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The scientific basis for water treatment using DabV

Contents

DabV AS

Abstract

DabV is a devise for water treatment based on autonomous utilization of vibration energy. DabV improves the quality of water through sound technologies at frequencies outside the range of human's perception. As a background to understand the platform of knowledge that DabV is built on, the present report gives scientific information on water, carbonate precipitation and biofilms in water systems, the physical principle of sound versus light, piezo technology and utilization of self-powered vibration energy. From the scientific established knowledge of the utilization of vibration energy from sound, DabV is a result of further development over years for optimal effects at low cost.

Still water and overnight stagnation in water distribution systems => water aggregation => bacteria growth and quality reduction

DabV splits the water clusters

Water is one of the most widely spread substances on earth, essential for all life (https://en.wikipedia.org/wiki/Water). Designing and ensuring safe drinking water supply systems is a growing challenge world-wide (Kristani et al. 2022). As described by Geckil (2016), water has the unusual properties:

- A universal solvent
- The highest heat capacity, conduction of heat, and heat of vaporization
- The highest surface tension of all liquids
- The only substance occurring naturally in all three phases: solid, liquid, and gas
- Being the medium for bioactivity

Fig. 1. Water – the most important substance for life.

The water molecule

A water molecule consists of one oxygen (O) and two hydrogen atoms (H) that share electrons in the outer shells, thereby forming covalent bonds (**Fig. 2**). Each atom consists of a nucleus with protons, which are positively charged, neutrons without any charge, and electrons, which are negatively charged and circulate around the nucleus. Atoms always seek to fill the outer electron shells. Atoms with few electrons in the outer shells tend to give off the electrons and atoms that lack few electrons in the outer shell have strong attraction to electrons to fill the outer shells (the octet rule). Hydrogen has only one electron shell with one electron surrounding the nucleus. Oxygen has two electron shells with two electrons in the inner shell and six in the outer shell. As oxygen lack two electrons in the outer shell, it has strong tendency to attract electrons to full-fill the octet rule, and as hydrogen has only one electron in the outer shell it has tendency to deliver electrons.

The process of receiving electrons is oxidation and the process of giving electrons to other atoms is reduction. Oxygen is not the only oxidant, but oxygen has very high oxidizing ability and was one of the first to be discovered, and the name oxidants has been established for any atoms that tend to receive electrons. Atoms and molecules with strong tendency to give away electrons are called reductants or antioxidants. Among the atoms, there is a gradual scale of attractions to electrons. The electrons will move towards the atoms with the strongest attraction.

The process of electron transfer is called redox (reduction-oxidation) reaction. The electrons do not necessarily completely transfer from one atom to another, they may just change their relative position. In water, the hydrogens and oxygen form covalent bounds where electrons in the outer shell are shared.

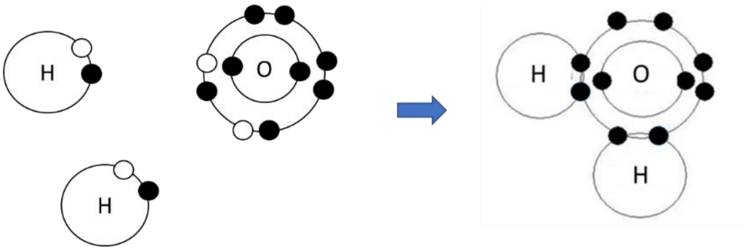


Fig. 2. Water molecules consisting of two hydrogen (H) and one oxygen (O) atom, sharing electrons in their outer shell, and thereby forming covalent bounds. Electrons circulate in shells surrounding the nucleus. Electrons (filed circles) and open positions for electrons (open circles) are marked.

The oxygen attracts the shared electrons stronger than hydrogen, which results in polar property of the water molecule with partial negative charge (δ-) at the oxygen atom and partial positive charge (δ-) at the two hydrogen atoms (**Fig. 3**). Because opposite charges attract one another, the partial negative charge of one water molecule has strong attraction to the partial positive charge of another water molecules resulting in the formation of hydrogen bounds between water molecules. Different water molecules thereby tend to interconnect to aggregates of water molecules held together by hydrogen bounds.

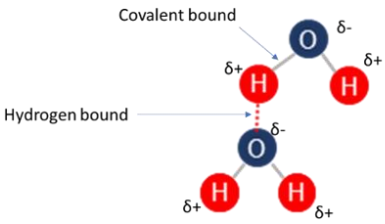


Fig. 3. Two water molecules (H_2O), each consisting of one oxygen atom (O) and two hydrogen atoms (H) held together by covalent bounds (shared electrons) tend to attract each other due to the attraction between the partial negative charge of the oxygen part (δ-) and the partial positive charge at the hydrogen part (δ+) forming hydrogen bounds between the water molecules (https://en.wikipedia.org/wiki/Water). The water molecule is thus an electric dipole.

As water molecules attract each other by hydrogen bounds, clusters of water molecules can grow to very large clusters of water forming a hydrogen-bonded network (Ludwig 2001, Buck et al. 2014). Water can thereby be considered as a transition between liquid and crystals with different configurations and properties (Limmer and Chandler 2011 and 2013, Palmer et al. 2018, Gao et al. 2022). Although detailed information on a molecular level to accurately calculate and understand the properties of liquid water is a challenge, growing information is obtained on water that permits insight into the molecular understanding of water (Keutsch and Saykally 2001, Torrent-Sucarrat et al. 2011, Kaatze 2018, Moqadam et al. 2018, Gao et al. 2022).

In water clusters, more than 95% of the water molecules may form hydrogen bonds, resulting in large networks that may consist of thousands of molecules extending beyond 3.0 nm (Gao et al. 2022). Liquid water is a dynamical mixture of tetrahedral-like and "ring-and-chain"-like structures with a slight bias toward the former, thereby forming a three-dimensional hydrogen bond network continually undergoing topological reformation. The water molecules in the small clusters have a preference for being more tetrahedral than large water clusters (Gao et al. 2022). An important feature of water hydrogen bonded network is its variability (Gudkovskikh and Kirov 2022). The relative stability of the water clusters is determined by the polarization of hydrogen bonds (Tokmachev et al. 2010).

The polar property of water molecules also attracts charged molecules (ions) and hydrophilic molecules in its sorroundings. Water is therefor regarded as "universal solvent," an invaluable life-sustaining force. In biology, water's role as a solvent helps cells to transport and use substances like oxygen and nutrients (https://sitn.hms.harvard.edu/uncategorized/2019/biological-roles-of-water-why-is-water-necessary-for-life), and water is playing an important role as a universal solvent for a wide variety of chemical processes with ionic and organic substances present in e.g. the soil, the plant, free water bodies, and the landscape (Reichardt and Timm 2020).

The most fundamental chemical reaction in water is the water dissociation reaction, where water splits into its ions (self-ionization). As the oxygen attracts the shared electron more than the hydrogen, the electrons may move completely over to the oxygen. This reaction results in hydroxide ions (OH^-), and hydrogen ions (H^+). The hydrogen ions immediately connect to another water molecules forming hydronium (H_3O^+) (**Fig. 4**). The self-ionization of water is important in chemistry, biology, and technology. The ability of the water molecule to form strong hydrogen-bonded structures and to transfer electrons rapidly between the water molecules, and to ionize to produce positively charged hydronium and negatively charged hydroxide ions, gives water unique properties unlike any other materials (Chaplin 2022).

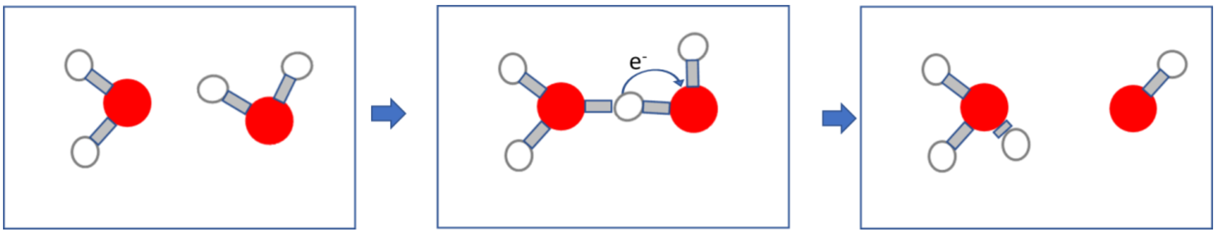


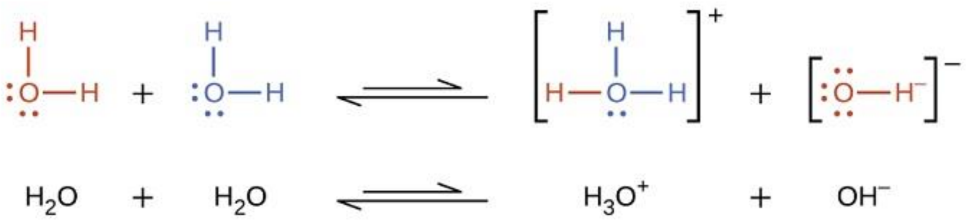
Fig. 4. Self-ionization of water (H_2O), showing oxygen (red circles) and hydrogen atoms (open circles), where the negatively charged electron (e^-) in one hydrogen atom is transferred over to the oxygen atom resulting in hydronium (H_3O^+) and hydroxide ions (OH^-).

When hydrogen loses its electron there is only the proton left. Thus, hydrogen ion is a proton. The transfer og a proton from one substance to another is an acid-base reaction. A hydrogen-containing substance that is capable of donating a proton to another substance is an acid, and a molecule or ion capable to accept a hydrogen ion from an acid is a base.

An aqueous solution that consists of a mixture of a weak acid and its conjugate base is a pH buffer. The pH in an acid-base buffer changes very little when a small amount of acid or base is added to it.

Water can act both as an acid and as a base.

Water self-ionization described in molecular formulas (https://en.wikipedia.org/wiki/Self-ionization_of_water#/media/File:Autoionizacion-agua.gif) :



The equilibrium constant for this reaction is Ka:

$$Ka = a_{H3O+} \times a_{OH} / a^2_{H2O}$$

The activity constant (a) of pure liquid water is defined as having a value of a=1, which gives:

$$Ka = [H_3O^+][HO^-] / [H_2O]$$

When pure liquid water is in equilibrium with its ions H_3O^+ and OH^-, the concentrations of these ions are equal:

$$[H_3O^+]=[OH^-]=1.003\times10^{-7}M$$

$$Kw=[1.003\times10^{-7}][1.003\times10^{-7}]=1.006\times10^{-14}$$

Although the proportion water molecules that dissociated into its ions is small, it results in many ions per liter of water. To put numbers on this: There are approximately 3.36×10^{25} molecules water per liter, and this also leaves a substantial number of the ions H_3O^+ and OH^- in a liter of water.

When the concentrations of H_3O^+ and OH^- are equal, the water is neutral. The H_3O^+ concentration is a quantitative measure of acidity: the higher the concentration H_3O^+ relatively to OH^-, the more acidic is the solution and conversely, and the lower this ratio is, the more basic is the solution. pH is calculated as the negative logarithm of the concentration $[H_3O^+]$, and and pOH is the negative logarithm of the concentration of [OH-]. In a neutral solution pH and pOH are 7.

$$pH + pOH = -\log(1.006\times10^{-14}) = 14$$

$$pH = -\log[H_3O^+] = 7 \text{ in a neutral solution}$$

$$pOH = -\log[OH^-] = 7 \text{ in a neutral solution}$$

There is an ongoing debate on the stability of the equilibrium constant (K) of water. Zhong et al. (2019) described that the equilibrium constant of water is different for the inner water molecules in bulk of water cluster (Ka^{bulk}) compared with the water molecules at the interface of water-air (Ka^{int}):

$$Ka^{int} > Ka^{bulk}$$

Although difficult to probe experimentally and challenging to simulate Moqadam et al. 2018 found that the rate of self-ionization is initiated by anomalies in the water structure and can thereby be manipulated.

Dynamics of a water molecules

The hydrogen structure is under constant intra- and intermolecular vibration (Yang et al. 2021). The vibrations are illustrated dynamically in this link https://www.youtube.com/watch?v=Yk6GZqjXclo

The dynamic nature of hydrogen bonding network of liquid water lay a fundament of the physical, chemical, and biological properties of water (Dutta and Benderskii 2017). The molecular vibration of liquid water can be observed as absorption across a wide range of wavelengths. In the visible part of the electromagnetic spectrum, the absorption of water is weak, which explains why water is transparent to us (**Fig. 5**).

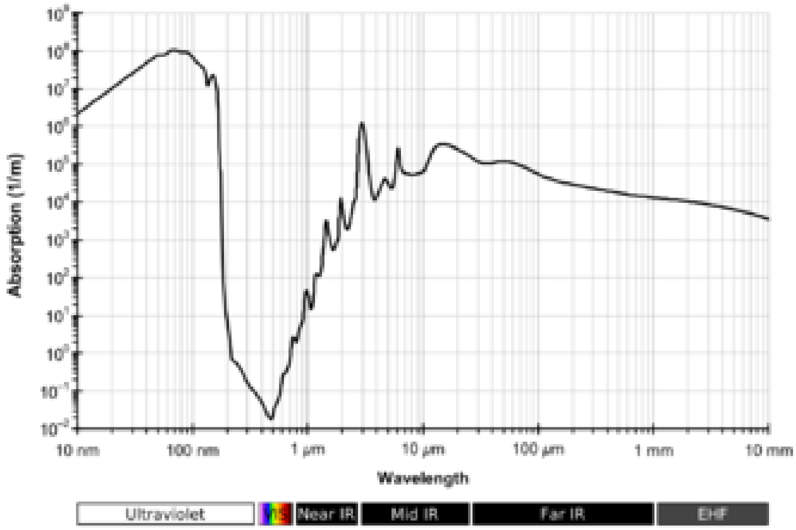


Fig. 5. Absorption spectra of liquid water (https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water). The absorption of water is low in the visible part of the electromagnetic spectrum, which is at wavelengths of 0,740 µm to 0,380 µm, corresponding to frequencies pr time unit of 4×10^{14} to 8×10^{14} cycles per second (Hz), and frequencies pr length unit of 25,000-14,286 cm^{-1} (wavenumber).

The vibration energy of water plays and important role in a wide variety of biological, environmental, and technological processes (Hsieh et al. 2013). The vibration energy of the water molecules is different within bulk water molecules compared to water at water/air interface. At the water/air interface, the hydrogen-bonding interaction is abruptly truncated, which imply free OH^- ions with higher vibration energy than the OH^- ions in bulk water. Free OH^- groups at hydrophobic interfaces affects the hydrophobicity and it can be observed by the contact angle of the water droplet.

Distribution systems of drinking water and its challenges

As described by WHO (2004): "A drinking-water distribution system provides a habitat for microorganisms, which are sustained by organic and inorganic nutrients present on the pipe and in the conveyed water. A primary concern is therefore to prevent contamination from fecal material that might build up near pipes or contaminate surface or soil water. Generally, bacteria present in the water and on surfaces are harmless, but they are at the base of a food-chain for other free-living organisms such as fungi, protozoa, worms and crustaceans. These organisms may be present in a distribution system, even in the presence of residual disinfectant, and the water can still be free of health risks. However, excessive microbial activity can lead to deterioration in aesthetic quality (e.g. tastes, odours and discolouration) and can interfere with the methods used to monitor parameters of health significance. Therefore, additional treatment may be needed to control the quality of the treated water in a distribution system, to prevent excessive microbial growth and any associated occurrence of larger life forms."

It is estimated that 30% of people worldwide lack access to safe, readily available water at home (Jalali 2021). In Norway, we use to think that the water quality is very good. However, there is a major need to improve the water distribution systems. The Norwegian Institute of Publich Health describe: "The problem with contaminated drinking water is likely to increase for years to come if old pipelines are not repaired or replaced at a faster rate. At the current rate of replacement, it is estimated to take about 145 years before all pipelines are improved to a satisfactory quality." (https://www.fhi.no/en/op/hin/infectious-diseases/drinking-water-in-Norway/).

Fig. 6. A water pipe from a Norwegian city (Drammen) laid down in 1970. The Norwegian Institute of Publich Health predict that there may be more stomach and gut diseases in the years to come as the water pipes in Norway are old and leaky (https://www.aftenposten.no/norge/i/zgz39/gamle-roer-kan-gi-mer-magesyke).

Water stagnation causes environmental conditions that favors bacterial growth (WHO 2022). In some ground water and in stagnated water in the distribution system bad taste and odor (rotten eggs feeling) may result from hydrogen sulfide, as a result of oxygen depletion and the subsequent reduction of sulfate by bacterial activity (WHO 2022).

As the bulk water flows through the water main, a pipe wall biofilm may form on the inner surface of the pipe in drinking water distribution systems and reduce the water quality (Liu et al., 2013).

The bacterial community structure and diversity are affected by the pipe materials, particles, disinfection strategies, and age of the biofilm. Controlling microbial growth during drinking water distribution is difficult because of the complexity of the distribution systems. The distribution systems are usually complex systems consisting of hundreds of thousands of meters long transport systems. The conditions are variable with different hydraulic conditions, different pipe materials, and different feed water quality. The survival and growth of microbes are complex processes that depend on the interactions of many factors, such as temperature, nutrients, water age, and types and concentrations of disinfectant residuals, and the survival and growth of microbes are complex processes that depend on the interactions of many variable factors, such as temperature, nutrients, water age, and types and concentrations of disinfectant residuals.

Under water stagnation, both in the nature and in water distribution system, the bacterial level in the water increases (Zastajajocih et al. 2010, Lautenschlager et al. 2010, Nghi et al. 2018, Chen et al. 2020, Ley et al. 2020). Indoor heating and overnight stagnation in water pipes is well known to increase bacterial growth and reduce the tap water quality (Zhang et al. 2022). The physical structure of pipes can affect water stagnation and degrade water quality (Zastajajocih et al. 2010, Ling et al. 2018). A secondary disinfection at household's tap using ultrasound technology is suggested as one alternative to contribute to control the drinking water quality Ley et al. (2020).

Redox chemistry

In the interface of the water/air surface, electric field is generated because OH^- is more attracted to the air, and H^+ are more attracted to the water. In bulk water, the water molecules is considered to be a stable and relatively inert molecule with little self-ionization. Near the water–air interface of micron-sized water droplets, however, water molecules are spontaneously oxidized to form hydrogen peroxide (Lee et al. 2019). In the water-air interface the oxidation leads to reactive oxygen species (ROS), including the hydroxyl radical (OH^-) and hydrogen peroxide (H_2O_2) resulting from the combination of two hydroxyl radicals. Redox molecules produced in the water/air surface of micron droplets are found to give bactericide effects (Lee et al. 2019, Duenlay et al. 2020, Kateshpour et al. 2022). This is an observation undergoing further research also by others. It is tempting to rice the question if self-ionization in the water/air surface may contribute to explain the well-known phenomenon that running water in nature is more safe than stagnating water (**Fig 7**).

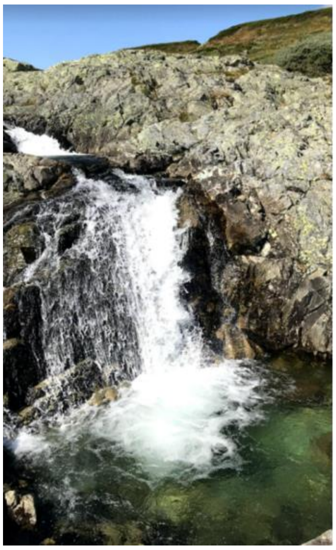


Fig. 7. Waterfall (to the left) and stagnated water (to the right).

Life is dynamic. It requires continuous supply of energy, and it is constantly evolving. Life has an inherited 'out- of-equilibrium' status that requires continuous changes to utilize energy for its cellular processes and to ensure appropriate adjustment according to the local environmental conditions. Redox processes play a fundamental role in this. Redox potential is needed to power living cells and to enable suitable environmental adaptations, and it is linked to most of the physiological processes (Santolini et al. 2019, Sies 2021). Santolini et al. (2019) defined the Redox interactions across different levels of organization as the 'Redox Interactome'.

Since the shared Nobel prize in medicine/physiology that was given to Ignarroe, Murad, Furchgott in 1998 (https://www.nobelprize.org/prizes/medicine/1998/summary/) for their discoveries on the importance of redox molecules, redox has been strongly focused within scientific research.

The redox (oxidation-reduction) state of a solution is measure as E_H where H stands for hydrogen and the unit volts, or it is expressed as negative logarithm of electrons pE = - log (e-). Different organisms and different compartments have evolved and adapted to redox potential and pH within range of the stability region of water (**Fig. 8**).

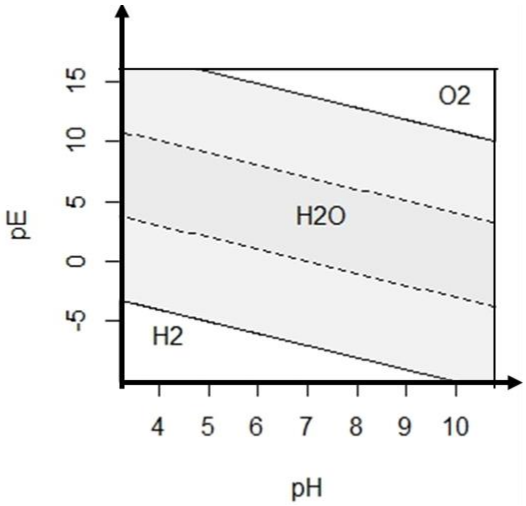


Fig. 8. pE-pH diagram of water. The stability region for water is within the outer solid lines at standard temperature and pressure. Above the upper line, water (H_2O) will oxidize to produce oxygen gas (O_2) and below the lower line water will be reduced to produce hydrogen (H_2). https://en.wikipedia.org/wiki/Pourbaix_diagram. Different organisms are adapted to their natural habits at different positions along the dark gray field between the hatched lines.

Anaerobe organism's cells have evolved in reducing environment where oxygen is absent, adapted to live in a lower region of the pE-pH diagram in **Fig. 8**, whereas aerobe organisms have evolved under oxygen availability, and thereby adapted to live in a higher region of the pE-pH diagram in **Fig. 8**. As a consequence, the same oxidation-reduction potential and pH environment may be beneficial to some organisms and detrimental to others (Oliver et al. 2021).

Through the whole natural circle of life (**Fig. 9**) each habit has their own optimal condition of pE and pH. For example, the gut bacteria grow well under conditions that are different from the optimal condition for human drinking water.

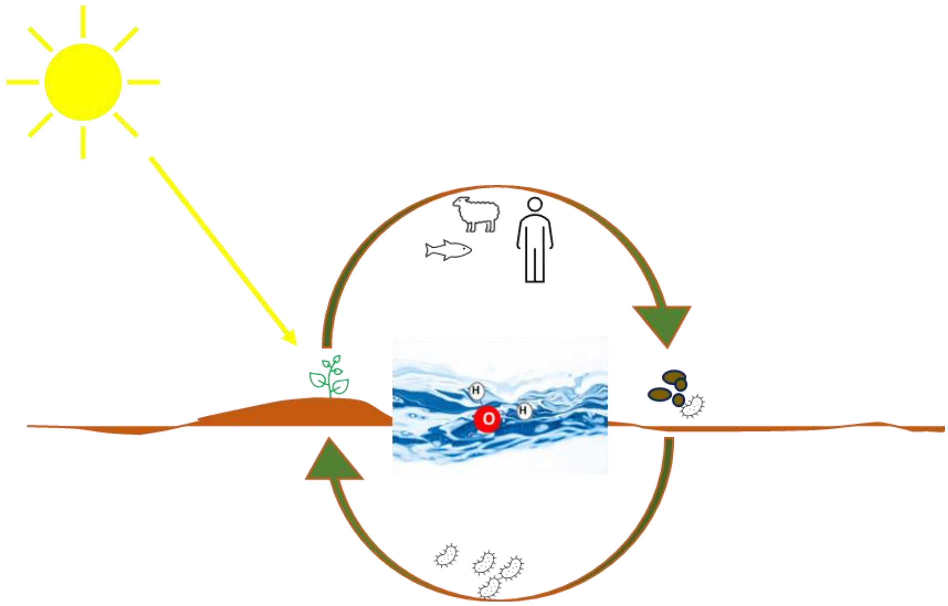


Fig. 9. Driven by the energy from the sun, captured by the plants during photosynthesis, all nutrition are circled in nature, with water as a necessary element. Each habitat on the circle has its own optimal condition with respect to pE and pH.

Highly sensitive and dynamic mechanism maintain the balance between oxidation, reduction and cellular homeostasis that is specific for different organisms, and it is compartmentalized. Pathogenic bacteria and their host have co-developed over the evolution, and both pathogens and hosts have evolved strategies to ensure their survival, and they use redox mechanisms to fight for their survival. During infection, the host produce an 'oxidative burst' at a level that may kill the bacteria. As a response the bacteria have devloped counterstratetis to survide the 'oxidative burst'. This process is different for different host and bacteria species, adapted to their natural environment. (Varatnitskaya et al. 2021).

Mechanisms of redox-sensing and systems that control the redox status of the cell are coupled. The cytosols (the inside of the cells) of both prokaryotic and eukaryotic cells have intracellular reducing environment to ensure that protein disulfide bonds rarely occur. The mechanism of redox sensing and control involve the ratio of the reduced and oxidated version of glutathione (GSH, and GSSG, respectively) and the ratio of reduced and oxidized version of nicotinamide adenine dinucleotide phosphate (NADPH and NADP+, respectively) (Zheng et al. 2009). The oxidated versions of these molecules, GSSG and $NADP^+$, tend to accept electrons, while the reductants (antioxidants) GSH and NADPH readily donate electrons. The intracellular distributions of these redox buffers are highly compartmentalized owing to specific localization of their biosynthetic enzymes and membrane permeability (Xiao and Loscalzo 2020).

Differences in the redox potential of the two major intracellular redox buffers GSH/GSSG and $NADPH/NADP^+$ will activate transcriptional factors to restore the redox balance and ensure suitable thiol-disulfide redox status. For example, when an 'oxydative burst' is produced by a host in fight towards bacteria attack, these redox buffers are thereafter involved in activating transcriptional factors to restore normal redox homeostasis.

Generation of ROS in the plasma membrane is a mechanism for cell signaling associated with activation of the enzyme by a variety of physiological response in the cell (Fisher 2009 and Private-Maldonado et al. 2019).

The utilization of nutrition to body energy are also redox processes. Eukaryotic cells produce energy from food by reactions with reactive oxygen in the inner mitochondrial membrane via the electron transport chain. The electron transport chain comprises an enzymatic series of electron donors and acceptors, where each electron donor passes electrons to an acceptor of higher redox potential, which in turn donates these electrons to another acceptor etc. The process continues down the series until electrons are passed to oxygen, the terminal electron acceptor in the chain. Each reaction releases energy because a higher-energy donor is converted to a lower-energy products by passing the electron to the acceptor (https://en.wikipedia.org/wiki/Electron_transport_chain). In **Fig. 10**, the cellular electron chain is compared with generation of waterpower from a waterfall. Without an initial difference in energy level between the altitude pool and the low pool, no energy will be generated. The same holds for the redox reaction in the cells, where redox potential is needed as a driving force. Strohmeyer (2022) explained the need for suitable oxidation-reduction potential (ORP) in a simple way: "a battery works only when a positive and a negative electrode are present to maintain an electrical current".

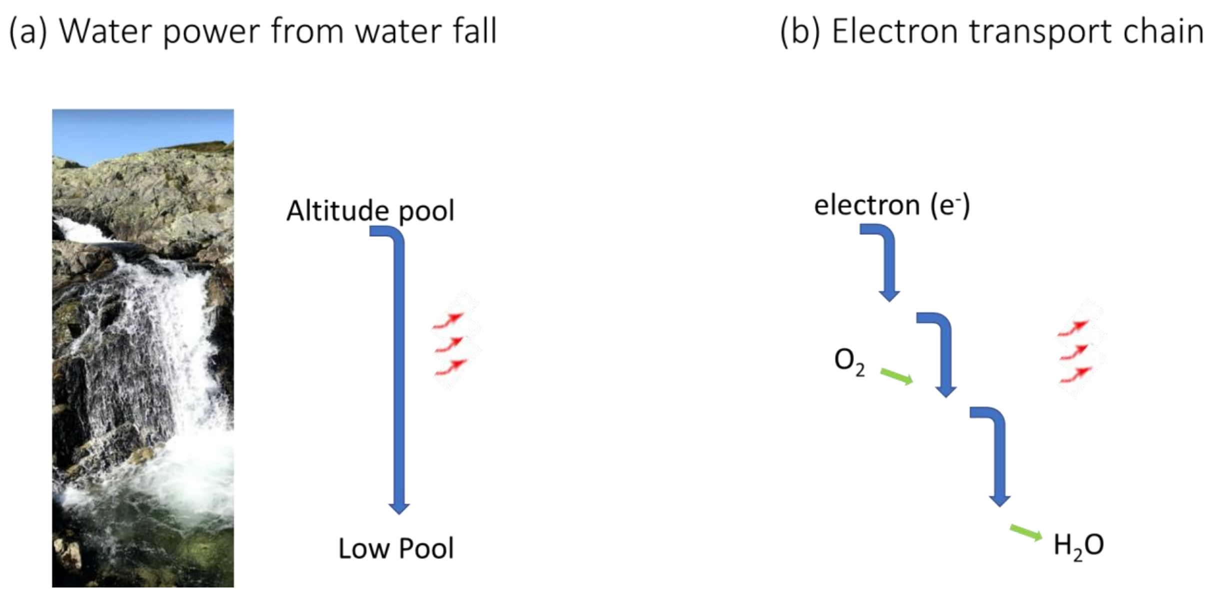


Fig. 10. A comparison. (**a**) Waterpower energy from a water fall and (**b**) cellular energy from the electron chain in the inner mitochondria.

As redox reaction is of major importance for bacteria inactivation, the redox potential is a vital indicator of the natural water condition and one of the main control parameters of wastewater treatment processes (Goncharuk et al. 2010). Molecules with oxidizing ability pulls electrons away from the cell membrane of bacteria, causing the bacteria to become destabilized and leaky (James 2004). For healthy aquarium, Strohmeyer (2022) pointed that the aquarium should aim for oxidation-reduction potential that provide enough oxidation to provide ample oxygen for the fish, allow for biological organic waste breakdown, and not allow too many bacteria in the water column, while at the same time, avoid oxidative stress to the inhabitants in the aquarium and allow optimum osmoregulation.

In water aquarium, water quality according to their needs is important (**Fig. 11**).

Fig. 11. Fish in an aquarium with good water quality.

Contact angle at the interface between solid and liquid

The contact angle between liquid and solid reflects the surface wettability (Bonn et al. 2009) and free energy in the interface between solid and liquid. The excess energy in the surface between solid and liquid are searching for partners, resulting in high wettability, whereas low energy of the surface is associated with low wettability (Trapuzzano 2019). Due to the hydrogen bonds between the water molecules, which contributes to high cohesive forces, the surface tension of water is one of the highest surface tensions for any liquid http://homeschool.scienceprojectideasforkids.com/2014/surface-tension/.

Freely suspended liquid takes on a shape that minimizes the free energy of the system (liquid and air in this case). For liquid water in the absence of gravity, this equilibrium shape is a perfect sphere that minimizes the surface area of the droplet. In the presence of gravity, however, liquid droplets can deform under their own weight (Trapuzzano 2019, 2020). External forcing with a large amplitude vibration at low frequencies that correspond to droplet volume resonance, is one way to alter the contact lines of droplets on a solid (Trapuzzano 2019).

Ultrasonic vibration affects the physical properties in liquid/solid interactions, such as wetting property of the liquid (Trapuzzano 2019). The magnitude of different vibration wetting effects (i.e., spreading) depends on the level of acceleration. For low frequency vibration, spreading of droplets is dependent on the amplitude of the liquid surface deformations. For a droplet that undergoes spreading, the amplitude of the surface waves diminishes as it reaches its final spread diameter.

Carbonate precipitation in water systems

Atmospheric carbondioxyd (CO_2) dissolved in water (H_2O) produce carbonic acid (H_2CO_3) and bicarbonate (HCO_3^{-1}). Grounds rich on the minerals Calsium (Ca^{+2}) and Magnesium (Mg^{+2}) releases these ions into the water causing calsium-carbonate percepitation ($CaCO_3$) (**Fig. 12**):

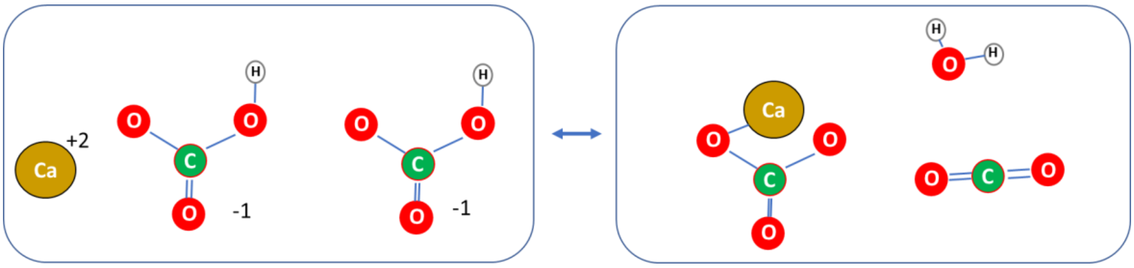


Fig. 12. Calsium-carbonate percepitation $Ca^{2+} + 2H_2CO_3 \text{->} CaCO_{3(s)} + H_2O + CO_2$

Calcium and magnesium in the water can thereby lead to water hardness problems. In addition to unpleasent taste it can cuase serios technical problems (Pecnik et al. 2016). Particular challenges are seen when hard water is processed in heat transfer equipmets such as heat exchangers, condensers, evaporations, cooling towers, boilers, pipe walls, and household applicants (Georgiou et al. 2018, Moya and Botella 2022, Brandão et al. 2022). The most common component of scale is calcium carbonate ($CaCO_3$). Scale formed on heat transfer equipments reduces the effects, and it may lead to rust accumulation, corrosion, increased growth of bacteria in drinking water, high machinery-mainteinance cost, decreaced productivity, equipment failure and even total damage (Georgiou et al. 2018). In recent years several new physical methods have been developed to solve the hardness problem including magnetic fields and ultrasound.

To avoid the problems of carbonate precipitation, there are different techniques in use. Some of the most common methods are chemical softening, the use of inhibitors to avoid precipitation, cation exchange, electrochemical and membrane treatments, among others. In addition to these techniques, which are considered “classical”, magnetic and electromagnetic techniques (Moya and Botella 2022) and ultrasound techniques are non-intrusive treatments (Vasyliew et al. 2018, Brandão et al. 2022, Kamar 2022).

Pulsed-power electro-magnetic fields are shown to prevent mineral scale formation on equipment surfaces, as well as reducing biofilms present in the piping system by changing the way minerals in the water precipitate. By this treatment the minerals form suspended clusters that turn into stable crystals and thereby avoiding hard-lime scale. Instead, non-adherent mineral powder is formed in the bulk water that is readily filterable and easily removed.

It is important to be aware that some of the method for analyzing water hardness only measures the level of the minerals, Ca and Mg, as an approximation. However, this does not reflect if the mineral ions (Ca^{2+} and Mg^{2+}) are bound to carbonate (CO_3^{2-}) and thereby causing a water hardness problem. A correct analysis method requires quantification to what degree the minerals is bounded to carbonate.

Sound versus ultra-violet radiation for water treatment

There are many methods for water treatments, with respective benefits and limitations. Waves are commonly utilized in water treatment.

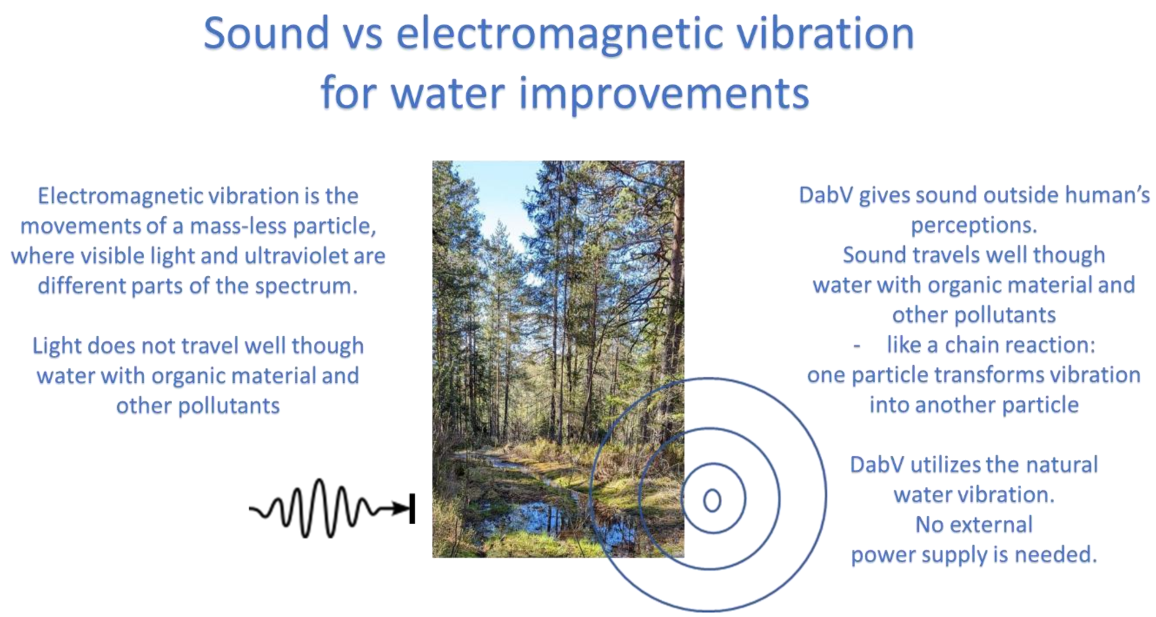


Fig. 13. An important difference between ultraviolet (UV) light and sound for water treatment is that UV light does not penetrate well through water with high level of organic substances, which gives high color in the water. In contrast sound such as ultrasound and infrasound moves well through dark materials and thereby works well for water with high content of organic pollution.

Although UV radiation is commonly used for water treatments (Alkan et al. 2006, Yang et al. 2014), it has challenges to peneterate particles. The UV transmittance is therefor affected by the particle content in the water, such as minerals, suspended solids, humic materials and organic dyes. Degradation of plant and animal material leaves substances that are yellow to black in color, with high molecular weight and refractory. As UV filtering is light, it does not penetrate well through water with dark color (Alkan et al. 2006). The UV light is therefor not well suitable for water that contains high level of dissolved and suspended solids. In contrast, as ultrasound is mechanical waves it peneterates well through the pollutant materials in water. An important effect of ultrasonic vibration is that it increases the wettability (Sarasua et al. 2021). The use of ultrasound driven by external power supply are shown to give cavitation, often with associated strong temperature incrfease.

To better understand the differences between water treatment by light and by sound, more in depth information on wave theory is hereby given.

Waves are described by the frequency (f), wavelength (λ), and velocity (v).

λ = wavelength (mm)
f = frequency (given by cycles per second, 1/s = Hz, or by cycles pr cm, cm^{-1})
v = velocity (m/s)

Frequency is a measure of the number of wave crests that pass a fixed point per second. At higher frequencies, more wave crests will pass the point each second; for this to happen, the wavelengths must be short. As frequency decreases, fewer waves will pass the fixed point per second, and the wavelengths are relatively longer. Thus, there is an inverse relationship between wavelength and frequency (**Fig. 14**), described mathematically as:

$$v = f \times \lambda \Leftrightarrow f = v/\lambda \Leftrightarrow \lambda = v/f$$

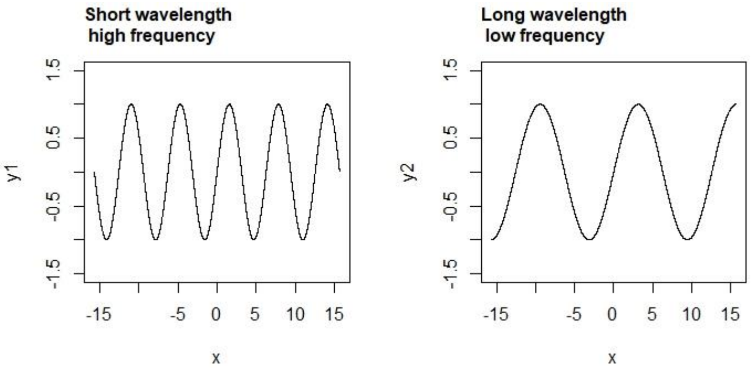


Fig. 14. The frequency and length of waves are inversely related.

Energy (E) is directly related to the frequency, the higher the frequency the higher the energy. In mathematic terms:

$$E = h \times f \Leftrightarrow h = E/f$$

h is a constant (Planck's, $h=6.62607015 \times 10^{-34}$ m2 kg/s) that relates the energy to the frequency.

At a constant speed of the waves (v) there is a one-to-one correspondence between wavelength and frequency as given in the equation above; the higher the frequency (f), the higher the corresponding energy (E).

Thus, both light and sound are waves, with major differences in the basic principles. Light is an oscillating electric and magnetic field, where visible light is only a small fraction of the electromagnetic spectrum (**Fig. 15**). Visible light corresponds to a wavelength regions from about 400 to about 700 nm, the longer waves are radio waves [>1 cm] and microwaves [1 mm-1 cm], and the shorter waves are ultraviolet [10 nm-380 nm], x-rays [0.01nm-10 nm] and gamma rays [<0.01nm].

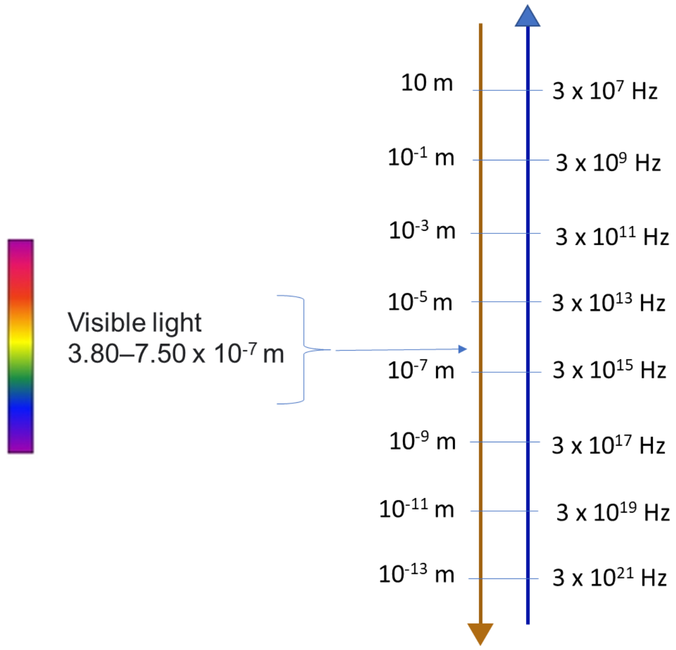


Fig 15. The electromagnetic spectrum where the wavelength (λ) and the corresponding frequency (f) is given when traveling through vacuum at the speed of light which is v= 299 792 458 m/s ≈ $3*10^8$ m/s and f = v/λ.

Electromagnetic waves are synchronized oscillations of electric and magnetic fields transvers of the direction of the movements (**Fig. 16**).

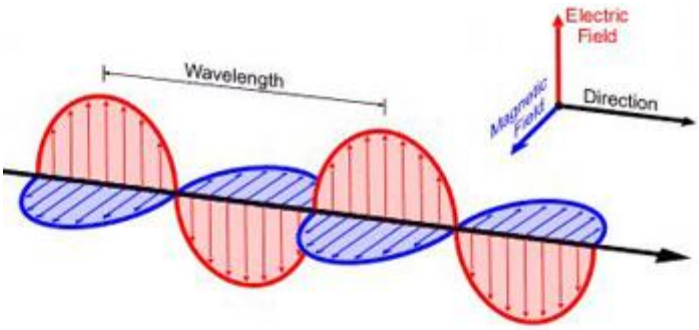


Fig 16. Electromagnetic waves comprises both magnetic and electric waves that oscillate at right angles of each other, and both waves move along a shared axis in the direction the combined wave is moving (https://wiki.seg.org/wiki/User:JudySmith/Electromagnetic_Spectrum).

For convenient purposes, the given unit of electromagnetic waves are often different depending on where on the scale that is presented. The longest waves, like radio and microwaves, are often presented by the frequency; the middle range of waves, like infrared, visible light, and ultraviolet, are often presented by their wavelength; and the shortest wavelengths, like x-rays and gamma rays, are often presented by the amount of energy they produce. However, all these parts of the spectrum have corresponding wavelength, frequency and energy, given constant speed.

Electromagnetic radiation has both particle and wave properties (Hill 2009). It behaves as waves, with properties of wavelength and frequency, and as particles, quantized in discrete packets of the massless photons. The name photon is derived from the Greek word for light. (https://en.wikipedia.org/wiki/Photon). In quantum mechanics, electromagnetic waves are considered as resulting from the high-speed movements of the uncharged massless particle photons, which in vacuum travels in the speed of light (appr. 3.00 x 10^8 ms^{-1}). Thus, to put this into a more easily understandable concept, when our eyes observe light from the sun we observe the mass-less particle photons that has travel all the way from the sun till it hits our eyes.

Sound on the other hand, is mechanical waves that can be considered as chain reactions, where each particle travels only a short distance. The sound waves are waves that travels in the same direction as the movement; thus, the waves are longitudinal. Sound needs material for its travel (https://en.wikipedia.org/wiki/Sound). When an object vibrates, it causes movement in surrounding air molecules. The vibration of one molecule affects molecules close to them, causing them to vibrate as well which results in longitudinal waves as illustrated dynamically in this link: (http://blog.soton.ac.uk/soundwaves/files/2013/12/monopolfinalptpt.gif).

The "chain reaction", caused by the movement of sound, keeps going until the molecules run out of energy as it loose energy by passing through medium. The following link illustrate sound as longitudinal waves (http://blog.soton.ac.uk/soundwaves/files/2013/12/monopolfinalptpt.gif).

Humans can only perceive a minor proportion of the whole spectrum through their ears (**Fig. 17**).

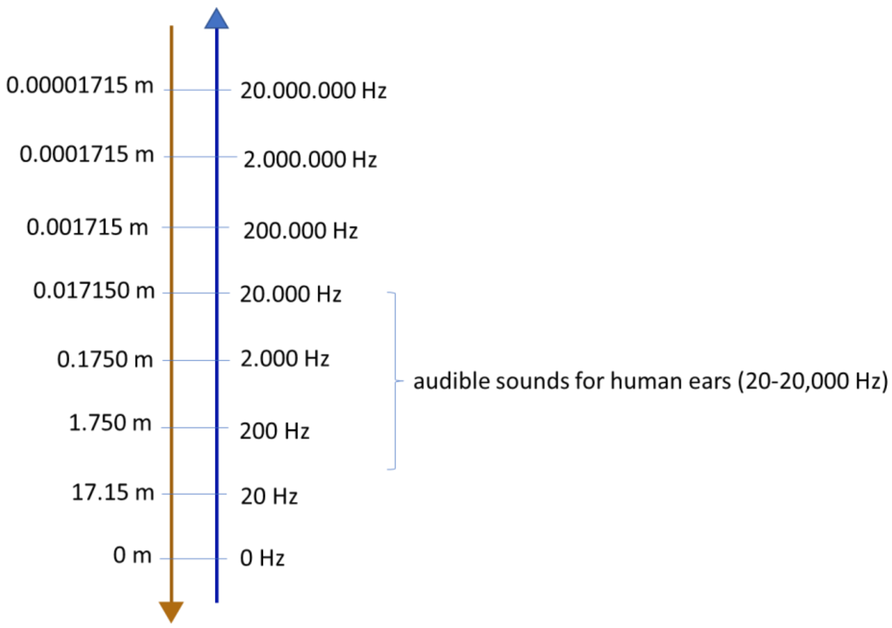


Fig. 17. The spectrum of sound from 0 to 20 MHz where the wavelength (λ) and the corresponding frequency (f) is given when travelling through air where the speed of sound is 331.5 meters/sec at 0° C and normal atmospheric pressure, and f = v/λ.

Water waves are also mechanical waves, but transverse to the movements.

The principal differences between sound waves, water waves and electromagnetic waves are illustrated in **Fig. 18**.

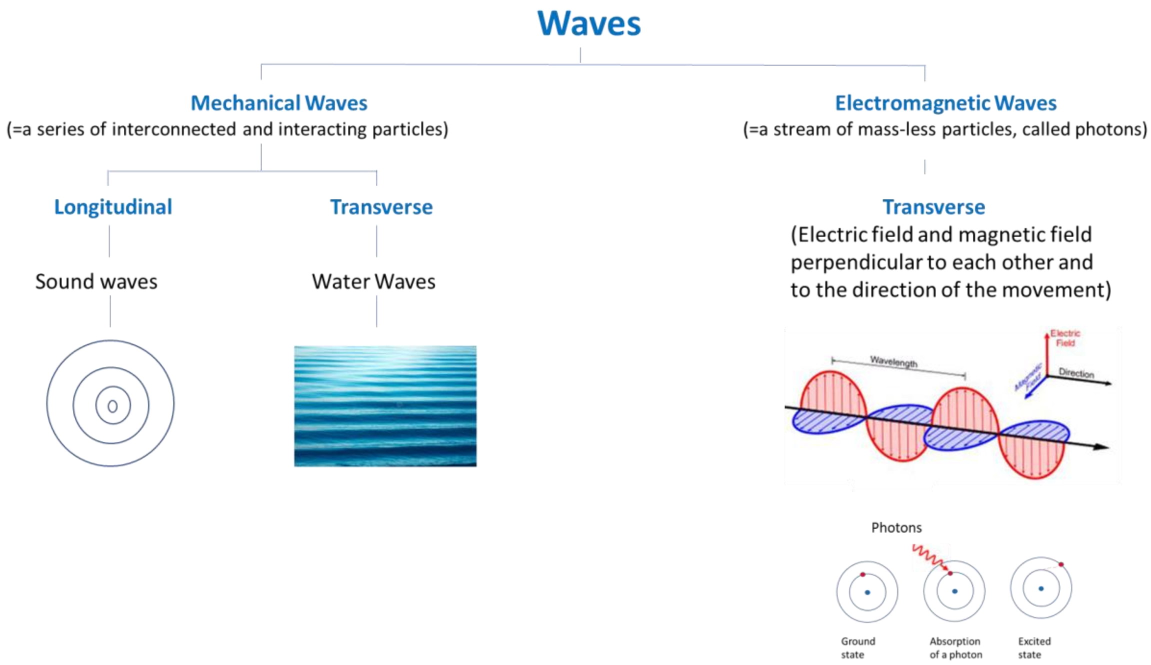


Fig. 18. Mechanical waves (sound and water waves) and electromagnetic waves.

Electromagnetic waves and mechanical waves have fundamentally different properties (Wayne 2022):
https://www.steadyrun.com/difference-mechanical-waves-electromagnetic-waves
https://www.pinterest.com/pin/378513543658145925

- Mechanical waves require material medium for the propagation. Electromagnetic waves do not require material medium for their propagation.
- Mechanical waves are formed due to vibrations of the particles of the medium. Electromagnetic waves are formed due to varying electric and magnetic fields.
- The speed of sound waves is low (v=332 m/s at 0°C in air, and about 1500 m/s in water at room temperature), whereas the speed of electromagnetic waves is very high (nearly 300,000 km/sec = $3 * 10^8$ m/s in vacuum).
- Mechanical waves can be transverse or longitudinal in nature. Water waves are transverse, thus they are perpendicular to the movements of the waves, whereas sounds are longitudinal.
- Electromagnetic waves are transverse in nature with both particle and wave properties.

In the electromagnetic waves the electric field and the corresponding orthogonal magnetic field oscillate with the same spatial and temporal periodicity. When light gets into a material, it interacts with the charged particles within the atoms where the interaction of the electric field with matter is dominating, and the energy can be transferred to the electrons. If the energy of the photon corresponds to the energy level between two layers of electron shells, this electron becomes excited and thereby raised to a higher energy level (**Fig. 19**). The absorbed energy can be released by emission back to its original state, or the energy can be converted to heat or released for work.

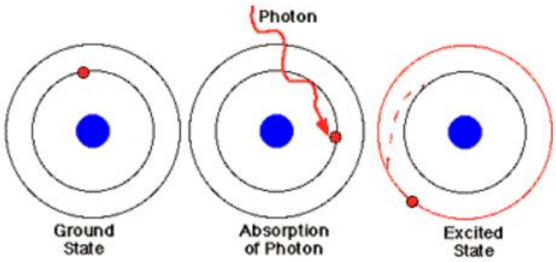


Fig. 19. When a photon of light hits an atom, it can transfer its energy to the outer electron. If the energy of the photon corresponds to the energy level between two layers of electron shells, this electron becomes excited and thereby raised to a higher energy level. The absorbed energy can be released by emission back to its original state, which releases fluorescence, or the energy can be converted to heat or released for work.

Photons travels in straight lines in vacuum without losing energy (https://en.wikipedia.org/wiki/Light, https://aty.sdsu.edu/explain/optics/optintro.html). Transparent materials, such as air, water, and glass, have small internal variations in their optical properties that bend the path of the light, where different light colors bend at different degrees resulting in optical phenomena such as rainbows (https://commons.wikimedia.org/wiki/File:Rainbow1.svg). When light encounters a material, depending on the wavelength of the light and the nature of the material, photons interact with the material by some combination of absorption, reflection, and transmission.
https://en.wikipedia.org/wiki/Transparency_and_translucency

Sound waves are illustrated and visualized in the following links.
https://en.wikipedia.org/wiki/Longitudinal_wave#/media/File:Onde_compression_impulsion_1d_30_petit.gif
https://www.khanacademy.org/test-prep/mcat/physical-processes/sound/a/sound-is-a-longitudinal-wave
http://blog.soton.ac.uk/soundwaves/files/2013/12/monopolfinalptpt.gif

Ultrasone has frequency above 20 kHz (Doosti et al. 2012, Brandão et al. 2022), which is above the range (20 Hz to 20 kHz) at which humans can hear and below the mega-sonic region (>600 kHz). On the other side of the scale of humans hearing range is infrasound, with a frequency below 20 Hz. https://en.wikipedia.org/wiki/Infrasound.

Different animals have different frequencies range that they can receive sound https://slev.life/animal-best-hearing. Some anials such as birds and fish are more sensitive than humans to sounds with frequencies below 40 Hz, and some animals are exceptionally good at perceiving low-frequency vibrations through their skin (Buskirk et al. 1981). The high perception of low-frequency vibration explains why animals can sence earth quicks where humans do not have the same sensitivity (Buskirk et al. 1981).

Sound technology at ultrasonic frequencies is often described as innovative technology for different applications of water treatment processes such as membrane filtration, turbidity and total suspended solid reduction, algae removal, disinfection process, water softening process and other types of pollutants removal (Xia et al. 2008, Ballo et al. 2021, Wang et al. 2021, Brandão and coworkers 2022). Acoustic cavitation generated by ultrasound (frequency > 20 kHz) is considered a safe and convenient tool to produce free radicals in bulk solutions without the use of external catalysts (Ashokkumar et al. 2016, Mondal et al. 2021).

In the ultrasonic frequency range, microbubbles may be generated, giving rise to cavitation energy when such microbubbles collapse (Entezari and Tahmasbi 2009, Brandão and coworkers 2022). Both high and low frequency ultrasonic waves are used for water treatment. The concept high-frequency ultrasonic waves (HFSU) refers to sound waves with an ultrasonic frequency of linear probe exceeding 10 MHz (https://www.storkultrasonic.com/what-is-high-frequency-ultrasound.html), and low-intensity pulsed ultrasound (LIPUS) have frequencies of 1.5 MHz (https://en.wikipedia.org/wiki/Low-intensity_pulsed_ultrasound).

Svendsen et al. 2017 found, in preliminary laboratory scale, that ultrasonic cavitation is effective in killing salmon lice even by relatively short exposure times. They suggested that cavitation may be a candidate disinfection method with the potential to be utilized as an additional tool for improved disinfection of discharge water from well boats, in particular with respect to sea lice.

Piezo technology

Piezo technology is one of several transduction mechanisms that can convert vibratory energy to useful energy, and this has led to development of nonconventional power sources during the past two decades. The piezoelectric effect, discovered by Jacques and Pierre Curie in 1880, is useful in transducers to generate and detect ultrasonic waves in air and water. Piezoelectric effect can convert kinetic or mechanical energy into electrical energy, and this direct piezoelectric effect is how ultrasound transducers receive the sound waves. The same effect can be used in reverse – inverse piezoelectric effect – whereby the application of an electric field converts electrical energy into kinetic or mechanical energy, and this is how ultrasound transducers produce sound waves (Safaei et al. 2019, Das Mahapatra et al. 2022).

The piezoelectric effect originates from the distribution of ions in the crystalline structure of certain materials. In the absence of an external force, there is a steady-state equilibrium between the positive and negative electric charges in the material, and it remains neutral. Compressive stress may cause changes in polarization leading to a piezoelectric effect (Das Mahapatra et al. 2022).

The conversion of dynamic mechanical energy into electrical energy using piezoelectric materials is typically called piezoelectric energy harvesting, where low-level energy, in the order of microwatts to milliwatts, are used to power low-power electronics, providing a permanent, autonomous power source that does not need replacement or maintenance. Energy harvesting using piezoelectric transducers including power scavenging from fluid sources, the human body, animals, infrastructure, and vehicles, and well as multifunctional and multi-source harvesting (Safaei et al. 2019).

The direct piezoelectric effect may be utilized for energy harvesting, wherein an applied force leads to electrical charge generation. Initially, the dipoles present in the piezoelectric material align randomly between two electrodes. Upon application of an electrical field, the dipoles align in the same direction as the applied field. Under the application of compressive force in the vertical direction, the material is polarized due to compressive strain, inducing piezoelectric potential between the electrodes. By this process, an output signal is acquired. On releasing the applied force, a slight tensile force develops that induces a reverse piezoelectric potential. A piezo electric energy harvester allows many distinct vibration modes to be used to generate electrical power, and it can be operated with limited strain and promotes longevity (Lee et al. 2015).

Flowing medium offers relatively high-density kinetic energy which is usually readily available (Safaei et al. 2019). Piezo electric technology has been developed for water disinfection resulting from electroporation and penetration of ROS of the microbes, and it has been used in waste treatment (Zhao et al. 2022).

The piezocatalytic efficiency of most piezoelectric materials is relatively low, and they require either additional poling treatment to align the polarization, or the use of external high energy input such as high-frequency ultrasound (KHz-MHz) to promote the deformation of piezoelectric materials. The poling treatment normally involves tedious process, yet the poled piezoelectric powders may be gradually depolarized due to residual stress release, and ultrasonic irradiation can consume high energy and produce a high-decibel sound harmful to human hearing.

Utilization of selfpowered vibration energy

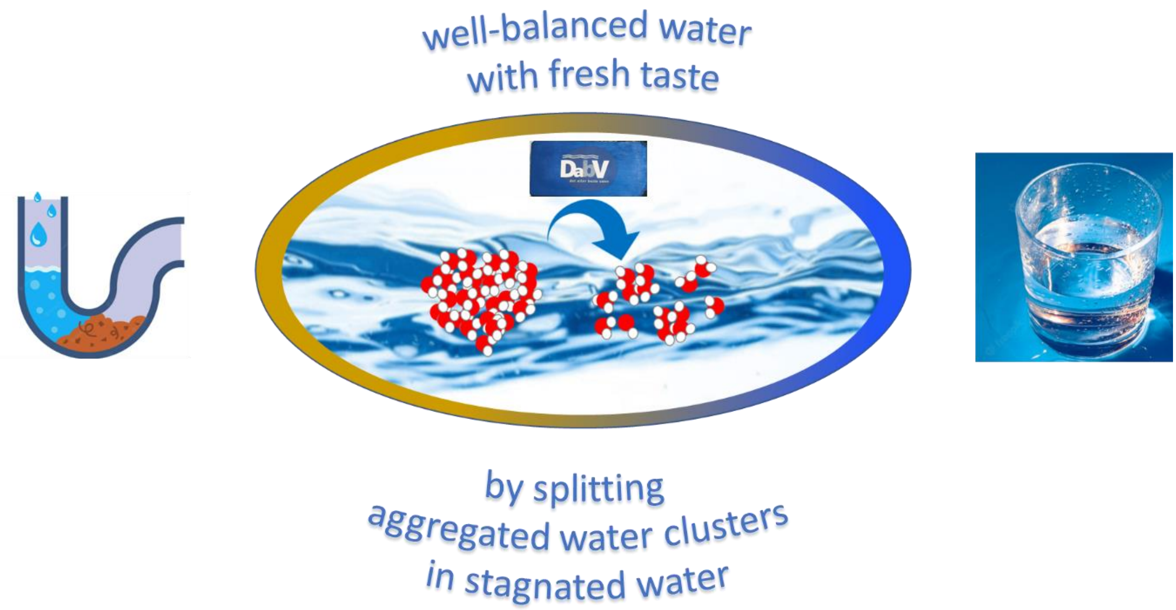
Vibration energy represents a persistent presence in nature and manmade structures (Safaei et al. 2019), and energy harvesting from vibration energy is a topic of intense interest with the aims to convert ambient forms of energy such as mechanical motion, light, and heat into useful energy (Chen et al. 2014, Safaei et al. 2019, Sharma et al. 2021, Zhang et al. 2022, Das Mahapatra et al. 2022).

Self-powered harvesting technologies are in focus using different technologies aiming for harvesting low-level vibration energy to provide a permanent device that does not need replacement or maintenance is in focus (Chen et al. 2014, Safaei et al. 2019, Sharma et al. 2021, Zhang et al. 2022, Das Mahapatra et al. 2022). Such technologies can be utilized for a variety of applications such as water splitting, catalysis, corrosion protection, degradation of pollutants, disinfection of bacteria and material synthesis.

Little focus has been paid to naturally derived hydromechanical energy (<100 Hz) (Liu et al. 2021). Low-frequency hydromechanics is employed as mechanical energy resource to achieve efficient disinfection by formation of ROS (Liu et al. 2021). The method is demonstrated for inactivation of bacteria and virus and reduction of total organic carbon content in wastewater, providing a green and feasible way for water disinfection.

DabV is an optimisation utilization of vibration energy for water treatment

DabV is a technology, based on piezo technology, developed for autonomous harvesting vibration energy from fluid, that is developed over many years for optimal water treatment at low cost. The DabV unit gives water with pleasant taste, and it contributes to bactericide effects and water softening.



No external power supply is needed

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