Springer.

Cereda, A., Hitchcock, A., Symes, M. D., Cronin, L., Bibby, T. S., Jones, A. K., & Han, A. (2014). A bioelectrochemical approach to characterize extracellular electron transfer by Synechocystis sp. PCC6803. *PLOS ONE*, *9*(3), 91484. https://doi.org/10.1371/journal.pone.0091484

Chen, X., Lawrence, J. M., Wey, L. T., Schertel, L., Jing, Q., Vignolini, S., Howe, C. J., Kar-Narayan, S., & Zhang, J. Z. (2022). 3D-printed hierarchical pillar array electrodes for high-performance semi-artificial photosynthesis. *Nature Materials*, *21*(7), 811–818. https://doi.org/10.1038/s41563-022-01205-5

Chou-Ren, D., Winters, M., Hernandez, J., Mcduff, D., Suh, J., Rodriguez, V., & Ramos, G. (2023). Do you even need sensors?: Synthetic biomusic as an empathic technology. In *11th International Conference on Affective Computing and Intelligent Interaction*, Cambridge, MA, USA.

Collins, N. (2008). The analysis of generative music programs. *Organised Sound*, *13*(3), 237–248. https://doi.org/10.1017/S1355771808000332

Collins, N., Schedel, M., & Wilson, S. (2010). *Electronic music*. Cambridge University Press. Cycling '74 2015. Ableton Max 7 Pitch and Time Machines.

Delgado, A. (2013). Diybio: Making things and making futures. *Futures*, *48*, 65–73. https://doi.org/10.1016/j.futures.2013.02.004

Dixon, D. P. (2009). Creating the semi-living: On politics, aesthetics and the more-than-human. *Transactions of the Institute of British Geographers*, *34*(4), 411–425. https://doi.org/10.1111/j.1475-5661.2009.00354.x

Dogane, Y., & Fujieda, M. (1994). Ecological Plantrons. https://emrecords.bandcamp.com/album/ecological-plantron

Douchi, D., Si Larbi, G., Fel, B., Bonnanfant, M., Louwagie, M., Jouhet, J., Agnely, M., Pouget, S., & Maréchal, E. (2024). Dryland endolithic chroococcidiopsis and temperate fresh water synechocystis have distinct membrane lipid and photosynthesis acclimation strategies upon desiccation and temperature increase. *Plant Cell Physiology*, *65*(6), 939–957. https://doi.org/10.1093/pcp/pcad139

Douenias, J., Frier, E., & Tesone, L. (2016). Living things. https://www.douenias.design/living-things-1#:~:text=The%20installation%3B%20Living%20Things%20contains,celebrated%20in%20the%20built%20environment

Duursma, R. A., Blackman, C. J., Lopéz, R., Martin-StPaul, N. K., Cochard, H., & Medlyn, B. E. (2019). On the minimum leaf conductance: Its role in models of plant water use, and ecological and environmental controls. *The New Phytologist*, *221*(2), 693–705. https://doi.org/10.1111/nph.15395

Eaton, M. L. (1974). *BIO-MUSIC*. Barton, VT: Something Else Press.

Elhadad, A., & Choi, S. (2023). Powering the internet of things in aquatic environments: Solar energy harvesting through a buoyant biosolar cell array. *Journal of Power Sources*, *581*, 233501. https://doi.org/10.1016/j.jpowsour.2023.233501

Eno, B. (1978). *Liner notes*. Music for Airports.

Eno, B. (1996). Liner notes. *Generative Music 1*. https://www.roughtrade.com/en-gb/product/brian-eno/ambient-1-music-for-airports

Esparza, G. (2017). BioSoNot 1.2. *Leonardo*, *4*, 418–419. https://doi.org/10.1162/LEON_a_01461

Freeman, S. E., Freeman, L. A., Giorli, G., Haas, A. F., & Radford, C. A. (2018). Photosynthesis by marine algae produces sound, contributing to the daytime soundscape on coral reefs. *PLOS ONE*, *13*(10), e0201766. https://doi.org/10.1371/journal.pone.0201766

Giron, L. B. (2023). Make like a leaf. https://ualshowcase.arts.ac.uk/project/471048/cover

Grond, F., Motta-Ochoa, R., Miyake, N., Tembeck, T., Park, M., & Blain-Moraes, S. (2022). Participatory design of affective technology: Interfacing biomusic and autism. *IEEE Transactions on Affective Computing*, *13*(1), 250–261. https://doi.org/10.1109/TAFFC.2019.2922911

Hanafi, W. H. H. (2021). Bio-algae: A study of an interactive facade for commercial buildings in populated cities. *Journal of Engineering and Applied Science*, *68*(1), 1–16. https://doi.org/10.1186/s44147-021-00037-5

Heffernan, J. (1887). On musical beats and their relation to consonance and dissonance. In *Proceedings of the Musical Association*, London, UK (Vol. 14. pp. 1–21).

Hermann, T., Hunt, A., & Neuhoff, J. G. (2011). *The sonification handbook*. Logos Publishing House.

Horowitz, D. (1994). Generating rhythms with genetic algorithms. *ICMC Proceedings*, Aarhus, Denmaker. http://hdl.handle.net/2027/spo.bbp2372.1994.035

Howe, C. J., & Bombelli, P. (2023). Is it realistic to use microbial photosynthesis to produce electricity directly? *PLOS Biology*, *21*(3), e3001970. https://doi.org/10.1371/journal.pbio.3001970

Hyoju Ahn, S. (2018). Sonic transformation with living matter. *ISEA2019: 25th International Symposium on Electronic Art*, Gwangju, South Korea.

Instruo Limited. (2017). *SCION – user manual*. https://www.instruomodular.com/wp-content/uploads/2021/06/SCION-Manual-Web.pdf

Knapp, R. B., & Lusted, H. S. (1990). Bioelectric controller for computer music applications. *Computer Music Journal*, *14*(1), 42–47. https://doi.org/10.2307/3680115

Kucho, K. I., Okamoto, K., Tsuchiya, Y., Nomura, S., Nango, M., Kanehisa, M., & Ishiura, M. (2005). Global analysis of circadian expression in the cyanobacterium *Synechocystis* sp. strain PCC 6803. *Journal of Bacteriology*, *187*(6), 2190–2199. https://doi.org/10.1128/JB.187.6.2190-2199.2005

Larsen, P., Gilbert, J., & Ravasi, T. (2013). Microbial bebop: Creating music from complex dynamics in microbial ecology. *PLOS ONE*, *8*(3), e58119. https://doi.org/10.1371/journal.pone.0058119

Lawrence, J. M., Egan Rachel, M., Hoefer, T., Scarampi, A., Shang, L., Howe, C. J., & Zhang, J. Z. (2023). Rewiring photosynthetic electron transport chains for solar energy conversion. *Nature Reviews Bioengineering*, *1*(12), 887–905. https://doi.org/10.1038/s44222-023-00093-x

Leudar, A. (2018). Surrounded: A series of sound installations that combine plant electrophysiology and 3D sonic art. *Leonardo*, *51*(5), 517–523. https://doi.org/10.1162/leon_a_01338

Logan, B. E., Rossi, R., Ragab, A., & Saikaly, P. E. (2019). Electroactive microorganisms in bioelectrochemical systems. *Nature Reviews Microbiology*, *17*(5), 307–319. https://doi.org/10.1038/s41579-019-0173-x

Lu, Y., Nishio, K., Matsuda, S., Toshima, Y., Ito, H., Konno, T., Ishihara, K., Kato, S., Hashimoto, K., & Nakanishi, S. (2014). Regulation of the cyanobacterial circadian clock by electrochemically controlled extracellular electron transfer. *Angewandte Chemie International Edition*, *53*(8), 2208–2211. https://doi.org/10.1002/anie.201309560

Matmos. (1997). *Verber: Amplified synapse*.

Mazurowski, L. (2015). Generative electronic background music system. *AIP Conf Proceedings*, Rhodes, Greece (p. 660004). https://doi.org/10.1063/1.4912880

McAlpine, K., Miranda, E., & Hoggar, S. (1999). Making music with algorithms: A case-study system. *Computer Music Journal*, *23*(2), 19–30. https://doi.org/10.1162/014892699559733

McCormick, A. J., Bombelli, P., Bradley, R. W., Thorne, R., Wenzel, T., & Howe, C. J. (2015). Biophotovoltaics: Oxygenic photosynthetic organisms in the world of bioelectrochemical systems. *Energy Environ Science*, *8*(4), 1092–1109. https://doi.org/10.1039/C4EE03875D

McCormick, A. J., Bombelli, P., Scott, A. M., Philips, A. J., Smith, A. G., Fisher, A. C., & Howe, C. J. (2011). Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system. *Energy Environ Science*, *4*(11), 4699–4709. https://doi.org/10.1039/c1ee01965a

McGuire, S., & Van Der Rest, N. (2015). *The musical art of synthesis* 1st ed. Routledge.

McLean, A., & Dean, R. T. (2018). *The oxford handbook of algorithmic music*. Oxford University Press, Oxford.

Melchiorri, J. (2017). Exhale: Bionic chandelier. https://www.julianmelchiorri.com/Bionic-Chandelier

Miller, P. V., & Cox, C. (2024). Music from plant biosignals: A conceptual and analytical orientation. *Music Theory Online*, *30*(1). https://doi.org/10.30535/mto.30.1.6

Miranda, E. R., Adamatzky, A., & Jones, J. (2011). Sounds synthesis with Slime Mould of *physarum polycephalum*. *Journal of Bionic Engineering*, *8*(2), 107–113. https://doi.org/10.1016/S1672-6529(11)60016-4

Monroe, M. C., Andrews, E., & Biedenweg, K. (2008). A framework for environmental education strategies. *Applied Environmental Education and Communication*, *6*(3–4), 205–216. https://doi.org/10.1080/15330150801944416

NASA. (2024). *A universe of sound*. https://chandra.si.edu/sound/

Nilson Ltd. (2022). A2M real-time audio to MIDI. https://apps.apple.com/gb/app/a2m-real-time-audio-to-midi/id1569569145

Nishida, K., & Jo, K. (2020). Modules for analog synthesizers using aloe vera biomemristor. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, Birmingham, UK.

Nishio, K., Pornpitra, T., Izawa, S., Nishiwaki-Ohkawa, T., Kato, S., Hashimoto, K., & Nakanishi, S. (2015). Electrochemical detection of circadian redox rhythm in cyanobacterial cells via extracellular electron transfer. *Plant Cell Physiology*, *56*(6), 1053–1058. https://doi.org/10.1093/pcp/pcv066

Okedi, T., Yunus, K., & Fisher, A. (2022). Decomposing biophotovoltaic current density profiles using the Hilbert–Huang transform reveals influences of circadian clock on cyanobacteria exoelectrogenesis. *Scientific Reports*, *12*(1), 1–19. https://doi.org/10.1038/s41598-022-15111-y

Pisciotta, J. M., Zou, Y., Baskakov, I. V., & Yang, C.-H. (2010). Light-dependent electrogenic activity of cyanobacteria. *PLOS ONE*, *5*(5), e10821. https://doi.org/10.1371/journal.pone.0010821

Russolo, L. (1986). *The art of noises*. Pendragon Press.

Sawa, M., Fantuzzi, A., Bombelli, P., Howe, C. J., Hellgardt, K., & Nixon, P. J. (2017). Electricity generation from digitally printed cyanobacteria. *Nature Communications*, *8*(1), 1–10. https://doi.org/10.1038/s41467-017-01084-4

Small, C. (1999). Musicking — the meanings of performing and listening. A lecture. *Music Education Research*, *1*(1), 9–22. https://doi.org/10.1080/1461380990010102

Sturm, B. L., Santos, J. F., Ben-Tal, O., & Korshunova, I. (2016). Music transcription modelling and composition using deep learning. *arXiv*. https://doi.org/10.48550/arXiv.1604.08723

Texas Instruments. (2013). AN-240 wide-range current-to-frequency converters. *Texas Instruments Application Report*. https://www.ti.com/lit/pdf/snoa594

Texas Instruments. (2015). LMx31x precision voltage-to-frequency converters. *Texas Instruments Application Report*. https://www.ti.com/lit/gpn/LM331

Transformative Narratives. (2024). *Choir of Kin*. https://brut-wien.at/en/Programm/Kalender/Programm-2024/03/Transformative-Narratives-Lena-Kuzmich-Tony-Wagner-Guests-Installation

Tripaldi, L. (2022). *Parallel minds: Discovering the intelligence of materials*. Urbanomic.

Tucci, M., Bombelli, P., Howe, C. J., Vignolini, S., Bocchi, S., & Schievano, A. (2019). A storable mediatorless electrochemical biosensor for herbicide detection. *Microorganisms*, *7*(12), 630. https://doi.org/10.3390/microorganisms7120630

Wahab, M. F., Gritti, F., & O'Haver, T. C. (2021). Discrete Fourier transform techniques for noise reduction and digital enhancement of analytical signals. *TrAC Trends in Analytical Chemistry*, *143*, 116354. https://doi.org/10.1016/j.trac.2021.116354

Wai, Y. C., & Chao, E. C. (2023). Bioacoustics as forms of resistance: Growing mycelium instruments and mushroom communication in a high-tech city-state. *East Asian Science, Technology & Society: An International Journal*, *17*(1), 105–110. https://doi.org/10.1080/18752160.2023.2167837

Weintraub, L. (2012). *To Life! Eco Art in Pursuit of a Sustainable Planet*. University of California Press.

Wenzel, T., Härtter, D., Bombelli, P., Howe, C. J., & Steiner, U. (2018). Porous translucent electrodes enhance current generation from photosynthetic biofilms. *Nature Community*, *9*(1), 1–9. https://doi.org/10.1038/s41467-018-03320-x

Wey, L. T., Bombelli, P., Chen, X., Lawrence, J. M., Rabideau, C. M., Rowden, S. J. L., Zhang, J. Z., & Howe, C. J. (2019). The development of biophotovoltaic systems for power generation and biological analysis. *Chem Electro Chem*, *6*(21), 5375–5386. https://doi.org/10.1002/celc.201900997

Wey, L. T., Lawrence, J. M., Chen, X., Clark, R., Lea-Smith, D. J., Zhang, J. Z., & Howe, C. J. (2021). A biophotoelectrochemical approach to unravelling the role of cyanobacterial cell structures in exoelectrogenesis. *Electrochimica Acta*, *395*, 139214. https://doi.org/10.1016/j.electacta.2021.139214

Wroe, E. I., Egan, R. M., Willyam, S. J., Shang, L., & Zhang, J. Z. (2024). Harvesting photocurrents from cyanobacteria and algae. *Current Opinion in Electrochemistry*, *46*, 101535. https://doi.org/10.1016/j.coelec.2024.101535

Zanella, A., Harrison, C. M., Lenzi, S., Cooke, J., Damsma, P., & Fleming, S. W. (2022). Sonification and sound design for astronomy research, education and public engagement. *Nature Astronomy*, *6*(11), 1241–1248. https://doi.org/10.1038/s41550-022-01721-z

Zhang, J. Z., Bombelli, P., Sokol, K. P., Fantuzzi, A., Rutherford, A. W., Howe, C. J., & Reisner, E. (2018). Photoelectrochemistry of photosystem II in vitro vs in vivo. *Journal of the American Chemical Society*, *140*(1), 6–9. https://doi.org/10.1021/jacs.7b08563

Zhu, H., Meng, H., Zhang, W., Gao, H., Zhou, J., Zhang, Y., & Li, Y. (2019). Development of a longevous two-species biophotovoltaics with constrained electron flow. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-12190-w

Zumbahlen, H. (2008). *Linear circuit design handbook*. Newnes.