BIOMIMICRY WATER TOOL

Nature's Solutions to Water Treatment Challenges

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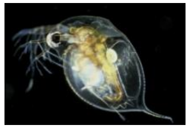
Particulate removal

The filtration process is often used to remove particulate matter from water. Examples of particulates in water include

- clay and silt particles,
- microorganisms,
- colloidal and precipitated humic substances and other natural organic particulates,
- precipitates, often metal precipitates from softening processes.

Biomimicry research has revealed a number of innovations for particulate removal. The innovations are inspired by natural organisms and systems that are specialists in removing particulates from water or other fluids, and based on millions of years of natural selection have evolved highly efficient and effective sustainable solutions in each case. The following subsections summarise the key innovations from natural "champion" or specialists in each case. They are classified as champions in this context based on the fact that of all the organisms that perform this particular function, these organisms are the specialists identified in each case.

Removal of multiple particle sizes/types.
Self-cleaning filters.
(Balaenidae Whales)



Self-cleaning filtration of very small particles
(Daphnia)

Filtration of a large range of particle sizes
(Flamingos)

Cross-flow filtration of a range of particle sizes. Hydrosol filtration of particles smaller than filter size
(Gill Raking Fish)

Filtration of small particulates using grooved channels with moving elements and a mucus-like substance
(Peacock & Feather-duster worms)

Filtration of very small particulates (using a slimy membrane net)
(Salps)

Filtration of range of particle sizes (by means of a complex particle trap & mucus)
(Sea Cucumber)

Filtration of small particulates (by means of a basket-like membrane, mucus & siphon)
(Sea Squirts)

Separation of blood from water
(Vampire Bats)

Filtration of particulates through a fine-mesh basket
(Venus Flower Basket)

Back

Balaenidae Whales

Filtration of multiple particle sizes/types through membrane sheets with directional variation to allow for self-cleaning.

Figure 1: Balaenidae Whale

Biomimicry Innovation:

This innovation is inspired by the structure and filtering mechanisms of the Balaenide Whales. The filtration mechanism is a highly-efficient non-pressurised self-cleaning solution for separating solids from wastewater streams, and offers several benefits and advantages over conventional systems. It can overcome problems with traditional systems of treating industrial and municipal wastewaters, which typically involve segregation of contaminants by less effective settling or flotation methods, which can create adverse effects like increased odours, and significant maintenance issues, such as sludge handling. (Ask Nature 2009) Self-cleaning filtration inspired by the baleen whale can yield much reduced costs for maintenance of wastewater treatment systems, increased water recycling/reuse and easy recovery of by-products.

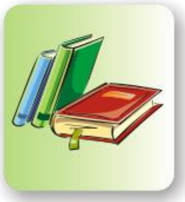

Design principles


Possible applications


Biological Foundation


Context


Case studies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Balaenidae Whales

Design Principles

Structure:

Sheets of filters, feathered at the edges that hang down like stiff, parallel curtains from the upper surface. Water is passed through the filters and particulates are captured on the surface of the filter. The biomechanical shape of the filtration cavity induces internal pressure changes via Bernoulli and Venturi Effects which promote the flow of water through the filters via both hydrodynamic and hydraulic effects

Process:

The combination of a sweeping action of a cleaning swipe motion (through water pulse or scraping device) and the reversing of the water flows during filtration, enables filtration of particulates, then cleaning of the filters prior to the next filtration process.

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Balaenidae Whales

Possible Applications

Filtering various sizes of particles out of water. Self-cleaning filters. Baleen filters have been used in industrial and municipal wastewater treatment systems, in mining applications, and in food and beverage production. Baleen filters can be used for load reduction and solids dewatering and polishing. They can filter a variety of mediums, including grease, blood, oil, and semi-aqueous constituents to a specified micron rating (Baleen Filters, 2011). In wastewater treatment, these filters can be used to filter out fibres and rags at the inlet works, with minimal operating and maintenance costs.

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Balaenidae Whales

Biological Foundation

Biological Strategy

Whales belonging to the suborder Mysticeti (balaenid whales) comprising the families Balaenidae (Bowhead and Right whales), Balaenopteridae (Humpback, Fin, Bryde's, Sei, Minke and Blue whales) and Eschrichtiidae (Gray whales). The word 'Baleen' is an anatomical description for the whalebone that belongs to a group of filter-feeding whales. The baleen is essentially the filter mechanism that enables the whale to collect plankton, small fish and other marine organisms from the water during feeding. The combination of a sweeping action of the tongue and the reversing of the water flows as the whales dive and re-surface during feeding, enable them to capture and strain food, then clean their baleen prior to the next dive. All Mysticetian whales filter-feed using baleen plates, but the feeding mechanism differs amongst and within the 3 families of this suborder. The Balaenopteridae family of whales (Rorquals) forage using a technique known as lunge-feeding, which represents the largest biomechanical event on earth (Potvin, Goldbogen and Shadwick 2012). The Balaenid family, on the other hand, feed by continuous filter feeding.

Biological Mechanism

Lunge feeding

The Balaenopteridae whales (Rorquals) lunge dive, accelerating to high speeds while simultaneously opening their mouths to large gape angles. The water pressure generated by these processes allows the mouth to engulf large volumes of prey-containing water (Potvin et al., 2012). The walls of the throat (buccal cavity) are surrounded by extensible tissue known as the ventral groove blubber which unfurls like a parachute to accommodate large volumes of water. The quantitative influx of water into the buccal cavity via extension of the ventral groove bladder is controlled by eccentric muscle action which results in a reflux, adding significant hydrodynamic drag to the lunge process (Potvin et al., 2012). At this point, the forward movement of the whale slows considerably and the engulfed water is filtered at several cubic metres per second (Goldbogen, et al. 2011). It is thought that the rebound reflux increases the efficiency of cross-flow filtration during purging of the engulfed water/prey, preventing prey from sticking in the baleen (Potvin et al., 2012). In the basic lunge-feeding model proposed by Potvin et al. (2012), the mouth closure and pre-purging is divided into two sub-stages: bulk ejection and partial ejection (Figure 1). The angle of the buccal cavity wall is shallower during partial ejection, so hydrodynamically there is less rebound and ejection of water during this sub-stage (Figure 1). The purging mechanism itself (stage 5) has still not been comprehensively described.

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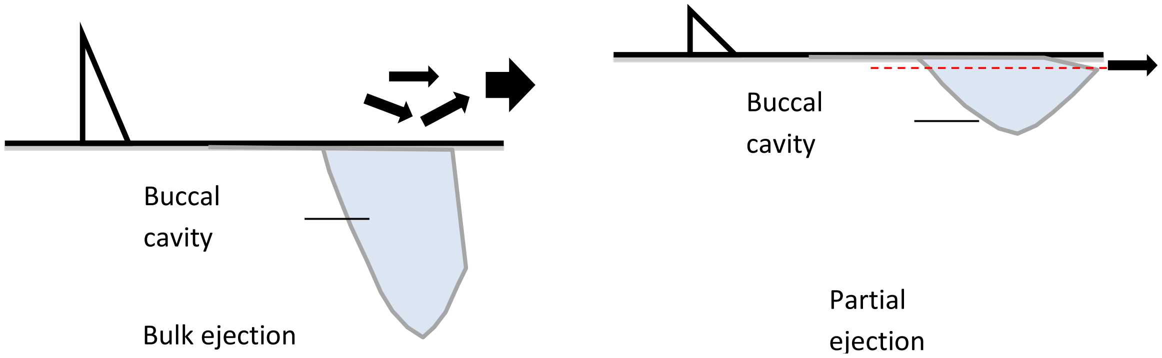

Figure 1: Schematic diagram showing the two sub-phases of the mouth-closing and pre-purging phase of a lunge-feeding whale. In the first sub-phase (bulk ejection), the mouth is still relatively open and there is significant rebound of engulfed water throughout the buccal cavity. During the second sub-phase (partial ejection), much of the water (below the doted red line in the diagram) becomes stationary.

Continuous feeding

The Balaenid family of whales filter-feed continuously. The oral cavities of these whales are designed for continuous, unidirectional flow of water and the baleen is exceptionally long, springy and finely fringed (Werth, 2004). As the whales swim with open mouths, it is thought that velocity changes outside the head, creating a pressure gradient, and enabling water to enter the mouth at the point of high pressure and exit at a point of low pressure (Werth, 2004). Mathematical and physical models suggest that the biomechanical shape of the mouth of the whale induces internal pressure changes via Bernoulli and Venturi effects which promote the flow of water through the baleen via both hydrodynamic and hydraulic effects (Werth, 2004).

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Balaenidae Whales

Context/Working Conditions

An artificial baleen-type filter has been developed and patented by Baleen Filters (Pty) Ltd. (2011). Baleen filters are manufactured with a range of micron ratings for the removal of suspended solids from a wide range of wastewaters, including pre-screened municipal, agri-industrial, abattoir and tannery wastewaters. These filters can handle up to 10l/s of organic-rich wastewater and 25l/s of dilute wastewater at filter screen media of 100µm/m^2 and 50 µm/m^2, respectively. They can remove up to 100% of visible solids and 90% of suspended BOD and COD from raw influent streams. However, these filters do not remove ions and microorganisms.

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Balaenidae Whales

Existing Biomimicry:

The baleen filter technology is an adaptation of this natural technique, used by whales to keep their baleens clean and free from long-term deposits. The baleen filter uses a double act of high pressure, low volume sprays, one which dislodges material caught by the filter media, whilst the other spray sweeps the material away for collection. This process removes even the most troublesome of constituents such as grit, suspended and fibrous matter, grease and oil from water without blocking the filter. As water flows through the filter media, solids initially suspended in the water are left behind. But before they accumulate to block the screen media the second spray transports these contaminants away from the filtering zone, enabling the filtering process to continue without disruption (Baleen Filters 2011). Major benefits for industry include:

- Lower capital costs, compared with traditional settling and clarifying methods.
- Very versatile - can be adapted for use as a mobile clean-up system and emergency pollution response.
- Small footprint - saving valuable land.
- Ideal for resource recovery.
- Environmentally friendly - reduced or no chemicals required.
- Low operating costs, low energy needs and low maintenance.
- Simplicity in industrial wastewater management.

On Barrow Island, in Western Australia, baleen filters are to be used in four desalination plants in conjunction with reverse osmosis filters. A coal mine uses baleen filters to recover +90 micron saleable coal from the tailings stream. Another mine removes all solids from the tailings stream to 25 microns, and reuses the water as process water.

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Balaenidae Whales

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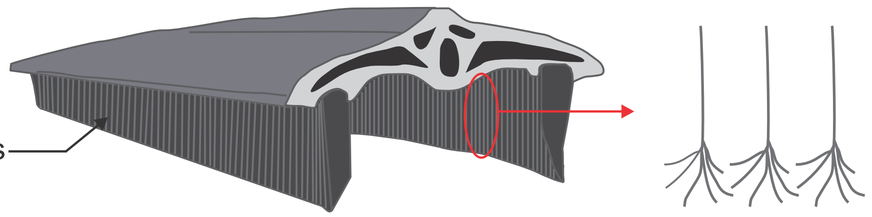
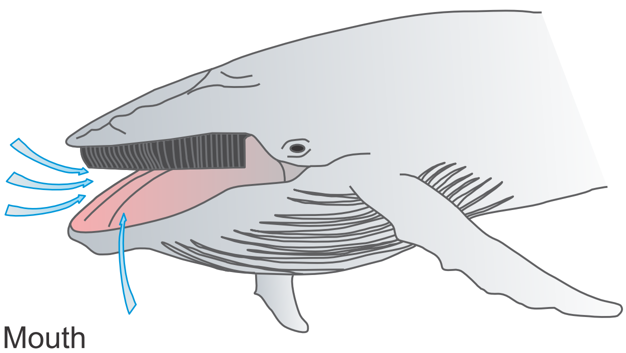
BALAENIDE WHALES

Mouth of whale

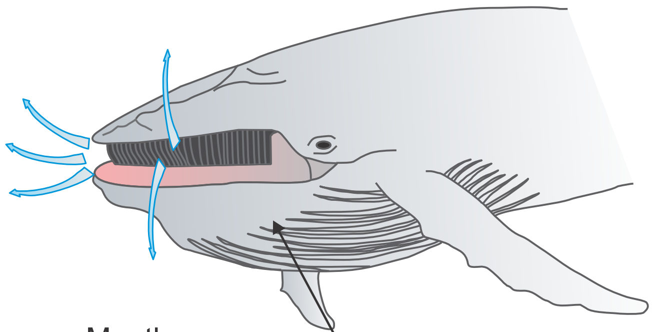


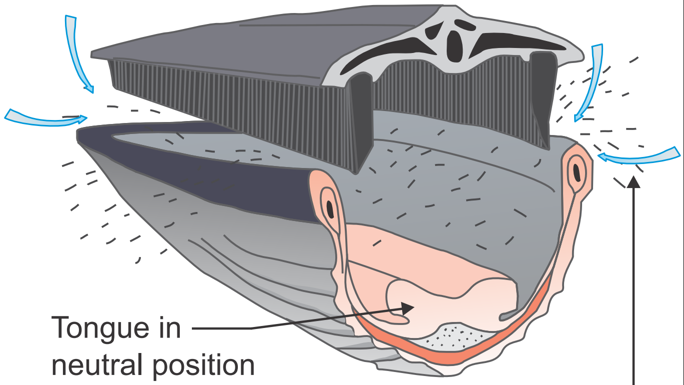
Feeding process:

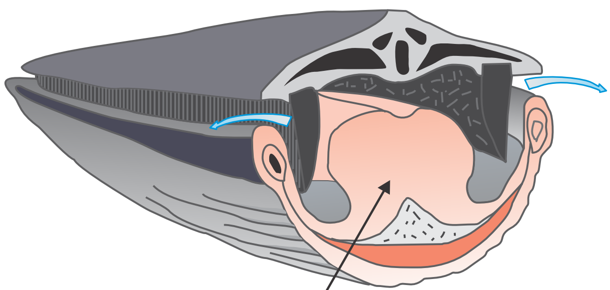
1. Copious amounts of food and water engulfed



2.
- Using movement of the tongue, water is forced out of the baleen
- Food trapped in the baleen, collected in the throat and then swallowed







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Daphnia

Self-cleaning filtration of very small particles

Figure 1: Illustration of membrane containing aquaporins

Biomimicry Innovation:

This innovation is inspired by the structure and filtering mechanisms of the daphnia. The filtration mechanism is based on tiny bristles that can move at different speeds allowing them to operate at different Reynolds numbers. They can filter particles as small as 1 micron. Self-cleaning is enabled by filter combers that act as sweepers to remove particles and transport them to a capturing vessel.

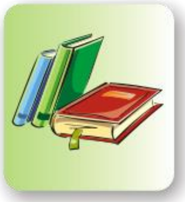
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Daphnia

Design Principles

Structure/Process:
Tiny bristles on fine fibres that move in water/fluid. The size of the fibres and speed at which they move determines what function the movement will have. Large and fast movements result in a rake or filter function, while small and slow movements enable mobility.

The fibres act as a suction and pressure pump. The third and fourth fibres have screens that filter particles from water. The steps involved include:

1. Capturing of the particles by tiny bristles.
2. Removing the particles by means of filter combs acting as sweepers
3. Transport of the particles along the groove towards a component for capturing particles.

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Daphnia

Possible Applications

The mechanism could be used for the filtration of extremely small particles, including bacteria. It could also be adapted for larger particle sizes by increasing the spacing between the appendages. The principle of multi-functional design could be achieved by studying and mimicking the daphnia to design a self-cleaning filter.

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Daphnia

Biological Foundation

Biological Strategy

The daphnia is a tiny crustacean found mainly in fresh water. The feeding mechanism of the daphnia relies on specialized appendages which it also uses for paddling (movement). The appendages act as paddles in stagnant water, enabling movement. They are also used as rakes, filtering edible particles from the surrounding water as they pass between the bristles. The function, (movement or filtering) is determined by the Reynolds number at which the appendages operate. Although the environmental conditions determine the viscosity and density of the water, the size of the appendages and the speed of motion provide the operative variables. Large and fast movement results in a raking function; and small and slow movement promotes paddling (Vogel, 2003). Studies indicate that daphnia are able to filter particles as small as 1µm. The filtering apparatus is self-cleaning.

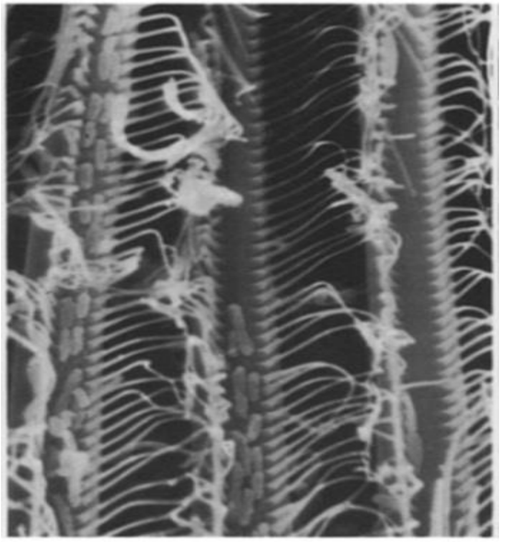

Figure 2: Microscopic view of Daphnia appendages

Biological Mechanism

The filtering apparatus of daphnia is constructed of specialized thoracic appendages for the collection of food particles. Five pairs of thoracic limbs act as a suction and pressure pump. The third and fourth pair of appendages carry large filter-like screens which filter the particles from the water. The efficiency of the filter allows the uptake of particles as small as 1µm, which includes some bacteria (Fisheries and Aquaculture Department, 1996).

The appendages of daphnia are used for both paddling movement and filter feeding because they are equipped with bristles, allowing them to operate at different Reynolds numbers for different functions. The principle behind the alternate paddling and filtering is based on the speed at which an appendage moves. The speed along with the degree of movement of the appendage, in turn, decide what function the movement will have. According to Vogal (2003), large and fast results in a rake or filter, and small and slow allows for movement
The steps involved in daphnia feeding include:

1. Capturing of the particles by setae.
2. Removing the particles by means of filter combs acting as sweepers.
3. Transport of the particles (food) along the groove towards the mouth opening.

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Daphnia

Context/Working Conditions

These appendages are extremely small, in a region in which the Reynolds number has a large effect on the outcome of the movement. If this principle is to be used on a larger scale or in a reactor or other such system, the size and speed of movement must first be calculated according to the Reynolds number that is needed.

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Daphnia

Existing Biomimicry: No case studies

There are no known cases where this system has been mimicked.

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Daphnia

References

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Vogel, S. (2003). Comparative Biomechanics: Life's Physical World. *Princeton: Princeton Universty Press*, 580.

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DAPHNIA

Appendages

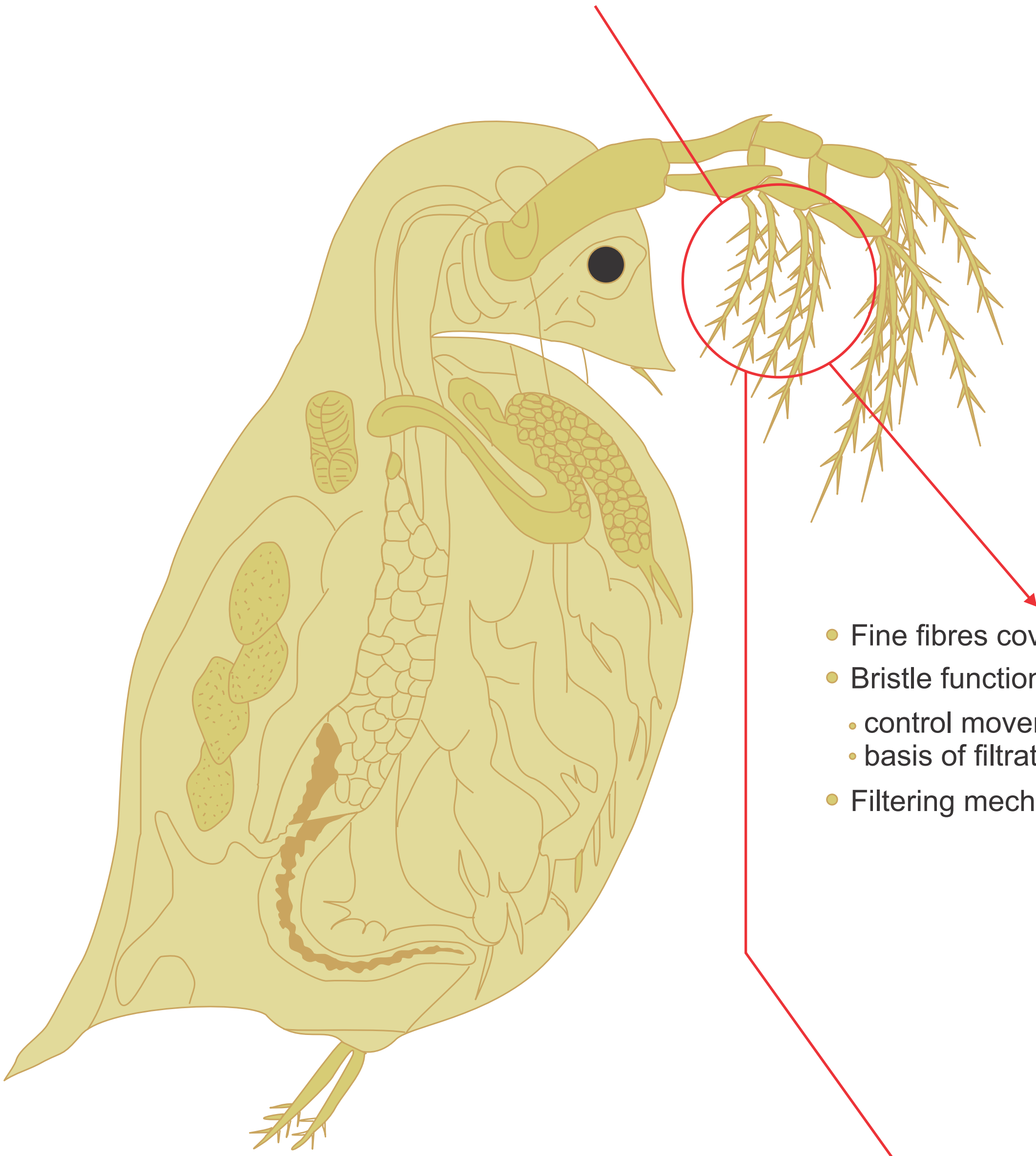
- Food particles captured by tiny bristles

↓

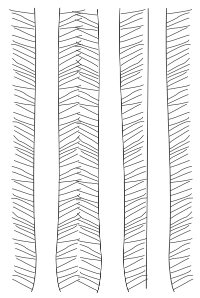
- Filter combs remove particles by acting as sweepers

↓

- Food is transported towards the mouth opening



- Fine fibres covered in tiny bristles
- Bristle functions:
  - control movement, determining function
  - basis of filtration mechanism
- Filtering mechanism is self-cleaning



Appendages :

Serves as suction and pressure pumps

→ Appendages functions depends on their size and movement

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Flamingos

Filtration of a large range of particle sizes

Figure 1: A Flamboyance of Flamingos

Biomimicry Innovation:

This innovation is inspired by the structure and filtering mechanisms of flamingos that enable the filtration of a large range of particle sizes from water. The filtration mechanism is based on forcing water-containing particles back and forth over multiple layers of thin plate-like structures that are able to filter a range of particle sizes, depending on the gaps between each plate.

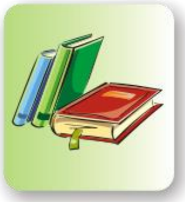
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Flamingos

Design Principles

Process:

Strong, flexible, and cylindrically shaped material creates a pumping action, forcing water-containing particles back and forth (up to 4 times/second) over multiple layers of thin plate-like structures, very close to one another, with open spaces in-between. Spines are found towards the back of the plates, to direct the particles into a component for capturing the particles. Unwanted materials and excess water are then pushed out by a sweeping action of the material.

Materials: The filtration systems should consist of a strong, flexible material inspired by a muscular tongue, while the plates could be inspired by biomineralized bone-like structures. The shape of the structure could be significant, possibly inspired by the shape of the cavity within a flamingo's beak.

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Flamingos

Possible Applications

This type of filter could be used in multiple applications, including places where a small and non-bulky filter is needed to remove visible and smaller solids. The flamingo feeding mechanism could inspire filtration systems filtering a large range of particle sizes. Larger particles could be trapped at the tip and separated from smaller particles which could be filtered using the lamella mechanism (see biological mechanism).

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Flamingos

Biological Foundation

Biological Strategy

The beak of the flamingo is adapted for filter feeding on small particles in water. They have filters on the underside of the maxilla (upper beak). Larger particles are caught with beak tips and 'thrown' to the back of the mouth. Smaller particles are filtered as the tongue moves back and forth acting as a pump. Unwanted materials and excess water are then pushed out with the tongue. While feeding, the mouth is open slightly and the tongue is tucked back, creating a negative pressure in the mouth for water and organisms to enter. The bill then closes, the tongue moves forward, and the water is filtered by the lamellae (comb-like structures covered with fine hairs) that line the inside of the bill. The flamingo's tongue moves back into its original position, and by doing so, forces the water to be released. The food that the flamingo has collected gets forced to the back of the mouth for swallowing by the curvy spines on the back of the tongue-at the same time more water enters the mouth.

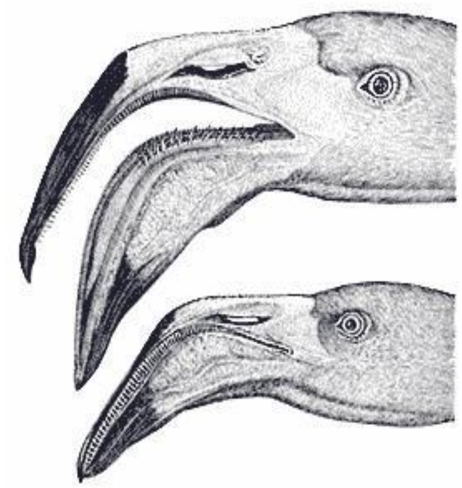

Figure 2: Shape of the flamingo's beak

Biological Mechanism

The bill of the flamingo filters food of various sizes using complex rows of hair-like structures called lamellae. The bill is adapted uniquely for filter feeding. The bill is lined with numerous complex rows of lamellae, which filter the various small crustacea, algae, and unicellular organisms on which flamingos feed. Flamingos feed with their heads upside down, allowing water to enter their mouth. Swinging the head to and fro, water enters the beak, and the tongue moves back and forth acting as a pump, sucking the water in and forcing it out up to four times a second (Ehrlich, Dobkin, & Wheye, 1988).

The Lesser, James's, and Andean flamingos have deep-keeled bills and feed mainly on algal diatoms. The Greater Caribbean and Chilean flamingos have shallow-keeled bills, and feed on insects and small fish. The Caribbean flamingo also feeds on insects and small fish.

The tongue of the flamingo is a cylindrical structure lying in a bony trough that is formed in the deep lower jaw. Multiple layers of lamellae cover the interfacing regions, trapping particles as the water is pumped back and forth. Posterior spines on the tongue help the particles move inward, to the back of the mouth and into the oesophagus.

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Flamingos

Context/Working conditions

Applicable in an aqueous media. The flamingo beak itself is applicable for smaller particle sizes, but the mechanism can be applied to a wide range of particle sizes.

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Flamingos

Existing Biomimicry: No case studies

This type of filter has not yet been mimicked.

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Flamingos

References

Ehrlich, P., Dobkin, D., & Wheye, D. (1988). *Flamingo feeding*. Obtido em November de 2012, de Stanford Education: http://www.stanford.edu/group/stanfordbirds/text/essays/Flamingo_Feeding.html

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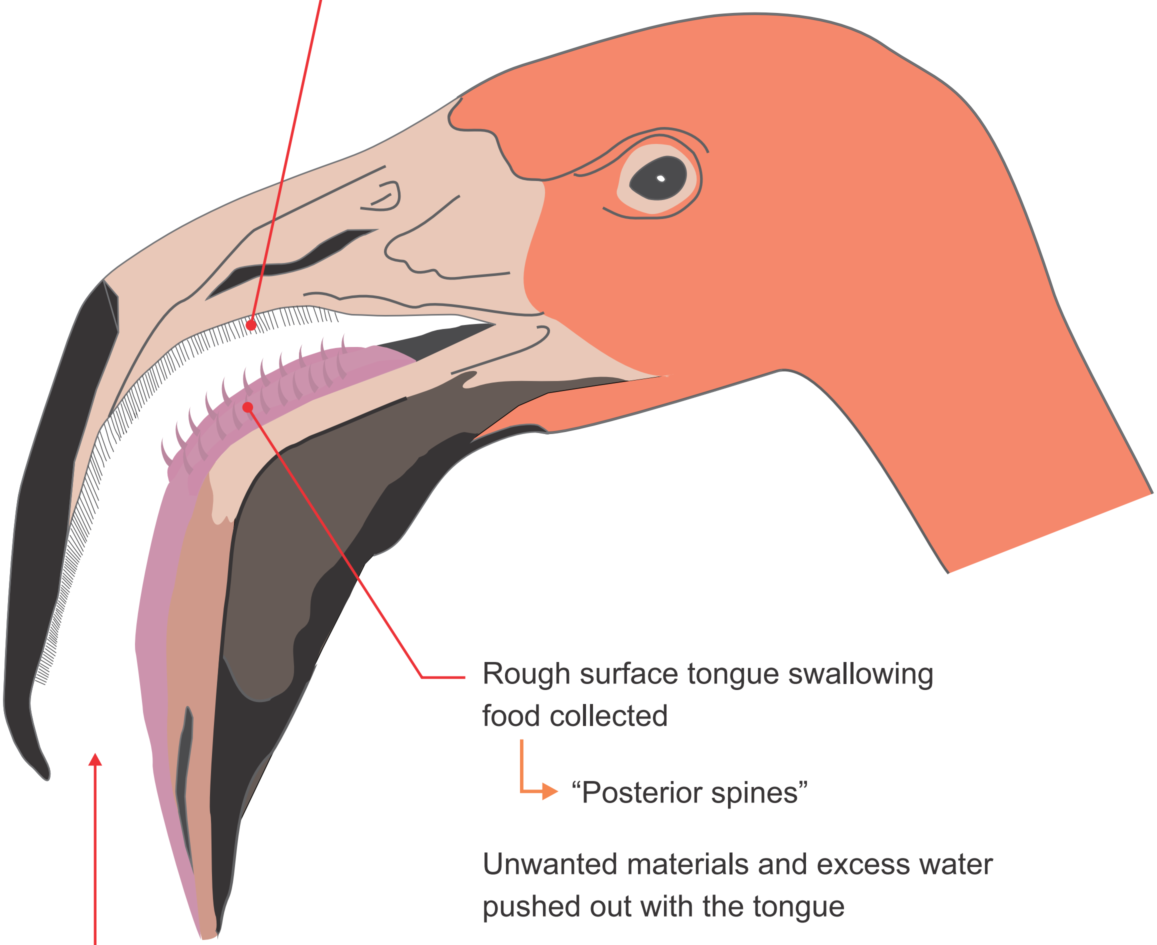
FLAMINGO BEAK

- **Lamellae** line the inside of the bill
- Filter water pumped in by the tongue
- Food filtered by lamellae
  (e.g.) Crustacea, algae, etc.)



Rough surface tongue swallowing
food collected

“Posterior spines”

Unwanted materials and excess water
pushed out with the tongue

Water enters mouth when the head is upside down, allowing water to enter the mouth

Water is “pumped” by the tongue as it moves back and forth

Back

Gill Raking Fish

Cross-flow filtration of a range of particle sizes. Hydrosol filtration of particles smaller than filter size

Figure 1: A feeding Basking Shark

Biomimicry Innovation:

This innovation is inspired by the filtering mechanisms and chemistry of gill raking fish. This innovation enables the separation of particles from water using cross-flow filtration across rakes, and/or hydrosol filtration, where particles which are smaller than the filter size are trapped my mucous. The hydrosol filtration mechanisms could be used in many filtration processes to trap particles smaller than filter sizes allow.

Figure 2: A feeding Whale shark

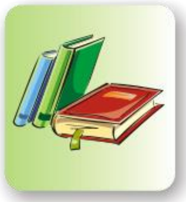
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Gill Raking Fish

Design Principles

Process/Structure: Cross flow filtration is achieved as the water flows parallel to a series of rake-like filters on the sides of a filtration cavity. As the cavity narrows, the spacing between the rakes becomes smaller, which concentrates the particles towards a capturing unit. Suction or movement through water is used to draw high concentrations of particles across the rakers. This process can filter particles between 5µm and 3 000µm from water.

Hydrosol filtration is also used where the presence of mucous retains particles smaller than the pore size of the filter elements. The particle-laden mucous is then transported to the capturing unit for removal. These hydrosol filters are less prone to clogging because particles can be entrained by passage of water over (not through) the filter apparatus.

Chemistry: The mucous is a sticky, viscous substance made up of water, salts and glycoproteins, that traps smaller particles which adhere to it. Rakes could be made out of a biomineralized bone-like structure, similar to the gills of these fish.

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Gill Raking Fish

Possible Applications

A range of particle sizes could be filtered from water by mimicking the cross-flow rake filtration. Very small particles could be removed from suspensions using a mucous like substance for hydrosol filtration. These could also be mimicked to remove gelatinous or mucous like solids from water.

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Gill Raking Fish

Biological Foundation

Biological Strategy

21 families of fish, comprising one quarter of the world catch, forage by filtering suspended food particles of sizes between 5µm and 3000µm from water. There are three shark species which filter feed: the Whale Shark (*Rhicodon typus*), the Basking Shark (*Cethorinus maximus*) and the Megamouth Shark (*Megachasma pelagios)*. In all filter feeders, water enters the mouth via movement of the animal through the water or via internal suction, and exits through the gills. Bristle-like rakers on the gills aid in the filtration process. The exact mechanism of particle retention has only been described for a few species, including various species of Tilapia (*Orechromis niloticus, O. esculentis, O. aureus,*) (Sims, 2000) (Smith & Sanderson, 2007).

Biological Mechanism

Whale Sharks and Megamouth Sharks use suction to draw high concentrations of zooplankton across their gill rakers, while Basking Sharks swim forward with open mouths to swallow prey which are filtered by passive water flow over the rakers (ram filter-feeding) (Sims, 2000). In comparison with its cruising speed, the foraging speed of Basking Sharks is slower, due to the increased drag associated with the opening of their mouths (Sims, 2000).

Two mechanisms for particle retention during feeding have been described in fish of the Tilapia species: hydrosol filtration and crossflow filtration, with sieve filtration being uninvolved. Hydrosol filtration relies on the presence of mucous to retain particles smaller than the pore size of the filter elements. The food-laden mucous is then transported to the oesophagus for swallowing. These hydrosol filters are less prone to clogging because particles can be entrained by passage of water over (not through) the filter apparatus (Smith & Sanderson, 2007). In pump suspension-feeding Tilapia species such as *O. esculentis* and *O. aureus*, water is pumped parallel to the rakers and particles are transported towards the oesophagus via cross-flow. The filtrate exits between the rakers and the food particles become more concentrated as the oral cavity narrows..

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Gill Raking Fish

Context/Working Conditions

Various Gill Raking fish can be found in oceans around the world. The mechanism requires an aqueous medium in order for the mucous to be effective.

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Gill Raking Fish

Existing Biomimicry: No case studies

There were no biomimicry case studies for gill raking fish recorded at the time of the study.

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Gill Raking Fish

References

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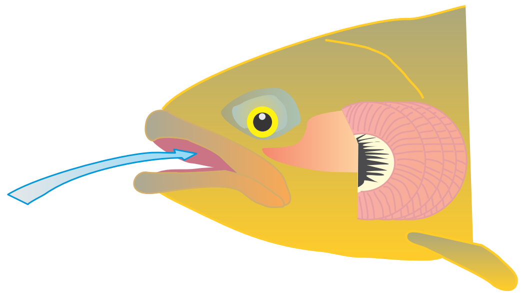
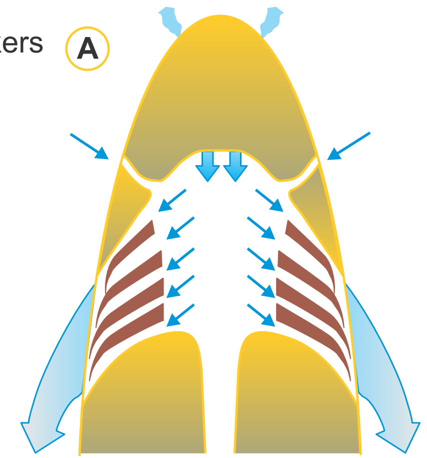
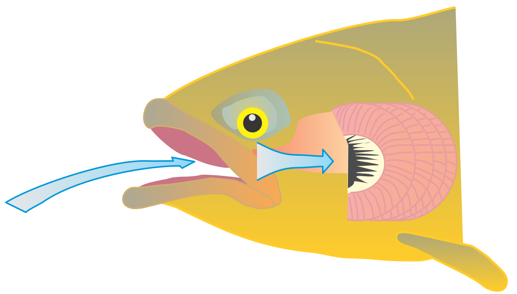
GILL RAKING FISH

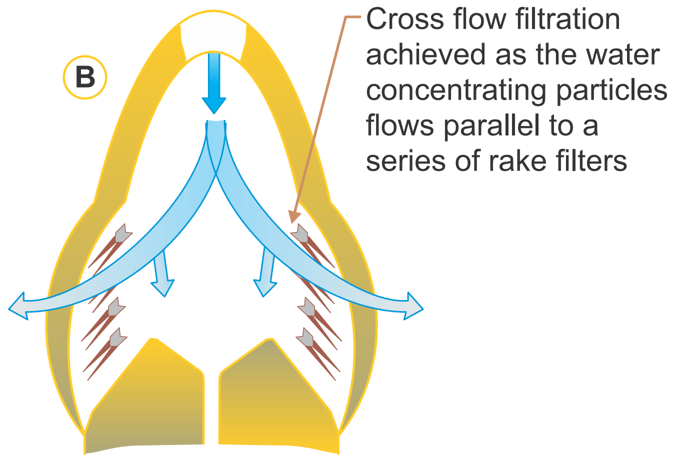
A Suction / movement through water used to draw high concentrations of particles across the rakers





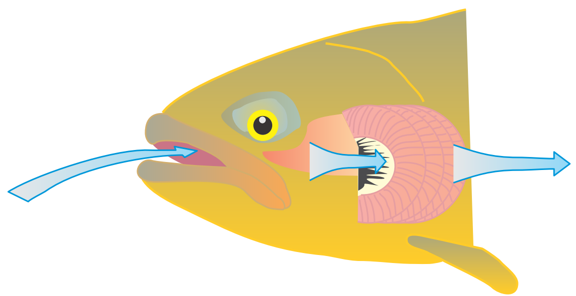
- Hydrosol filtration based on using mucous-substance
- Mucous retains food particles
- Particle laden mucous then transported to the throat to be swallowed

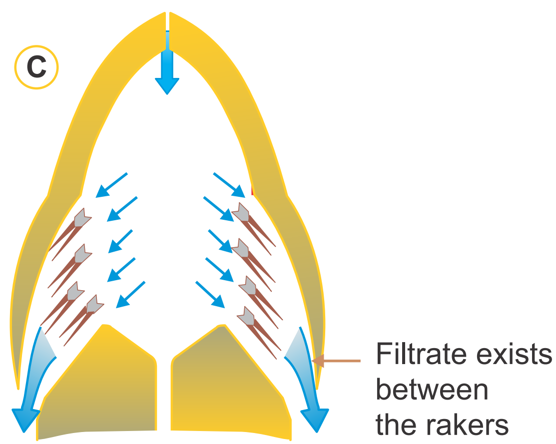




B Cross flow filtration

- Water pumped parallel to rakers and particles are transported towards the throat via cross-flow





C As the cavity narrows, the rakers are closer together, concentrating the particles towards the capturing unit

- Food particles become more concentrated

Back

Peacock & Feather-Duster Worms

Filtration using grooved channels with moving elements and a mucous-like substance

Figure 1: Peacock Worms swaying in water. (Warren, 2012)

Biomimicry Innovation:

This innovation is inspired by the filtering mechanisms of peacock and feather-duster worms found in intertidal zones of oceans. It involves the combination of the movement of fine filtering hair-like projections that can separate particles of different sizes, and a mucous layer that traps inorganic and organic particles in water. The mucous innovation could be used in a number of applications, for example, in many water filtration processes where a build-up of mucoid material occurs, and could be taken advantage of to trap unwanted particles.

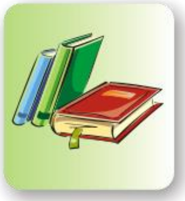

Design principles


Possible applications


Biological Foundation


Context


Case studies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Peacock & Feather-Duster Worms

Design Principles

Process: The Peacock Worm has a narrow tube (between 30cm-40cm in length) with a fan of feather-like fibers protruding from the front end of the tube. The fibers are covered in a slimy mucous layer. Organic or inorganic particles are brought to the feather-like fibers by flow currents caused by the projections that move in rhythmic unison. Particles are trapped by the slimy layer on fibers (adhesion and electrostatic forces) acting like a sieve, and channeled down the tube.

Structure: The structure consists of grooved channels with moving elements that filter particles from water, by generating vortices when water flows through the spaces between elements. Particles are captured by a slimy mucous layer and transported down the groove via moving elements that separate particles, based on size via a stepped v-shaped groove design.

Materials: Mucous is a sticky, viscous substance made from water, salts and glycoproteins. The tubes could be made from proteins and small particulates (e.g. sand) and a slimy substance immiscible with water. The fine hair-like protrusions for filtering could be made of a fibrous material or protein-like substance.

Back

Peacock & Feather-Duster Worms

Possible Applications

The mechanism and mucous could be mimicked separately or in combination for filtering a range of particulate sizes and types from water. The 'worms' themselves could also be used. The application of such a filter system where low flow speeds are experienced would be advantageous as the worm draws water to itself by beating cilia. The application of this principle as a polishing step for a low suspended solids environment would also be applicable.

Back

Peacock & Feather-Duster Worms

Biological Foundation

Biological Strategy

This small marine polychaete worm (*Sabella penicillus*) found in shallow water, tidal pools and sand, uses a fan of tentacles for filter feeding.

Biological Mechanism

The peacock worm resides in a tube made from mud and mucous, between 30cm and 40cm in length. Only its fan of feathery tentacles sticks out the front end of the tube. The tentacles are covered in a mucous layer and are used for both feeding and respiration. The tentacles therefore serve a dual purpose. The organic and inorganic particles which the worm feeds on are brought to the feathers by currents caused by beating cilia, which are located on the tentacles. The particles become trapped by the mucous on the tentacles via adhesive and electrostatic forces which act like a sieve. The particles are then brought to the mouth by the flow of the mucous down food grooves (Foy, 1983; Encyclopedia Britannica, 2012)

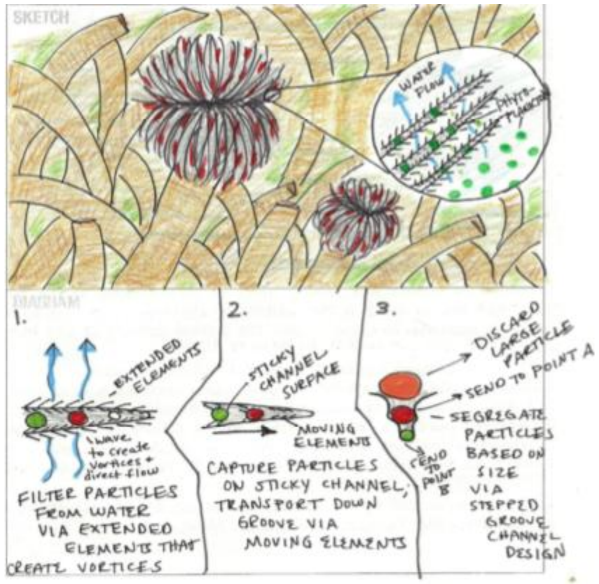

Figure 2: Marsha Forsthoefer, Salt Spring Island Genius of Place, October 2012

A similar mechanism with more detailed research has been observed in Feather-Duster Worms which are found in intertidal zones in colder climates (e.g. Pacific North-West). These worms are encased in tubes built from proteins and collected materials. They are filter feeders, feeding primarily on phytoplankton (80 microns) suspended in the water and can only thrive in areas with moving currents that bring in phytoplanktonic food supplies. They have feather-like gills which capture and move the phytoplankton to their mouths.

Cilia on the feathers move water through the crown of feathers from bottom to top, creating vortices that carry particles to the feather's groove. The groove is covered in mucous which captures the particles. Cilia move the particles down the groove which takes on a stepped V shape such that: large particles stay on top and are discarded, small particles (phytoplankton) drop to the bottom and are moved to the mouth and eaten; medium particles drop to the middle 'step' and are diverted to the bottom of the animal for use as tube building material. Food must have the correct density (to remain suspended in water and stick to mucous) and size (to sink to the bottom of the groove).

Back

Peacock & Feather-Duster Worms

Context/Working Conditions

The mechanism appears to work well within intertidal zone temperature and saline ranges.

The worm itself is found in the intertidal zone and shallow subtidal zones (Encyclopedia Britannica, 2012) of the sea in Western Europe and the Mediterranean. They seem to be particular about their environment and have disappeared from a number of their natural habitats. This will limit the use of the Peacock Worm in bio-utilisation applications.

The principle will however be adaptable to conditions outside these constraints if the mucous chemistry is altered to prevent the mucous from hardening, drying out, or being adversely affected by surrounding conditions. Low suspended solid environments will be better suited for this type of filter system.

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Peacock & Feather-Duster Worms

Existing Biomimicry: Case Study

The Peacock Worms have not yet been emulated in biomimicry applications for water purification.

Back

Peacock & Feather-Duster Worms

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Salps

Particle removal using a slimy membrane net

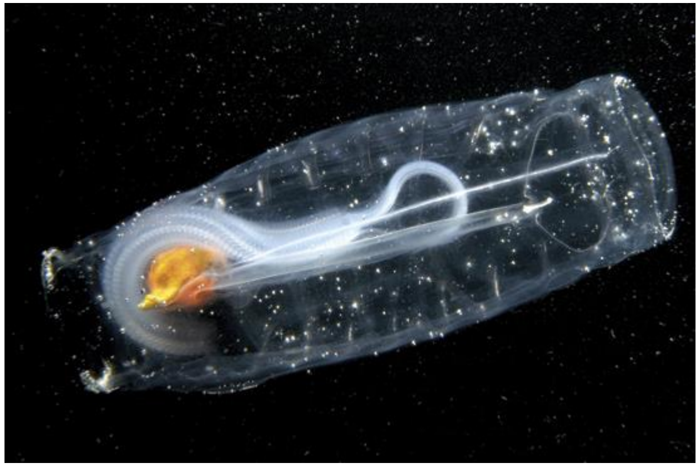


Figure 1: Sea Salp (Bioinformatics, 2012)

Biomimicry Innovation:

This innovation is inspired by the filtering mechanisms of Salps. It involves jet propulsion of particles in water through a slimy membrane net with a mucous layer that traps particles as small as 0.5 microns. The mucous innovation could be used in a number of applications. For example, in many water filtration processes there is a build-up of mucoid material which could be taken advantage of to trap unwanted particles.

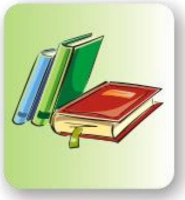
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Salps

Design Principles

Structure/Process: The mechanism for filtration is similar to that of a jet engine, where a substance is drawn in at the one end and expelled at a force larger than that of the intake. This creates a net backward force which results in forward movement (jet propulsion). This is facilitated by the way in which the filtration component contracts and expands at different sections. The same force is used to run the water through a slimy membrane net within the filtration component to capture particles. Once sections of the slimy net reach capacity, they collapse and are drawn into the particulate capturing unit. The net typically has 1.5 micron sized holes, and can catch particles as small as 0.5 microns, since they stick directly to the mucous.

Back

Salps

Possible Applications

This filter may be adapted for use in industrial applications or as a polishing step in wastewater treatment processes, if the chemistry of the mucous can be mimicked. This may work in systems that do not contain large amounts of suspended solids (Salps, 2011). The filter may be applied as a self-cleaning system if the regeneration of the slimy membrane can be done automatically, and the removal of the saturated and collapsed section is facilitated.

Back

Salps

Biological Foundation

Biological Strategy

Salps (*Salpidae* spp.) are free swimming marine creatures with gelatinous bodies, which feed on algae. They have an inner mucous net which traps food which enters during movement by jet propulsion.

Biological Mechanism

Salps draw water into a siphon at one end and force it out of a siphon at the other end, providing movement by jet propulsion, and allowing water to enter the body. The water drawn in is also used for feeding, as it is strained through a bag-like net of mucous inside the body, which traps any tiny algae which are present. Organisms, such as phytoplankton, get caught in the mucous net which has 1.5 micron sized holes. It was found however that organisms as small as 0.5 microns are also caught and eaten, since they stick directly to the mucous (Joel Greenberg, 2010). The mucous net which captures the food and mineral particles rolls into a strand and goes into the gut, where it is digested. Waste products are released as solids (Shuker, 2001).

Back

Salps

Context/Working Conditions

The mucous net on the inside of the Salp is very intricate and extremely thin, which will make it difficult to manufacture. The fact that it forms a strand each time it fills with food and minerals may require regular maintenance of such a system. The system may be able to overcome these limitations with the use of different mucous chemistry in the filter.

The use of the mucous will work under ambient temperature and pressure for aquatic systems across the globe.

To apply this principle the following is required:

- Liquid/air environment
- Flexible material that can be used in the construction of the vessel
- Membrane that will allow particles to pass through selectively
- Mucous layer on the membrane to trap smaller particles
- Method of cleaning the particles off of the net

Back

Salps

Existing Biomimicry: No Case Studies

Salps have not been used in biomimicry applications in water purification.

Back

Salps

References

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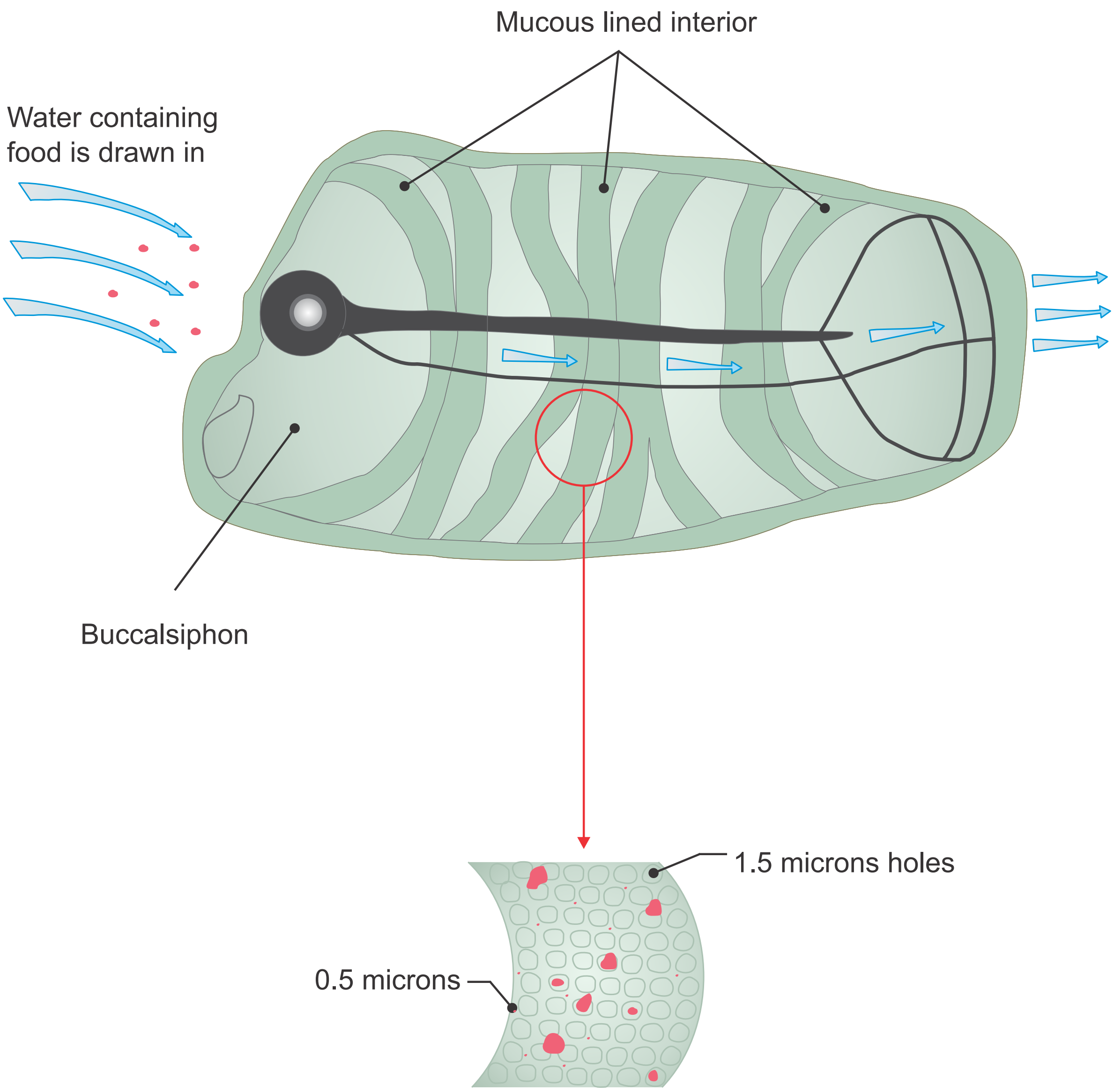
SALPS



Inner mucous membrane net

- Strains water as it passes through
- Food trapped in net
- Particles smaller than net holes stick to the mucous and are also captured
- To digest food, the net is rolled into a strand and into the gut where it is digested

Back

Sea Cucumber

Filtration by means of a complex particle trap & mucous

Figure 1: Sea Cucumber (Biology Blog, 2012)

Biomimicry Innovation:

This innovation is inspired by the feeding mechanisms of sea cucumbers. It involves a complex particle trap and a mucous layer. The mucous innovation could be used in a number of applications. For example, in many water filtration processes there is a build-up of mucoid material, which could be taken advantage of to trap unwanted particles.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

Back

Sea Cucumber

Design Principles

Structure: The structure consists of a complex particle trap of suspended appendages which move independently in water. A scraping mechanism removes the particles trapped on the appendages.
Chemistry: Particles adhere to a sticky mucous-like substance on the appendages. The mucous-like substance is a sticky, viscous substance made up of water, salts and glycoproteins.

Back

Sea Cucumber

Possible Applications

A self-cleaning filter that can extract minerals from the environment through collection by mucous and transfer collections to a central location for disposal. This may be employed in industrial and municipal wastewater treatment scenarios as a polishing step to remove the fine suspended solids in a system. It is also self-cleaning, which may help in systems where operation and maintenance is difficult (Nature, 2012).

Back

Sea Cucumber

Biological Foundation

Biological Strategy

These ocean animals are long cylindrical cucumber-shaped creatures. They are suspension feeders with long dendritic tentacles, which collect/filter the food from the ocean.

Biological Mechanism

The tentacles of the Burrowing Sea Cucumber capture floating particulate food matter using a complex particle trap, mucous, and an oral passageway. Sea cucumber tentacles secrete mucous, causing particles to adhere to them. The tentacles then one-by-one enter the mouth, the mouth closes and the tentacles are pulled out, wiping the particles off of the tentacles into the mouth (Cronodon, 2007). In this way, the Sea Cucumber filters out particles which are suspended in the water. This is referred to as suspension feeding (Lambert, 1997).

Back

Sea Cucumber

Context/Working Conditions

Sea Cucumbers are found naturally in all the world's oceans with habitats ranging from the Alaskan coast to the coral reefs in the Indian Ocean. This will allow for the operation of filter systems to be applicable in a range of temperatures similar to that of the ocean temperatures. The process can also be applied at a range of different pressures similar to that of the species' ocean habitat. The operational water chemistry would be dependent on the ingredients required to manufacture the mucous and tentacles.

Back

Sea Cucumber

Existing Biomimicry: No Case Studies

Sea Cucumbers have not yet been mimicked in biomimicry water-treatment applications.

Back

Sea Cucumber

References

Biology Blog. (2012). *Sea cucumbers fast track organ regrowth*. Retrieved 2012, from Biology-Blog.com: http://www.biology-blog.com/blogs/permalinks/10-2007/sea-cucumbers-fast-track-organ-regrowth.html

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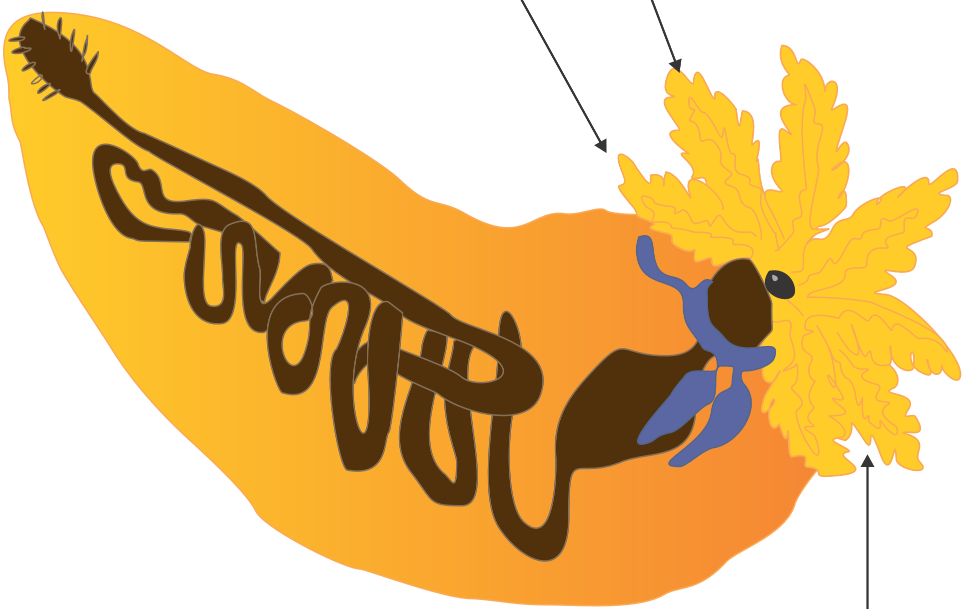
SEA CUCUMBER

Feeding tentacles; flexible and able to be pulled into the mouth

Tentacles extended in the water until they are filled with food particles

Once filled, the tentacles are placed over the mouth opening where food material is scraped off into the mouth

Suspended tentacles (appendages) that move independently in water



- Particles adhere to a sticky mucous-like
- substance on the appendages
- The mucous is a sticky, viscous substance made up of water, salts and glycoproteins

When feeding, it always orientates itself into the prevailing water current

Back

Sea Squirt

Filtration by means of a basket-like membrane, mucous & siphon

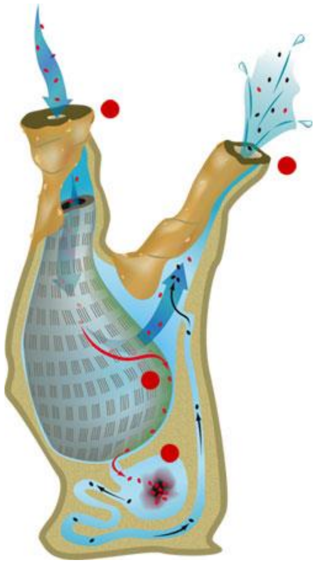


Figure 1: Schematic indicating the flow of water through a Sea Squirt

(Woods Hole Oceanographic Institute, 2005)

Biomimicry Innovation:

This innovation is inspired by the feeding mechanisms of the sea squirt. It involves a basket like membrane and a mucous layer. Water flows through or is siphoned through the system. The system can take advantage of natural water currents to filter water. The mucous innovation could be used in a number of applications. For example, in many water filtration processes there is a build-up of mucoid material, which could be taken advantage of to trap unwanted particles.

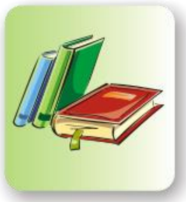
Design principles

Possible applications

Biological Foundation

Context

Case studies



References

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Sea Squirt

Design Principles

The system consists of a vessel constructed from an organic material that is not subject to degradation in an aqueous medium. The filter has a small opening and a slimy layer to allow selective filtering of organic and inorganic particles. The system takes advantage of an existing flow to force the particles through the filter. To apply this principle the following is required:

- Water
- Flexible material that can be used in the construction of the vessel
- A basket-like membrane interior that will allow water to pass through selectively
- Mucous layer on the membrane for capturing particulates
- (Optional) The ability to adapt to changing water flow directions in order to remain in the optimal position to take advantage of local water currents

Back

Sea Squirt

Possible Applications

The mechanisms would be more applicable in small-scale water filtration systems. The filter could be applied using flexible tube systems that align with directional flow in order to reduce short circuiting. The filters may be suited for the removal of metals in industrial waste water as part of a (MR3) filter system (this is a removable tube system in a fixed pipe system) (Ask Nature, 2012).

Back

Sea Squirt

Biological Foundation

Biological Strategy

Sea Squirts are cylindrical marine animals that differ in size ranging from 5cm to 15cm. Sea Squirts are filter feeders, using tiny cilia to propel water through their bodies, filtering food from the water to their mouths. The main body cylinder of a Sea Squirt filters food and oxygen from water using an oral siphon.

Biological Mechanism

The Sea Squirt has two openings, the inhalant and exhalant apertures. The water comes in through the inhalant aperture, and comes into contact with the basket-like interior of the Sea Squirt which is lined with mucous. The interior is covered with tiny gill slits with cilia which help to propel the water and filter food from the water current. Cilia are minute hair-like structures that line the surfaces of certain cells and beat in rhythmic waves, providing locomotion and moving liquids along internal tissues. Gill slits are a series of openings between the gill arches, through which water passes from the pharynx to the exterior, bathing the gills in the process.

The food attaches to mucous and flows into the oesophagus at the lower end of the body of the Sea Squirt. The remaining water exits through the exhalant aperture (Vogel, Comparative Biomechanics: Life's Physical World, 2003). The small size of the exhalant aperture results in the formation of a rapid jet of water which carries the Sea Squirt's waste well beyond the incoming water current. The Sea Squirt takes advantage of the sea current to force the flow through its filter system, which reduces the energy expenditure required for feeding. The Sea Squirt (*Styela* spp.) has the ability to adapt to changing water flow directions in order to remain in the optimal position to take advantage of local water motion for this feeding process (Vogel, Comparative Biomechanics: Life's Physical World, 2003)

Back

Sea Squirt

Context/Working Conditions

Different species of Sea Squirts are found in vastly different temperature and pressure environments in the ocean: from the intertidal zone to the greatest depths. The systems could therefore be applied in conditions of high pressure and varying temperatures.

Back

Sea Squirt

Existing Biomimicry: No Case Studies

Sea Squirts have not yet been mimicked in biomimicry water treatment applications.

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Sea Squirt

References

Ask Nature. (2012). *Flexible stalk adjusts to flow forces: Styela sea squirt*. Retrieved 07 04, 2012, from Asknature.org: http://www.asknature.org/strategy/a2874138b59c23f13fdcf857081bc191

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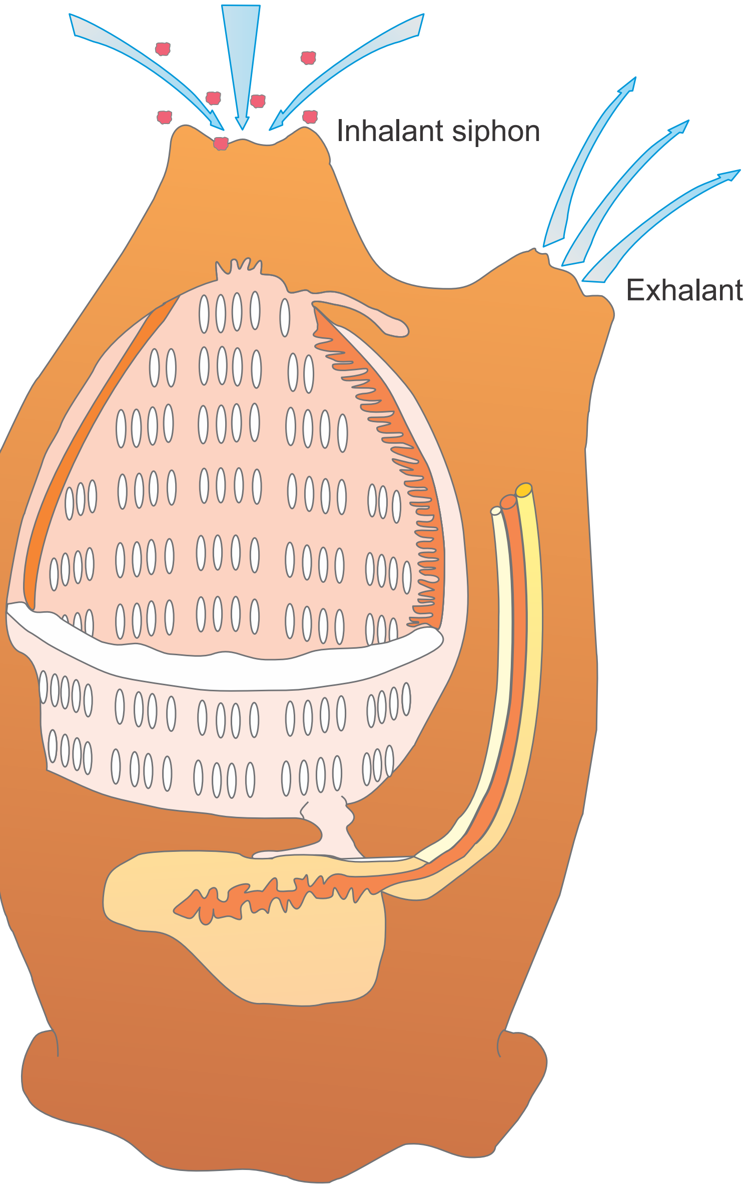
SEA SQUIRTS

Water flow is siphoned through system

Tiny cilia used to propel water through the body

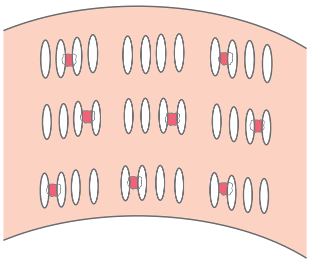
Water passing through comes into contact with the interior which filters out food

Basket-like interior is covered in tiny gill slits with cilia



Food attaches to the mucous lining and then flows into the esophagus

Remaining water exits through the exhalant aperture



Remaining water exits through the exhalant aperture

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Vampire Bats

Self-cleaning filtration of very small particles

Figure 1: Vampire Bat (Fogden/ Corbis, 2012)

Biomimicry Innovation:

This innovation is inspired by the kidneys of Vampire Bats. The digestive and circulatory systems of Vampire Bats are able to rapidly separate blood from water by concentrating the blood and excreting the water content through a combination of hydrostatic and osmotic pressure gradients, across a filtration medium.

Design principles

Possible applications

Biological Foundation

Context

Case studies

References

Back

Vampire Bats

Design Principles

Water and other undesirable substances are separated from blood in an ambient filtration system. A combination of hydrostatic pressure and osmotic gradients allows for the selective separation of blood (and related minerals/substances).

To apply this principle the following is required:

- Solution requiring extraction of specific substances (e.g. blood in water)
- A concentration gradient between the solution and the extraction point
- Selective filtration media

Back

Vampire Bats

Possible Applications

The application of such a filter system lies in both the speed at which it operates as well as its ability to successfully remove blood from water. This system has applications in waste water filtration at medical facilities as well as abattoirs. The speed at which the system operates would make it beneficial for systems requiring filtering at high volumes, at intermittent periods and with minimal start-up time.

Back

Vampire Bats

Biological Foundation

Biological Strategy

Vampire Bats feed exclusively on blood. These bats are able to remove water from blood to lighten their weight, so that they may ingest as much blood as possible and still be able to fly. A typical female Vampire Bat weighs 40 g and can consume over 20 g of blood in a 20 minute feed. This feeding behaviour is facilitated by its anatomy and physiology for rapid processing and digestion of the blood, to enable the animal to take flight soon after the feeding. The stomach lining rapidly absorbs the blood plasma, which is quickly transported to the kidneys from where it passes to the bladder for excretion. A common Vampire Bat begins to expel urine within two minutes of feeding. Despite shedding much of the blood's liquid content, the bat has added almost 20 – 30 % of its body weight in blood, and is able to take flight with this additional weight. Typically, within two hours of setting out, the Common Vampire Bat returns to its roost and settles down to spend the rest of the night digesting its meal.

Biological Mechanism

The ingested blood plasma is absorbed rapidly through the stomach lining from where it transported to the kidneys for filtration. It is in the kidneys that the water and other undesirable substances are separated from the blood in a filtration system similar to that of a human kidney (refer to human kidney example in this tool.) A combination of hydrostatic pressure and osmotic gradients allows for the selective separation of blood (and related minerals/substances).The water forms weak urine and is passed on to the bladder to be excreted. The process is rapid and urine is excreted within a few minutes after the bat starts feeding. (Singer, 2002; Crump, 2005).

Back

Vampire Bats

Context/Working Conditions

The actual kidney of the bat has not been studied in detail. Further studies are required in order to mimic this application.

Back

Vampire Bats

Existing Biomimicry: No Case Studies

The vampire bat kidneys have not yet been mimicked in biomimicry applications for water purification.

Back

Vampire Bats

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Venus Flower Basket

Removal of particulates through a fine-mesh basket

Figure 1: Venus Flower Basket

Biomimicry Innovation:

This innovation is inspired by the filter feeding mechanism of the sea sponge known as the Venus Flower Basket. The sponge has a cylindrical structure containing an intricate fine-mesh silica-based basket with which it is able to filter fine particulates from water. The structure of the mesh-like basket could be emulated for filtration mechanisms. There are spicules at the end of the basket filter which are able to filter silica from water. This could be useful for the removal of silica (or similar chemicals) from wastewater.

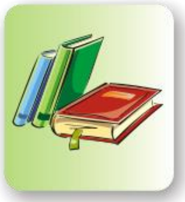
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Venus flower basket

Design Principles

Structure/Process: This filter works as an intricate mesh filtration system. The basket is structured with openings all along its length and at the end. Spicules at the end of the basket are able to extract silica from water.

Materials: The system could consist of a strong, glass-like structure based on the biomineralisation of silica at seawater temperature and pressure. This material is being investigated for emulation by the Harvard Wyss Institute.

Back

Venus Flower Basket

Possible Applications

Though the basket is in fact a filter, it has not yet been artificially produced. However, it was found that it has similar light transmitting properties to optic fibres, with a structure that is stronger and more flexible. This finding has promoted research into the construction of better and cheaper fibres (Carmody, 2003). The structure could be mimicked to manufacture strong and flexible mesh filters.

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Venus Flower Basket

Biological Foundation

Biological Strategy

The sea sponge, known as the Venus Flower Basket (*Euplectella aspergillum*), has a basket-like filter that it uses to extract food from seawater. The sponge lives in a symbiotic relationship with a shrimp. The latter is protected from predators and obtains food from the hollow interior of the sponge. In turn, the shrimp cleans keeps the pores of the flower basket of the sponge.

Biological Mechanism

The structure of the Venus Flower Basket has a dual function. It adds to the strength of the structure and forms a fine mesh, trapping particles on which the shrimp living in the structure can feed. The basket also filters silica by means of special cells called spicules. The spicules extract silica from the water which is then transported to the top of the basket. The basket continues to grow through biomineralisation of the silica.

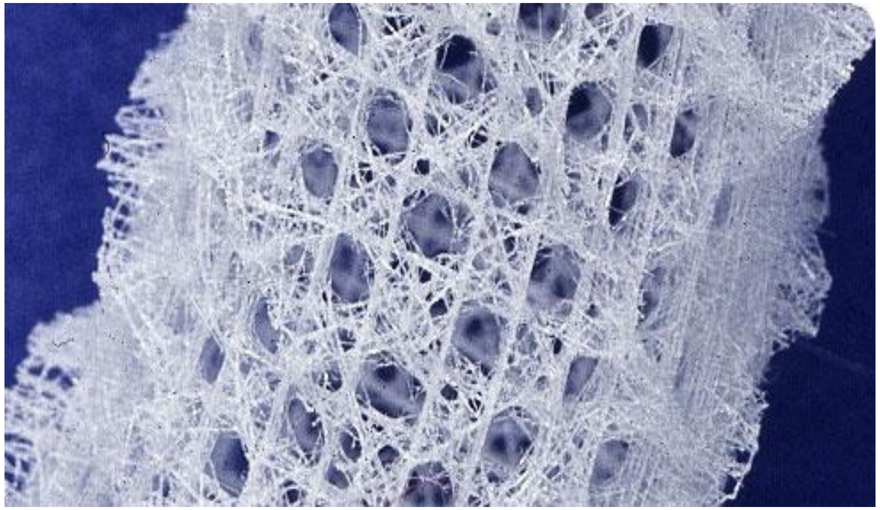

Figure 2: Structure of the Venus Flower Basket

Back

Venus Flower Basket

Context/Working Conditions

The actual organism only lives in the deep sea where the hydraulic pressure is high.

Back

Venus Flower Basket

Existing Biomimicry: Case Studies

There is a large amount of research taking place on the formation and structure of the fibres of the basket (Hill, 2003). The Wyss Institute at Harvard is investigating how to emulate the glass-like material (Aizenburg, 2012). To date however, there are no known final products that have been made which are based on this animal.

Back

Venus Flower Basket

References

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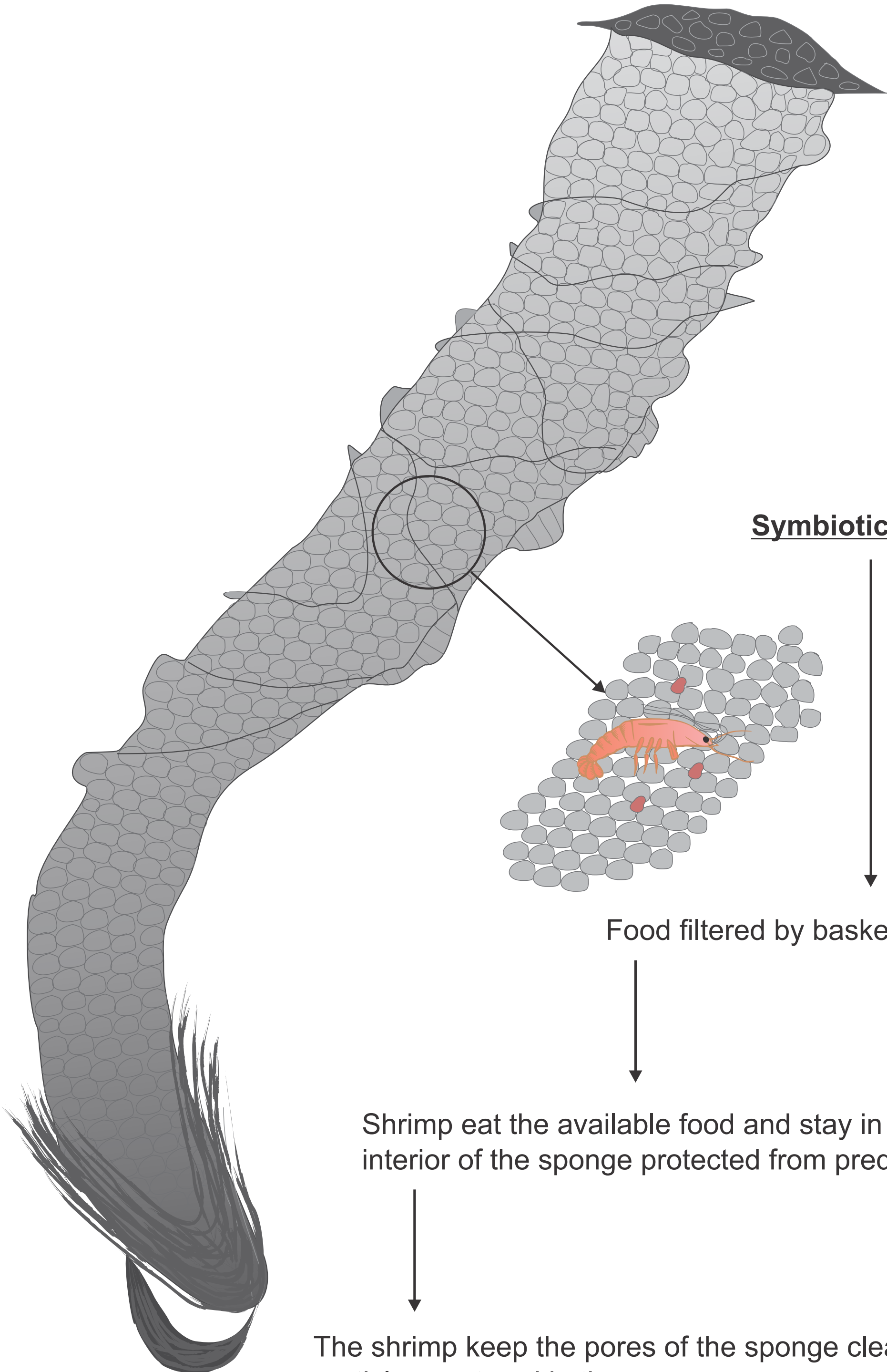
VENUS FLOWER BASKET

- Intricate mesh filtration system
- Basket structured with opening all along its length and at the end



Symbiotic Relationship

↓

Food filtered by basket-like filter

↓

Shrimp eat the available food and stay in the hollow interior of the sponge protected from predators

↓

The shrimp keep the pores of the sponge clean, eating particles captured in the pores

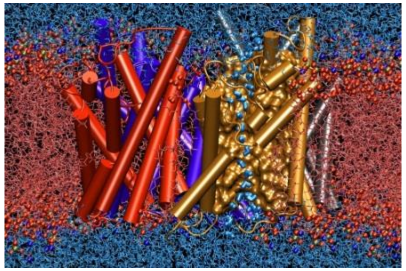
Back

Dissolved Solids Removal

Dissolved solids are conventionally removed using:

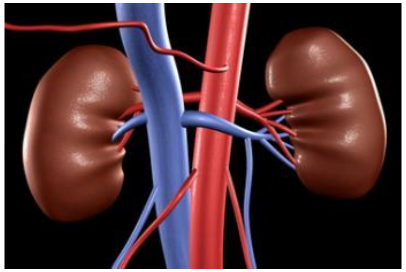
- Chemical precipitation
- Ion exchange
- Reverse osmosis membranes
- Crystallisation processes

Biomimicry research has revealed a number of innovations for these processes. The innovations are inspired by natural organisms and systems that are specialists in removing dissolved solids from water, and based on millions of years of natural selection have evolved highly efficient and effective sustainable solutions in each case. The following subsections summarise the key innovations from natural “champion” or specialists in each case. They are classified as champions in this context based on the fact that of all the organisms that perform this particular function, these organisms are the specialists identified in each case



Dissolved solids removal through selective water gates in membranes
(Aquaporins)

Dissolved solids removal through (solar-based) osmotic effects for drawing in water & expelling salts.
(Mangroves)



Dissolved solids removal through gradients & dual membranes.
(Kidneys)

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Aquaporins

Dissolved solids removal through selective water gates in membranes.

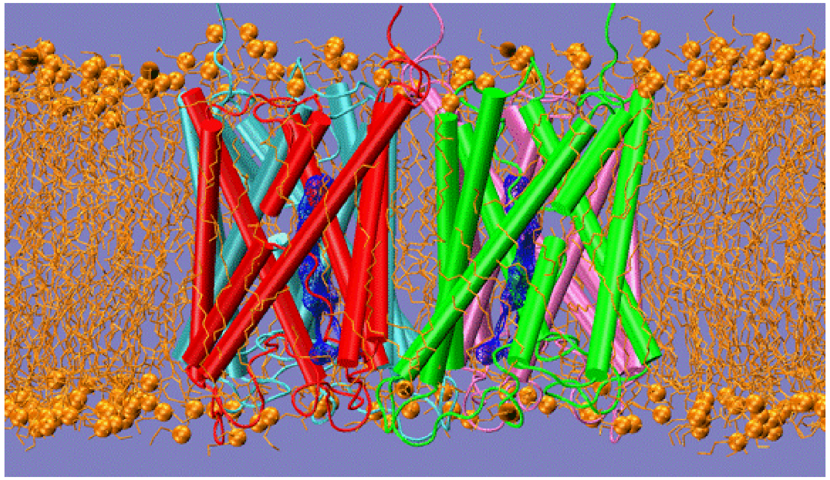


Figure 1: Illustration of membrane containing aquaporins

Biomimicry Innovation:

Conventionally, membrane processes, especially reverse osmosis membrane processes, require a high pressure and therefore high energy input in order to remove dissolved salts from water. This is a problem in the context of rising energy costs and concerns relating to green house gas emissions (climate change). This innovation is inspired by aquaporins found in membranes in many biological organisms. Aquaporins have the ability to separate water from dissolved solids (e.g. salts) at ambient/body temperature and pressure, resulting in significant energy savings for these processes (initial research indicate up to 70% savings on specific energy consumption for reverse osmosis applications – (Agre, Bonhivers, & Borgonia, 1998).

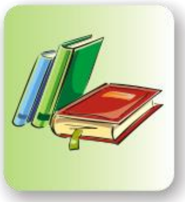
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Aquaporins

Design Principles

Structure: The narrow opening and specific shape of a pore within a membrane -“water gate”- is specifically shaped and rejects molecules larger than the water molecule whilst the electrostatic charge on the gate rejects smaller charged particles. The transport selectivity strongly depends on the spatial and physiochemical properties of the pore. The pore has two main restrictions that function as sieves, one in the middle and one on the outer membrane wall. Water molecules cross the channel in single file with the hydrogen atoms pointing toward the closest “exit” so that they are oriented in the opposite direction on each side of the channel. The constrictions are too narrow for the passage of large solutes. Electrostatics also partly determine the selectivity function.

Materials: Phospholipid basis for membrane and protein basis for aquaporin?

Back

Aquaporins

Possible Applications

Incorporation of aquaporins into synthetic polymers for biomimetic separation and sensor technologies. Low energy water purification technologies, including ultrapure water production, wastewater purification, desalination and salinity gradient power production for renewable energy. These can be achieved by embedding orthodox aquaporins in artificial biocompatible supports such as amphiphilic triblock copolymers (Gena, Pellegrini-Calace, Biasco, Svelto, & Calamita, 2011).

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Aquaporins

Biological Foundation

Biological Strategy

Aquaporins selectively conduct water molecules across cell membranes whilst preventing the passage of ions and other solutes. Orthodox aquaporins are permeable to water only, whilst aquaglyceroporins conduct water, glycerol and other small solutes (Gena, Pellegrini-Calace, Biasco, Svelto, & Calamita, 2011).

Biological Mechanism

The transport selectivity of aquaporins strongly depends on the spatial and physiochemical properties of the pore. The pore has two main restrictions which function as sieves, one in the middle and one on the outer membrane wall. It has been shown that water molecules cross the channel in single file with the hydrogen atoms pointing toward the closest "exit" so that they are oriented in the opposite direction on each side of the channel. In orthodox aquaporins, the constrictions are too narrow for the passage of large solutes.

It has also been shown that electrostatics partly determine the selectivity function of aquaporins. Orthodox aquaporins have a distinctive electrostatic potential barrier while the channels of aquaglyceroporins are mostly neutral and impermeable to charged particles. (Gena, Pellegrini-Calace, Biasco, Svelto, & Calamita, 2011).

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Aquaporins

Context/Working Conditions

The temperatures at which artificial aquaporins will function are dependent on the material from which they are manufactured. Proteins, in general, lose their function at higher temperatures (above 43°C), and on repeated freezing. An investigation by (Ohshima , Iwasaki, Suga, Murakami, & Maeshima, 2001)) showed that although the energy of activation of plant aquaporins is dependent on temperature, it has little effect on the water transportation rate because it is so low. This group of researchers also found that sulphydryl reagents had a negative effect on the permeability of some plant membranes.

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Aquaporins

Existing Biomimicry: Case Study

A number of commercial companies are researching the principles of aquaporins for incorporation in membrane purification systems: Agua Via, Biophiltre, Danfoss, Novozymes, Aquaporin. Aquaporin membrane technology was tested by NASA in October 2011. This membrane is the most promising candidate to date in the quest for a small, lightweight system, able to convert the body fluids of astronauts into drinkable water. ((Aquaporin A/S, 2013)).

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Aquaporins

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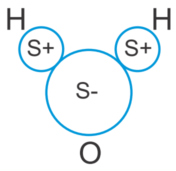
AQUAPORIN



Water Molecule

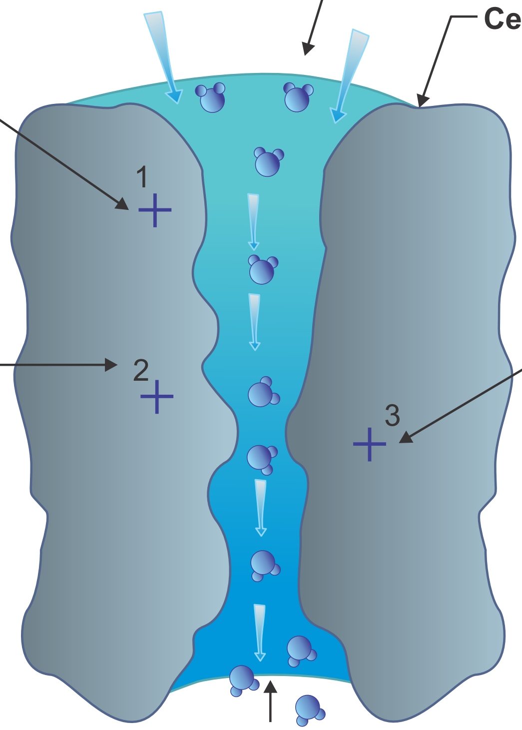
- Molecule polar
- Oxygen has a slightly negative charge
- Hydrogen molecules have a slightly positive charge

Channel

- Within the cell membrane
- Operates at thermodynamically lowest energy level for purification
- Positively charged at 1, 2 and 3

- Negative pole of water attracted by positive charge at the top of the channel
- Ensures all water molecules are facing the same way

Cell membrane



Cell interior

- Water molecules move through the channel by orientating themselves to the local electrical field that is formed by the channel wall
- Second positive charge keeps the molecules in line, allowing molecules to pass in a single line

Once the water molecules have lined up, the channel narrows
Only water molecules may pass, any molecules bigger, are not able to pass

- Molecules “flip” because of the positive charge on the opposite side of the channel towards the bottom
- Negatively charged oxygen molecules turning towards the charge causes the molecules to flip

Any molecules that do not “flip” do not enter the cell interior

Back

Mangroves

Dissolved solids removal through (solar-based) osmotic effects for drawing in water & expelling salts

Figure 1: Mangroves (Unsworth, 2010).

Biomimicry Innovation:

Conventionally, reverse osmosis and ultrafiltration processes require high energy input. This is a problem in the context of rising energy costs and concerns relating to green house gas emissions (climate change). This innovation is inspired by mangroves that use a combination of solar-based osmotic effects for rejecting salt when drawing in water and excreting excess salt. These innovations could improve low-energy or solar-based desalination or similar systems. Selective water gates in membranes (aquaporins - see separate section) are also found in mangrove systems and should be used in combination with these additional effects, for a solar-powered DSR/desalination system.

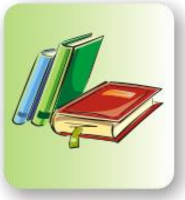
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Mangroves

Design Principles

Process:

The following principles are noted:

1. Salt exclusion: Solar-based evapo-transpiration creates a negative pressure that drives an ultra-filtration process through (integrated/multiple/modular) components of a processing unit that draws in water while rejecting salt. The ultrafiltration process is based on selective molecule transport (see aquaporins) and selective barriers for ions (reverse osmotic exclusion).
2. Salt is excreted in an energy-driven process using the principles of reverse osmosis.
3. Salt accumulation: Salt accumulates in certain components of the process structure, which are then removed from the system.
4. Low Energy: Conditions are created to exploit gradients of water potential to reduce energy consumption and to exploit low-energy fluid dynamics principles

Back

Mangroves

Possible Applications

The principles can be applied in solar powered desalination plants.
The mechanism for salt rejection by the leaves can be mimicked for the removal of minerals, salts and heavy metals from wastewater streams.
Application of principles in emerging forward osmosis technologies which facilitate flow of water from saline water by exploiting osmotic gradients. This technology will prevent ions from passing through semi-permeable membranes, while allowing water to pass through.
Improvement of existing technologies that exploit water potential gradients to facilitate passive extraction of fresh water from seawater (e.g. create low water potential fluids to attract water via osmosis/diffusion) (see also "ultrafiltration").
The development of a technology that creates and exploits electrochemical gradients using ion pumps that selectively transport certain ions. This may be supported by the development of membranes that function similarly to aquaporin proteins.
Use capillary action where possible to move water.

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Mangroves

Biological Foundation

Biological Strategy

Mangrove trees typically grow in the intertidal zone that is infiltrated by both fresh and seawater. As a consequence, they have evolved to survive in conditions of variable saturation and salinity. Plants experience many problems living in or near sea water which is 'physiologically dry', because most plant and animal tissues are more dilute than seawater. For osmosis to occur, water must move from a more dilute to a more concentrated compartment. This is why when most garden and pot plants are exposed to sea water, they will wither and die as the salty soil extracts water from the plant instead of replenishing it. The fluctuating salinities experienced in mangroves due to tides, desiccation and weather exacerbate this situation.

Mangroves desalinate water through exclusion, and/or secretion, and/or accumulation. Different parts of mangrove plants play vital roles in separating water from salt before and/or after entering the plant structure. The typical salt concentration in the sap is high, at about one-tenth that of seawater. In secretors, salt is excreted by an energy-dependant process in the salt glands of the leaves. The water from the concentrated salt solution evaporates near the gland, and salt crystals are formed, which are removed by wind or rain. Non-secreting mangroves selectively absorb only certain ions [(electrically charged atom(s) and/or group of atom(s)], while others are rejected from the saline solution, by a process called ultrafiltration. However, even with this, exclusion is not complete. Some salt is lost by transpiration through the leaf surface or accumulates in some cells of the leaf. Some species accumulate excess salts in the old leaves which are then shed.

Some fiddler crabs can eat the leaves of mangroves with high salt content. There may be something in the digestive capacity of these crabs to manage high salt content. Leaves also fall into the sea, returning the salt to the ocean slowly over time.

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Mangroves

Biological Mechanism

Figure 2: Mangrove leaf rejecting salt (Ask Nature, 2008)

The uptake of water by the roots of mangroves against an osmotic gradient is driven by evapotranspiration (evaporation of water from the leaves of the plants). The energy of the sun provides the energy for evaporation. To maintain homeostasis, some mangroves have a membrane barrier in the root system which is impermeable to salt. Others, known as secretors, actively secrete salt through pores in the foliage (Li, et al., 2008) (Paliyavuth, Clough, & Patanaponpaiboon, 2004).

Mangroves manage salt in one of three ways (Horst, 1998):

- Salt exclusion, where salt is prevented from entering the system, through ultrafiltration
- Salt secretion, where salt is excreted via salt glands found on the leaves.
- Salt accumulation and shedding – salt is stored in older leaves and bark and these are shed.

Salt excluding species, such as the Red Mangrove, separate salt from freshwater at the root surface via selective channels (including aquaporins). Transpiration at the leaf surface creates negative pressure in the xylem. This provides the energy for the uptake of water against the concentration gradient (reverse osmosis) at the root surface. The salt concentration of xylem sap in the Red Mangrove is about 1/70 the salinity of surrounding seawater, but this is still 10 times higher than in 'normal' plants.

Salt secreting mangrove species, including Black and White Mangroves, regulate ionic concentration by secreting salt through glands on the leaf surface. This temperature-sensitive enzymatic process involves active transport which requires energy. Xylem sap in these species is 1/7 the concentration of salt water, which is tenfold greater than in salt excluders.

Although Red Mangroves and White and Black Mangroves are primarily salt excluders and salt secretors, respectively, all three species utilize both mechanisms to varying degrees. For instance, the Red Mangrove stores and disposes of excess salt in the leaves and fruit, while Black and White Mangroves are capable of limited salt exclusion in the roots.

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Mangroves

Context/Working Conditions

Mangroves can be found in saline waters under a range of saturation conditions, from completely saturated to dry soils and from hyper-saline to fresh waters. These are generally found in temperate climates. Mangroves are found where salinity ranges from 0ppt-90ppt. Red Mangroves are found where soil salinities range from 60ppt-65ppt. Black and White Mangroves have been found in soil salinities greater than 90ppt. In restricted bays and flats, water salinities often range over 40ppt.

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Mangroves

Existing Biomimicry: No Case Studies

Aquaporins have been used in biomimicry applications. It is possible to expand the use of these to include the other useful processes that take place in mangroves - especially for desalination plants.

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Mangroves

References

Horst, W. (1998). *Mangroves.* Retrieved September 2012, from http://www.athiel.com/lib10/horstman.htm

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Unsworth, R. (2010, May 5). *16 % of worlds mangrove species at elevated risk of extinction: No Mangrove - No Fish.* Retrieved September 19, 2012, from Climate shifts: http://www.climateshifts.org/?p=5272

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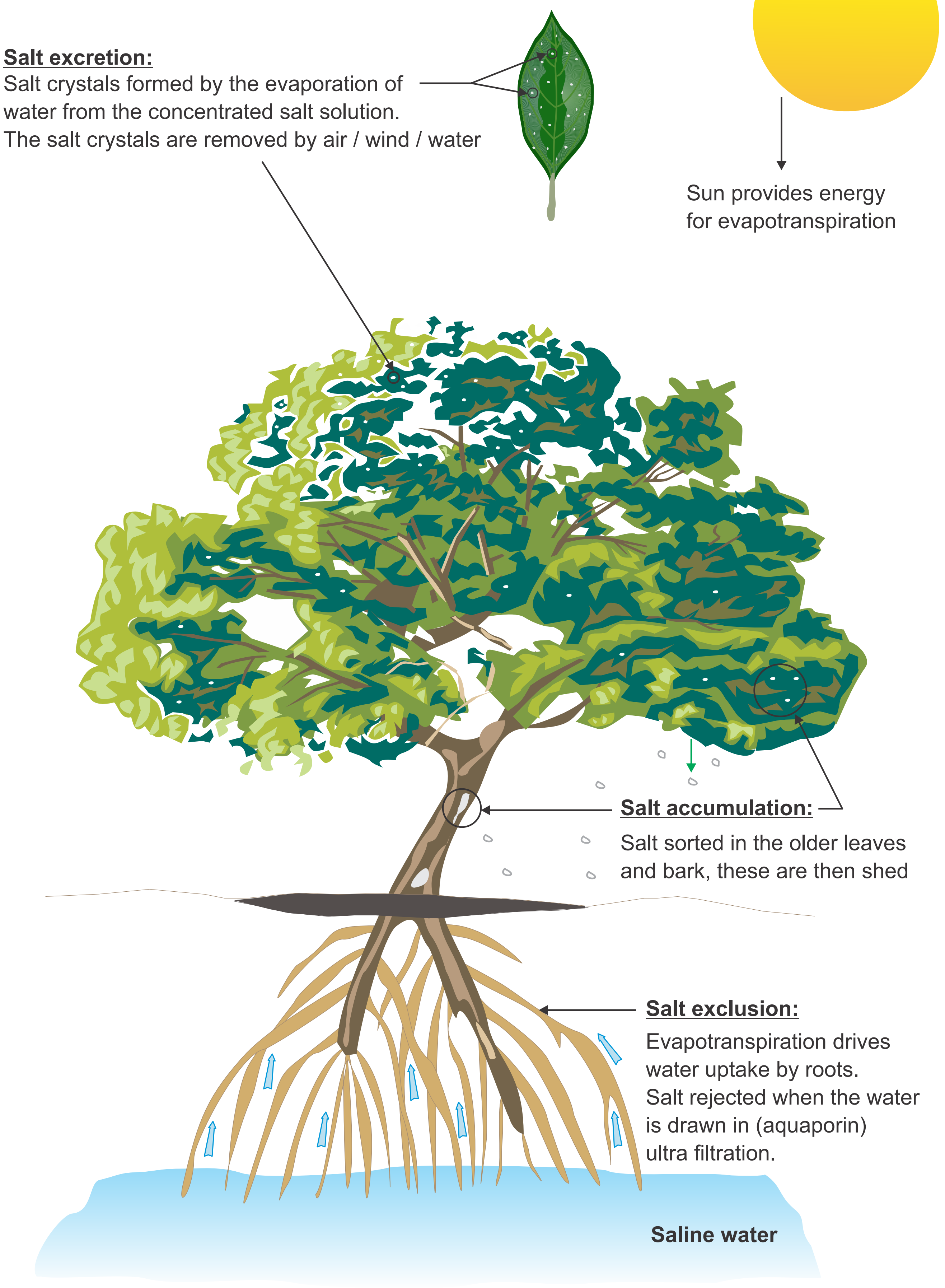
MANGROVES



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Kidneys

Dissolved solids removal through gradients & dual membranes

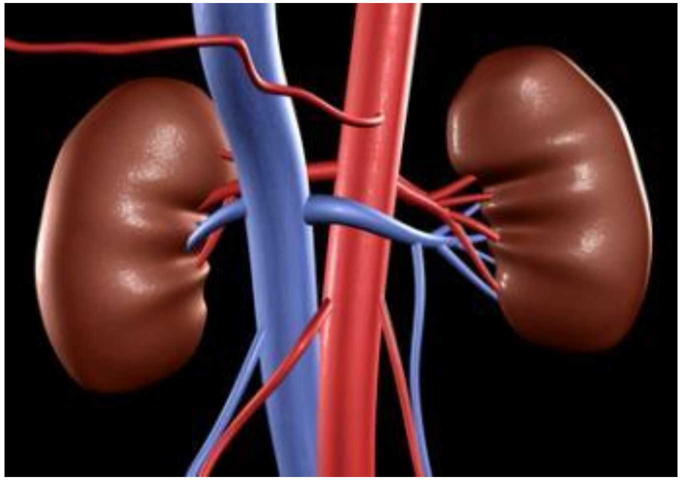


Figure 1: Illustration of the kidney, indicating the renal artery and renal vein.

Biomimicry Innovation:

Conventionally, the removal of dissolved solids involves the use of membrane technology and high pressure gradients. This innovation, inspired by the multifunctional kidney, involves a combination of processes that result in lower energy requirements and improved filtration of dissolved solids compared to conventional processes.

The use of some or all of the kidneys design principles would include:

- A high hydrostatic pressure gradient, and/or;
- Selective size, shape and charge of particles;
- An osmotic gradient; and
- Modular and dual membranes.

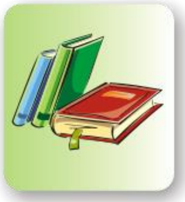
Design principles

Possible applications

Biological Foundation

Context

Case studies



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Kidneys

Design principles

Process:

High hydrostatic pressure gradient: a high rate of filtration is dependent on a hydrostatic pressure gradient created by decreasing the bore of the vessels.

Size, shape and charge of particles: for example, proteins, which are negatively charged, remain in the fluid because their high molecular weight and negative charge precludes them from passing through the membrane and associated channels.

Osmotic gradient: Water and solutes can move back and forth depending on the osmotic gradient.

Modular and dual membranes: Modular and dual membranes at different sections perform different functions relating to dissolved solid removal.

Structure: The macrostructure consists of one million small tubular structures that stretch across both the light outer region (Figure 2) and dark inner region (Figure 1, D) and are perpendicular to the surface. The tubules are long, thin and closed at one end having two twisted regions interspaced with a long hairpin loop followed by a long, straight portion at the ends.

Materials: Consists of selectively permeable, elastic material.

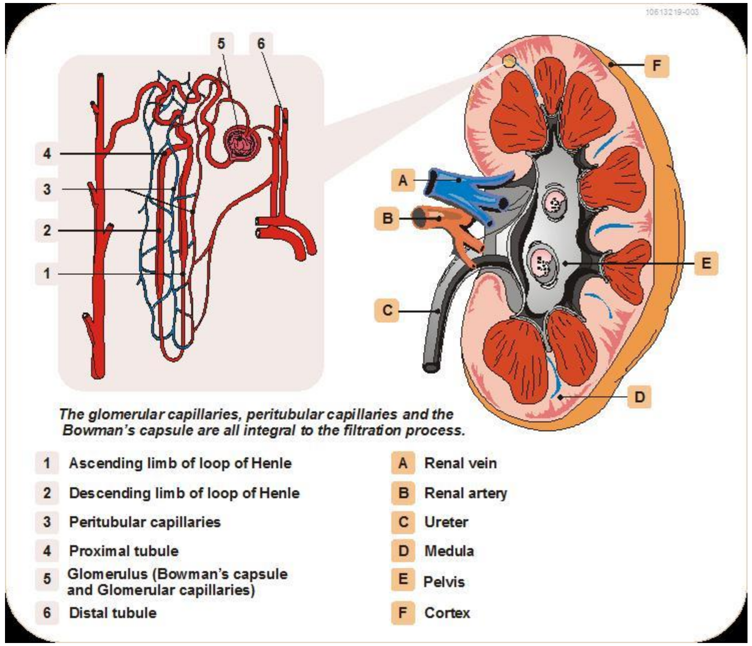

Figure 2: Illustration indicating the Bowmans capsule (Image courtesy of How Stuff Works.) (Freudenrich, 2001)

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Kidneys

Possible Applications

The size, shape and charge selective protein channels are discussed separately in the aquaporins information sheet.

The process whereby a high hydrostatic pressure gradient is formed by the narrowing of vessels can be applied in tubular reverse osmosis configurations.

Often wastewater streams generated in industry contain reagents required for the process mixed with water. By using the dual membrane approach, reagents can be recovered for reuse in the process.

The use of a dual membrane process can be used to recycle domestic wastewater (sewage) to levels that approach the quality of distilled water. These recycling plants use two membranes - one with larger holes to remove micro-organisms such as protozoa and bacteria that cause infection, while the second membrane separates salt from water.

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Kidneys

Biological Foundation

Biological Strategy

The kidney is responsible for acid/base regulation, maintaining electrolytic concentrations, extracellular fluid volumes and regulating blood pressure. They are also involved in the excretion of metabolic waste products such are urea, uric acid and creatinine.

Biological Mechanism

There are three basic functional processes associated with urine formation which take place consecutively in different regions of the glomeruli (the working units of the kidneys):

- Glomerular filtration;
- Tubular reabsorption; and
- Tubular secretion.

During these processes, movement of water, ions and molecules takes place in both directions between the blood and the glomerular lumen. The constituents of the lumen are collected into vessels which eventually amalgamate into a large tube, the ureter, and the waste is excreted from the body as urine. The maintenance of a proper balance of water and solutes (homeostasis) is maintained by the functioning of the kidneys. Kidney function is controlled by complex physiological mechanisms. In some sections, the renal tubules are highly porous and in others, only facilitated diffusion can take place (Guyton & Hall, 1996) (Vander, Sherman, & Luciano, 2001)

Back

Kidneys

Context/Working conditions

Kidneys operate under ambient temperatures. A pressure differential is required. Vessels are of a durable elastic media to enable constrictions and expansions.

Back

Kidneys

Existing Biomimicry: Case Study

Using a system based on the human body's kidneys - the ultimate in water recycling technology - Singapore and Orange County, CA have developed schemes that will use a dual membrane process to recycle domestic waste water (sewage) to levels that approach the quality of distilled water. Like the kidney, these recycling plants use two membranes; one with larger holes to remove micro-organisms such as protozoa and bacteria that cause infection, while the second membrane separates salt from water (Courtesy of The Biomimicry Guild).

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Kidneys

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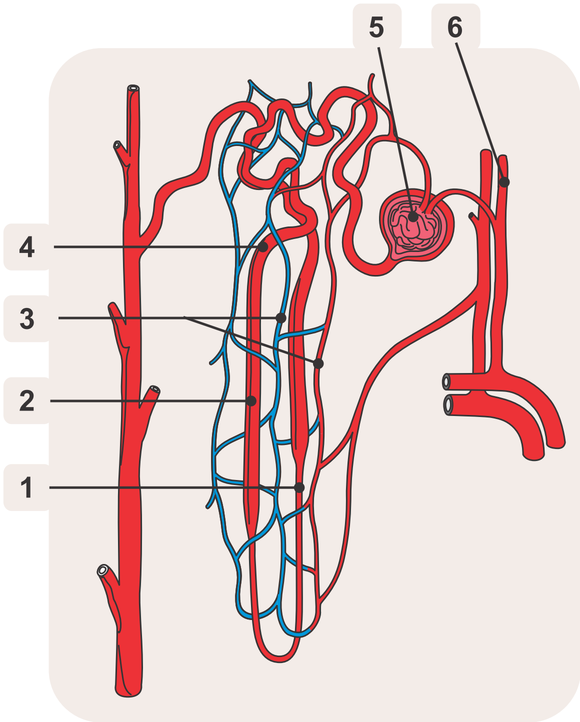
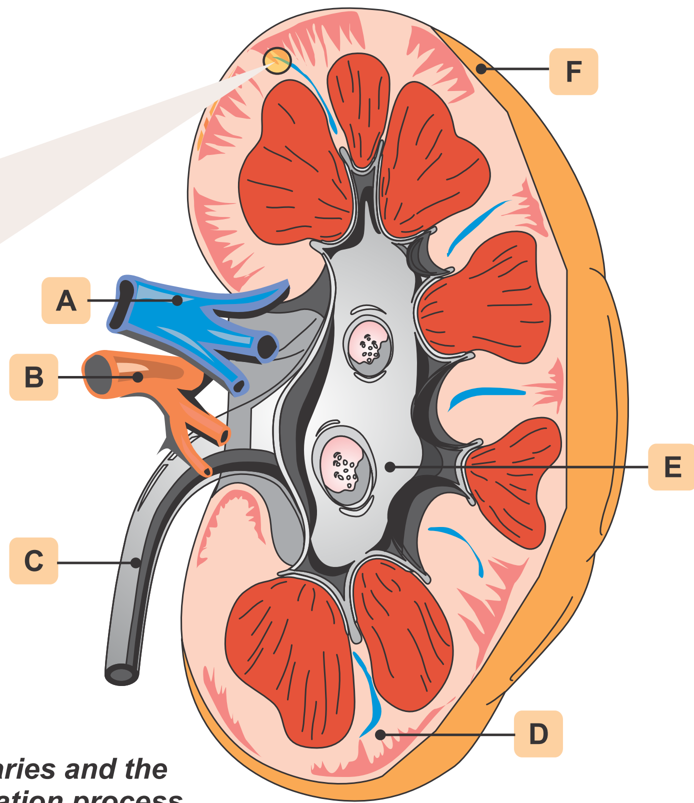




The glomerular capillaries, peritubular capillaries and the Bowman's capsule are all integral to the filtration process.

1	Ascending limb of loop of Henle	A	Renal vein
2	Descending limb of loop of Henle	B	Renal artery
3	Peritubular capillaries	C	Ureter
4	Proximal tubule	D	Medula
5	Glomerulus (Bowman's capsule and Glomerular capillaries)	E	Pelvis
6	Distal tubule	F	Cortex

Back

Pathogen & Toxin Removal

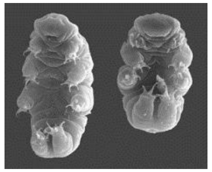
Pathogens are generally removed using disinfection methods such as

- Chlorine dosing
- Ozonation
- UV

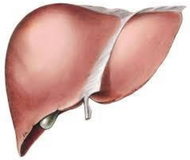
Management of toxins are generally toxin specific.

Biomimicry research has revealed a number of innovations for these pathogen removal. The innovations are inspired by natural organisms and systems that are specialists in removing pathogens from water/other fluids, and based on millions of years of natural selection have evolved highly efficient and effective sustainable solutions in each case. The following subsections summarise the key innovations from natural "champion" or specialists in each case. They are classified as champions in this context based on the fact that of the many organisms that perform this particular function, these organisms are the specialists identified in each case.

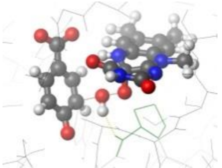
Removal of toxins in fixed-film biological treatment systems
(Beavers Dams)



Removal of toxins by utilizing radiation tolerant organisms
(Radiation Tolerant Extremophiles)

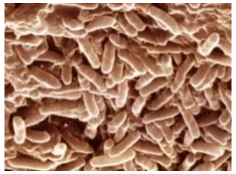


Removal of toxins and pathogens in a multi-functional (bio) chemical reactor
(Human Liver)



Removal of toxins by enhancing desirable redox reactions
(Microbial Enzymes)

Removal of pathogens and toxins by combined filtratio and chemical inactivation/detoxification
(Deep Sea Sponges)



Removal of toxins by changing chemical oxidation status
(Oxidising Reducing Bacteria)

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Beaver Dams

Removal of toxins in rivers using in-situ biological treatment systems

Figure 1: Typical Beaver dam. (Science Daily, 2012).

Biomimicry Innovation:

Worldwide, many river systems are contaminated by point and non-point source pollutants. Remediation of large volumes of water that are not contained is logistically difficult. This innovation focuses on treating contaminated rivers *in-situ*, using purpose-built remediation dams by utilizing the principle of Beaver Dams. The habitat created by Beaver Dams increases the hydraulic retention time by reducing flow rate and increases the surface area for the attachment of biomass/biofilm involved in the biodegradation of river pollutants.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

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Beaver Dams

Design Principles

Structure and materials: The structure consists of vertical poles interweaved with horizontal branches and covered with mud and weeds. Note: alternative materials could be used to achieve the same functionality.

Process: The structure increases the hydraulic retention time by reducing flow rate across the dam. It also increases the surface area for the attachment of biomass/biofilm involved in the biodegradation/metabolising of river pollutants (nutrients and toxins). The resulting increase in species diversity and abundance has a positive effect on water quality.

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Beaver Dams

Possible Applications

Similar principles can be applied in the design of constructed/treatment wetlands, passive treatment systems, biological sand filters, and phytoremediation applications. Construction of artificial Beaver Dams, seeded with selected microbes, to remediate contaminated riverine habitats. These could be particularly effective in remediating spills in rivers.

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Beaver Dams

Biological Foundation

Biological Strategy

Beavers build dams which decrease stream velocity and alter the landscape from terrestrial to wetland (Westbrook, Cooper, & Baker, 2011). Even beyond the pond, the effects of damming are evidenced by siltation and the development of vegetated areas known as Beaver meadows (Westbrook, Cooper, & Baker, 2011). The organic-rich wetland areas enhance the removal of nitrate, ammonia and organic pollutants from rivers (Bledzki, Bubier, Moulton, & Kyker-Snowman, 2010) (Landmeyer, Tanner, & Watt, 2004).

Biological Mechanism

The increase in species diversity and abundance in Beaver Dams has a positive effect on water quality. For instance, an abundance of predatory zooplankton in beaver ponds has been shown to control algal blooms (Bledzki, Bubier, Moulton, & Kyker-Snowman, 2010). In addition, the bioremediatory function of the benthic (sediment) microbial communities can mitigate the adverse effects of upstream spill events (Landmeyer, Tanner, & Watt, 2004). For example, in 2000, the largest ever spill of tributylin in the U.S. took place in a river in South Carolina. Tributylin is used as an anti-fouling agent and is classed as environmentally hazardous. It was found that the microbial communities in a beaver dam increased the degradation/mineralization of tributylin into inorganic tin, thus assisting remediation of the spill (Landmeyer, Tanner, & Watt, 2004).

Structure: Beavers start construction by diverting the stream to reduce the water's flow pressure. Branches and logs are then driven into the mud of the stream bed to form a base. Afterwards sticks, bark (from deciduous trees), rocks, mud, grass, leaves, plant mass, and anything else available, are used to build the superstructure. The average height of a dam is about 1.8m with an average depth of water behind the dam of 1.2m to 1.8m. The thickness of the dam is often around 1m or more. The length depends on the stream width, but averages about 4.5m long. Beavers vary the type of dam built and how they build it, according to the speed of water on the stream. In slow-moving water, they build a straight dam, whereas in fast-moving water they tend to be curved. Spillways and passageways are built into the dam to allow excess water to drain off without damaging it. Dams are generally built wider at the base and the top is usually tilted upstream to resist the force of the current. Beavers can transport their own weight in material; they drag logs along mudslides and float them through canals to get them in place. Once the dam has flooded enough area to the proper depth to form a protective moat for the lodge (often covering many acres), beavers begin construction on the lodge. Trees approaching a diameter of 90cm may be used to construct a dam, although the average is 10cm to 30cm. The length depends on the diameter of the tree and the size of the beaver. There are recorded cases of

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beavers felling logs of as much 45m tall and 115cm in diameter. Logs of this size are not intended to be used as structural members of the dam, but rather the bark is used for food, and sometimes to get at upper branches.

Process: Beaver ponds can cause the removal of nutrients from the stream flow. Farming along the banks of rivers often increases the loads of phosphates, nitrates and other nutrients, which can cause eutrophication and may contaminate drinking water. Besides silt, the Beaver Dam collects twigs, branches, and leaves from the beaver activity, most notably in the fall. The main component of this material is cellulose, a polymer of β-glucose monomers. This creates a more crystalline structure than is found in starch, which is composed of α-glucose monomers (cellulose is a type of polysaccharide). Many bacteria produce cellulose which can split off the glucose and use it for energy. Just as algae get their energy from sunlight, these bacteria get their energy from cellulose, and they form the base of a very similar food chain. However, a source of energy is not enough for growth. These bacterial populations face serious shortages of nitrogen and phosphorus compounds, and will absorb these nutrients as they pass by in the water stream. In this way, these and other nutrients are fixed into the beaver pond and the surrounding ecology, and are removed from the stream.

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Beaver Dams

Context/Working Conditions

Beaver Dams rely on the availability of suitable small to large trees to form the backbone of the construction. The woody material must be cut and transported to the site where the flow of water should not be too rapid or it is not possible to establish a dam. Beaver Dams do not stop the flow of water, merely retard it. Beavers usually live in cold climates.

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Beaver Dams

Existing Biomimicry: Case Study

Natural wetlands effectively remove nutrients and pollutants from water. Constructed wetlands are man-made wetland systems that emulate and enhance the functions of natural wetland systems. The fundamental principles of Biomimicry have been extensively and successfully applied to constructed wetlands even before the advent of Biomimicry as a discipline. Apart from nutrient (nitrogen and phosphorus) removal, degradation of toxic organic molecules can be achieved using constructed wetlands, in much the same way as in beaver dams. For example, it has been shown that phenolics and ethanol in winery wastewater can be completely mineralized in constructed wetlands or biological sand filters (unplanted constructed wetlands), provided the influent concentration falls within certain limits (Welz, Ramond, Prins, Cowan, & Burton, 2011) (Welz, Ramond, Cowan, & Burton, 2012). Recently, engineered wetlands were placed in the floodplains of a tributary river in China to intercept polluted water prior to discharge into the receiving river. This has resulted in a reduction of suspended solids, COD, nitrogen and phosphorus in the effluents from the wetland (Zheng et al., 2012)

Cleaning of river systems in situ have also been accomplished through floating islands or equivalent eco-machines such as the river restorers by www.toddecological.com.

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Beaver dams

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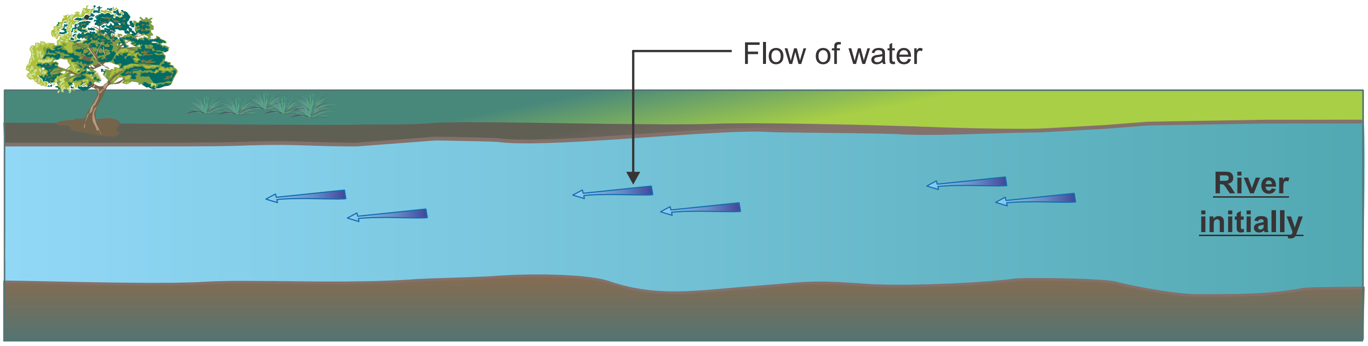
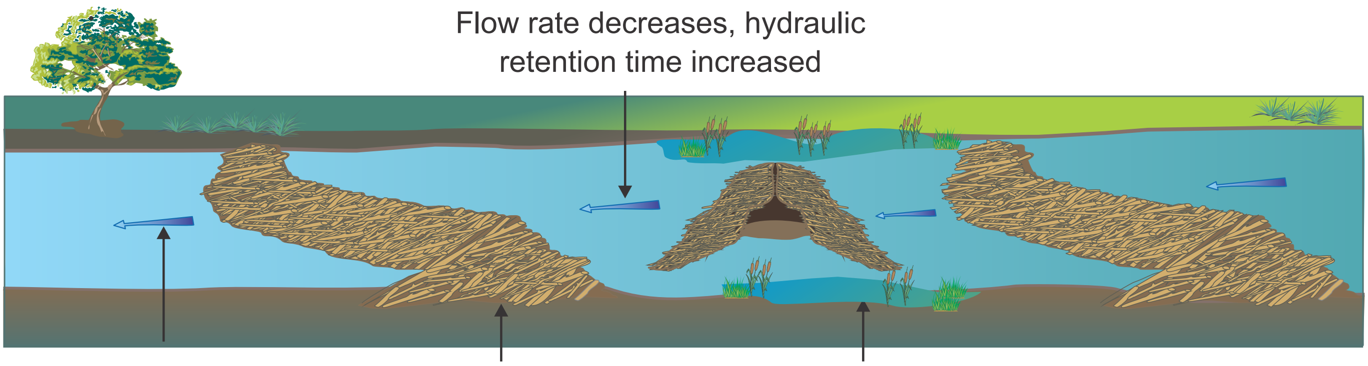
BEAVER DAMS

PLAN VIEW

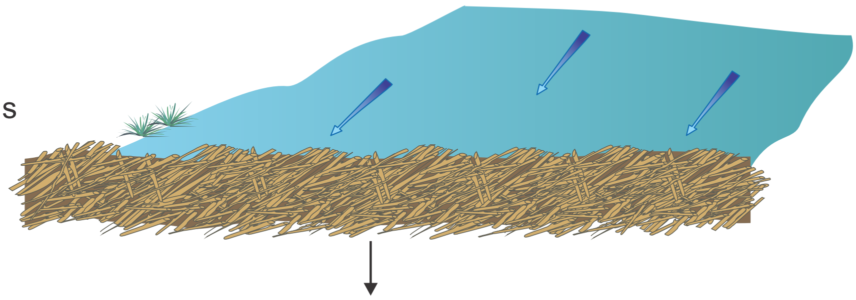




FRONT VIEW

STRUCTURE

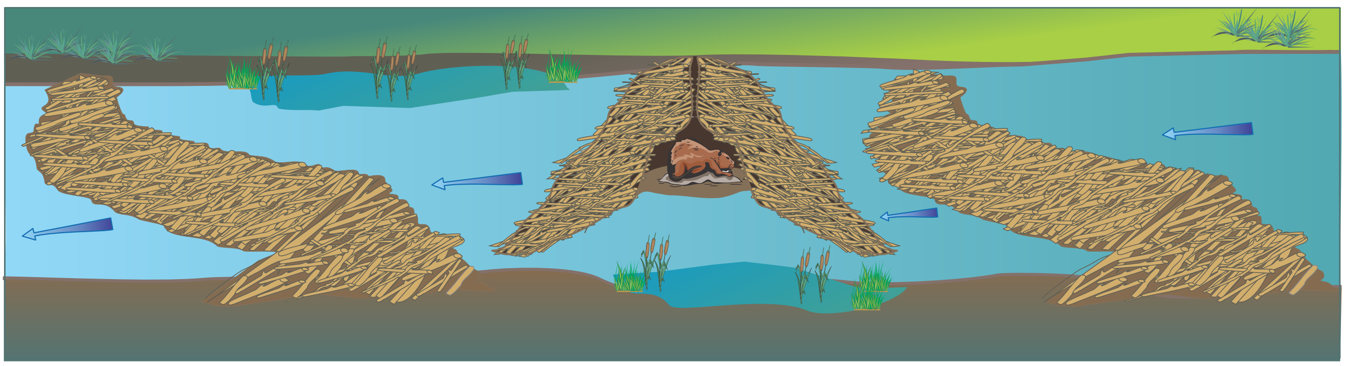
- Horizontal branches covered in weeds with vertically cris-crossed branches
- Suitable habitat for micro-organisms, capable of metabolising nutrients and toxins



SIDE VIEW

Beaver meadows:

- Organic rich wetland areas that enhance removal of nitrate ammonia and other organic pollutants



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Microbial Enzymes

Removal of toxins by enhancing desirable redox reactions

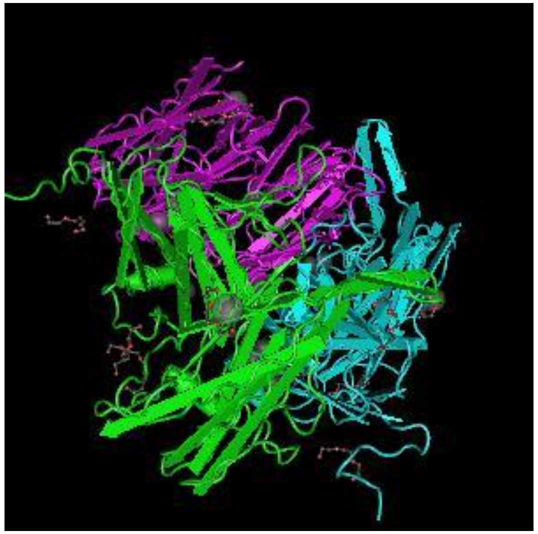

Figure 1: 3D structure of laccase from Streptomyces coelicolor (National Centre for Biotechnology, 2011)

Biomimicry Innovation:

Toxins can be degraded, transformed or mineralized into non-toxic inorganic or organic constituents. The natural detoxification processes are often slow or cannot occur under the prevailing environmental conditions. Specific biological enzymes can be added to wastewater as catalysts to speed up the degradation, transformation and mineralization of toxins.

Microbial Enzymes

Design Principles

Structure: Bioreactors for wastewater treatment can be designed with support matrices for enzymes. Many such systems are already in use and specific information is readily available in literature, depending on the application.

Chemistry: Enzymes are typically protein molecules that serve as biological catalysts, binding substrates selectively, lowering the energy of the transition state and directly promoting the catalytic event. The enzyme that is chosen is related to the function. This information is extensive and readily available in literature, depending on the application. For example, ammonia removal via nitrification/denitrification commences with the oxidation of ammonia to nitrite, which is catalyzed by microorganisms that produce ammonium monooxygenase and hydroxylamine oxidoreductase. This is more bioutilisation or biotechnology, rather than biomimicry.

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Microbial Enzymes

Possible Applications

Bioremediation of organic and inorganic wastewater pollutants (biotransformation/biodegradation).

Enzymes can be extracted, concentrated, and used separately from their biological progenitors. These catalysts can be manufactured separately and added directly to wastewater, where they will chemically convert specific toxins into non-toxic components. Alternatively, they can be produced *in-situ*, if the wastewater conditions do not adversely affect the process. The activity of enzymes can be inhibited or induced by organic or inorganic fractions in wastewater.

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Microbial Enzymes

Biological Foundation

Biological Strategy

Biological enzymes are produced by almost all plants and animals and play vital roles in cell growth and metabolism. Many enzymes catalyze chemical reactions involved in the bioremediation of wastewater. For example, ammonia removal via nitrification/denitrification commences with the oxidation of ammonia to nitrite, which is catalyzed by microorganisms that produce ammonium monooxygenase and hydroxylamine oxidoreductase (Atlas, 1997). Enzymes can be extracellular (made in the cell and released into the environment), cytoplasmic (remain in the cell), or membrane bound (form part of the cell membrane). Enzymes can be extracted, concentrated and used separately from their biological progenitors. The activity of enzymes can be inhibited or induced by organic or inorganic fractions in wastewater (Xu, et al., 2012).

Biological Mechanism

Catalysts are substances that increase the rate of chemical reactions without themselves changing in the overall process. During chemical reactions, molecules undergo conformational changes to form transition states which are intermediate between the initial and final (reacted) states. The change from initial to transition state requires energy, which is known as activation energy. Catalysts typically lower the energy of activation by binding to the substrate and forcing the molecule into an intermediate state that resembles the un-catalyzed counterpart, but has less energy (Matthews & van Holde, 1995). Enzymes are typically protein molecules that serve as biological catalysts, binding substrates selectively, lowering the energy of the transition state, and directly promoting the catalytic event (Matthews & van Holde, 1995).

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Microbial Enzymes

Context/Working Conditions

Enzymes can be immobilized on support matrices, preventing washout and increasing enzyme stability (Zimmerman, Shahgaldian, Corvini, & Hommes, 2011). The most important factors affecting the activity of enzymes are pH, temperature, substrate concentration, concentration of inhibitors, concentration of inducers, concentration of essential co-factors (e.g. external electron donors), redox status and contact time (Golan-Rozen, Chefetz, Ben-Ari, Geva, & Hadar, 2011) (Matthews & van Holde, 1995). Therefore, the enzyme extract or immobilized enzyme system should be carefully chosen bearing the characteristics of the wastewater in mind. For example, cold-active enzymes can be used (Kuddus, Roohi, & Ramteke, 2011) in situations where it is not economically feasible or practical to heat the wastewater for treatment.

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Microbial Enzymes

Existing Biomimicry: Case Study

These are bioutilisation or biotechnology case studies but may serve to inspire biomimicry applications:

Biological enzymes have been used extensively to remediate wastewater, for example:

Extracts of membrane-associated chromium reductase from *Pannonibacter phragmitetus* has been shown to be effective at reducing the mutagen/carcinogen Cr (VI) to Cr (III) under anaerobic conditions (Xu, et al., 2012).

Cytochrome P450 monooxygenase and manganese peroxidase from *Pleurotus ostreatus* have been shown to biodegrade the pharmaceutical carbamazepine (Golan-Rozen, Chefetz, Ben-Ari, Geva, & Hadar, 2011).

Laccase from *Coriolopsis polyzona* has been successfully immobilized on silica nanoparticles for remediation of wastewater containing aromatic compounds (Zimmerman, Shahgaldian, Corvini, & Hommes, 2011).

Bioreactors containing laccase from *Myceliophthora thermophila* have been shown to degrade estrogens (Lloret, Eibes, Feijoo, Moreira, & Lema, 2012).

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Microbial Enzymes

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Radiation Tolerant Extremophiles

Removal of toxins by utilizing radiation tolerant organisms

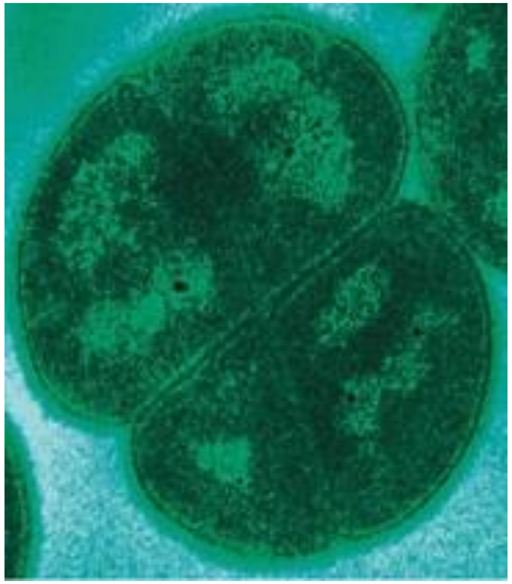

Figure 1: Schematic representation of the biological sulphur cycle

Biomimicry Innovation:

Extremophilic microorganisms grow in environments where one or more physico-chemical parameter is considered to be in the extreme range. For example, organisms which grow at very low temperatures (thermophiles), high temperatures (psychrophiles), highly saline conditions (halophiles), under extreme pressure, or in the presence of high ionizing and/or UV radiation.

Some extremophiles are capable of growing in radioactive environments where they either:

(i) Catalyze redox reactions, changing the speciation of toxic elements and elemental compounds into non-toxic species (See Microbial enzymes); or

(ii) Accumulate radionuclides intracellularly in inactive complexes which can then be separated from the aqueous phase by settling (Lloyd & Renshaw, 2005).

Many watercourses and groundwater supplies are contaminated with radioactive waste, much of this emanating from mining activities. Radiation-tolerant extremophiles may be utilized, or their functions may be mimicked to remediate such aquatic environments.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

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Radiation Tolerant Extremophiles

Design Principles

Chemistry: Radionuclides are changed from toxic to non-toxic species by oxidation or reduction. Apart from boasting a robust excision-repair system (the proteins that recognize damaged DNA, cut out the damaged sections, insert new sections and also bind any broken sections), the active component is also highly capable of coping with oxidative stress by:

(i) Eliminating oxidized macromolecules,
(ii) Protecting selected proteins from oxidative damage,
(iii) Suppressing the production or reactive oxygen species within the cell itself, and
(iv) Harboring antioxidant defense systems

Process: Radionuclides are concentrated and inactivated in cells. The cells containing the radionuclides are then allowed to settle to the bottom of the solution, where they can be separated and removed from the contaminated water as sludge.

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Radiation Tolerant Extremophiles

Possible Applications

Selected radiation tolerant microbial strains can be used to precipitate radionuclides from radioactive wastewater. Alternatively, radiation tolerant strains capable of accumulating radionuclides intracellularly can be grown in radioactive wastewater, and then removed in settling tanks. Strategies to promote the growth of the most useful species can be implemented *in-situ* in contaminated sites. These are bioutilisation applications. However, including these in systems such as eco-machines may make it more of a biomimetic system. It may be possible to explore mimicking the function of these microbes, however since they are already effective, utilization may be the best option.

Another interesting approach would be to establish the context in which these microbes exist so that they can apply their necessary function, rather than simply adding them to the system. This is however still bioutIlisation.

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Radiation Tolerant Extremophiles

Biological Foundation

Biological Strategy

Radiation results in the formation of reactive oxygen species that damage proteins, lipids, nucleic acids and carbohydrates in cells, as well as inducing potentially lethal double-stranded DNA breaks in the bacterial genome (Slade & Radman, 2011)Some extremophiles can overcome the damage induced by reactive oxygen species in the presence of chronic ionizing radiation in the most radioactive waste sites (Sghaier, et al., 2012). The organisms can also overcome similar damage instilled by UV radiation (Sghaier, et al., 2012).

Biological Mechanism (s)

Most biological cells, including bacterial cells, manufacture a collection of proteins (enzymes) that constitute an 'excision-repair' system. These proteins are designed to recognize damaged DNA, cut out the damaged sections, insert new sections, and also bind any broken sections (Matthews & van Holde, Biochemistry 2nd ed., 1995). If the amount of radiation induces changes that are over and above the capability of the excision repair system to 'fix', the cell dies. Extremophiles such as the model example, *Deinococcus radiodurans,* that can tolerate high levels of radiation, have more robust excision-repair systems than species that are more sensitive to radiation damage (Shuryak & Brenner, 2012).

Not only does radiation damage DNA directly, but it also creates reactive oxygen species (superoxides, hydrogen peroxide, hypochlorite and hydroxyl radicals) that damage the proteins, including those involved in DNA repair. Apart from boasting a robust excision-repair system, the extremophile *D. radiodurans* is also highly capable of coping with oxidative stress by:

(i) Eliminating oxidized macromolecules,
(ii) Protecting selected proteins from oxidative damage,
(iii) Suppressing reactive oxygen species production within the cell itself, and
(iv) Harbouring antioxidant defense systems (Slade & Radman, 2011).

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Radiation Tolerant Extremophiles

Context/Working Conditions

Growth requirements and tolerance levels are dependent of the species involved. *D. radiodurans* as an example, cannot grow at temperatures over 39°C and is sensitive to antibiotics because they inhibit RNA synthesis, protein synthesis and cell wall synthesis (Slade & Radman, 2011). The organism cannot synthesize the enzyme co-factor NAD, which it requires for growth. It also requires Fe, and cobalamin or methionine as growth factors (Shapiro, DiLello, & Loudis, 1977; Slade & Radman, 2011). This is an interesting approach to establish the context in which these microbes exist so that they can apply the necessary function, rather than simply adding them to the system. This is however still bioutIlisation case study.

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Radiation Tolerant Extremophiles

Existing Biomimicry: Case Studies

At a uranium tailings site in Colorado, acetate was injected as an electron donor into contaminated groundwater to stimulate the microbial reduction of soluble U(VI) to insoluble U(IV) by indigenous microorganisms. This proved successful initially, but after a month, the dominant bacterial species changed from U(VI) reducing *Geobacter* spp. to U(IV) oxidizing species (Anderson, et al., 2003). The ability of Geobacter to reduce U(VI) and oxidize Fe(II) simultaneously has also been reported by a number of other authors from field studies (Lloyd & Renshaw, 2005).

(Beyenal, Sani, Peyton, Dohnalkova, Amonette, & Lewandowski, 2004) isolated a Gram positive bacterium, closely related to *Arthrobacter ilicis*, capable of accumulating U intracellularly as precipitates with polyphosphates in granules suggesting U accumulation to be a detoxification mechanism in these organisms.

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Radiation Tolerant Extremophiles

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Deep Sea Sponges

Removal of pathogens and toxins by combined filtration and chemical inactivation/detoxification

Figure 1: Cluster of Deep Sea Sponges (Auatic Community, 2012)

Biomimicry Innovation:

A structure that provides a suitable habitat for the growth of useful bacteria. For example, pathogen removal could be enhanced by encouraging optimal growth conditions for selected antibiotic-producing microbial strains. The structure provides a suitable habitat for the growth of microbes that can compete with pathogens, produce natural antibiotics or remove toxins from water e.g. *Streptomyces* spp. produce the natural class of antibiotics, streptomycins; ammonia-oxidising bacteria detoxify ammonia via oxidation.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

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Deep Sea Sponges

Design Principles

Structure/Materials: A combination of hard external structure (composed of silica and calcium carbonate), and soft jelly-like inner structure (possibly composed collagen).

Structure/Process: The structure changes shape to suck and expel water. The action of fine hairs in the pores of the soft inner structure creates micro-currents, which together with the geometry of the pore labyrinth ensures unidirectional water movement. The surface area of the internal network of water passages is far larger than the inlet and outlet surface areas, so the movement of water is slowed internally, allowing for optimal uptake of pathogens. The internal structure provides an ideal habitat for the growth of useful microorganisms.

Chemistry: Antibiotic production and/or catalysis of redox reactions that convert chemicals from toxic to non-toxic forms.

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Deep Sea Sponges

Possible Applications

The structure of sea-sponges could be mimicked exactly or similarly to provide a suitable habitat for the growth of useful bacteria. For example, pathogen removal could be enhanced by the creation of optimal growth conditions for selected antibiotic-producing microbial strains. Specific toxin removal could also be accomplished by using the same principle. The removal of pathogens via a combination of filtration and microbial action (using specific bacterial species) could be applied to membrane bioreactors.

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Deep Sea Sponges

Biological Foundation

Biological Strategy

Figure 2: Micrograph showing the exoskeleton of a Deep Sea Sponge

Deep Sea Sponges (phylum: Porifera) are classed as animals. These organisms can filter thousands of liters of water per day. Although microorganisms are the source of nutrition for many sea-sponges, a large variety of bacteria and Achaea also survive within sponges as endosymbionts. Over the years, it has been found that many of the natural, and often useful substances, thought to be produced by sea-sponges, are actually generated by microorganisms that live within the sponges (Hann, Liu, Zhang, Li, & Lin, 2012).

Biological Mechanism

Sponges consist of a hard, structural exoskeleton, and a soft jelly-like endoskeleton called the mesohyl. The exoskeleton is typically composed of silica or calcium carbonate, while the mesohyl has many pores and channels made from collagen. Sponges change the shape of their bodies to suck in and expel water. The action of cilia in the pores of the mesohyl create micro-currents, which together with the geometry of the pore labyrinth, ensure unidirectional water movement (Ruppert, Fox, & Barnes, 2004; Kline & Ritman, 2012). Cilia are minute hair-like structures, that line the surfaces of certain cells and beat in rhythmic waves moving liquids along internal tissues.

The surface area of the internal network of water passages is far larger than the inlet and outlet surface areas, so the movement of water is slowed internally, allowing for optimal uptake of bacteria which are destroyed by phagocytosis (Ruppert, Fox, & Barnes, 2004; Eid, Albo-Elmatty, Hanora, Mesbah, & Abou-El-Ela, 2011).

The sponges provide a habitat for the growth of microbes, some of which develop a symbiotic relationship with the sponges, because they also produce chemicals which are beneficial to the sponges. These microbes, known as endosymbionts may help sponges retain nutrients, fight pathogenic infections, or

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remove toxins (Amade, Charroin, Baby, & Vacelet, 1987; Hann, Liu, Zhang, Li, & Lin, 2012). For example, endosymbiotic *Streptomyces* spp. produce streptomycins, which are natural antibiotics, and ammonia-oxidising endosymbionts can detoxify ammonia which is harmful to sponges in moderate to high concentrations (Amade, Charroin, Baby, & Vacelet, 1987).

Deep Sea Sponges

Context/Working Conditions

All Deep-Sea Sponges live in completely submerged saline environments, often under high hydrostatic pressure (deep sea bed). Each species of sponge will require different ranges of specific working conditions, usually linked to the particular habitat on an evolutionary basis. Depth, substrate, light, and food availability all play a role in colonization patterns and morphology (D'Aloia, Majoris, & Buston, 2011). For example, *Aplysina fistularis*, a sponge commonly found in the temperate waters of the Caribbean, are larger and grow faster at greater depths, where more nutrients are available (D'Aloia, Majoris, & Buston, 2011).

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Deep Sea Sponges

Existing Biomimicry: Case Study

Sea Sponges have been mimicked for other applications, but not for toxin removal purposes. For example, researchers at the Georgia Tech have patented a method for manufacturing nano-scale silica structures from biologically derived 3D templates. Conventional technologies require high temperatures for synthesis, and the product is often brittle. The bio-approach results in less brittle structures, which are formed at room temperature (Ask Nature, 2014). This principle could be incorporated to manufacture the material to create the structure described above. Further research into the microbial flora of deep-sea sponges may also lead to the discovery of new bacterial strains, e.g. bioremediation or antibiotic production.

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Deep Sea Sponges

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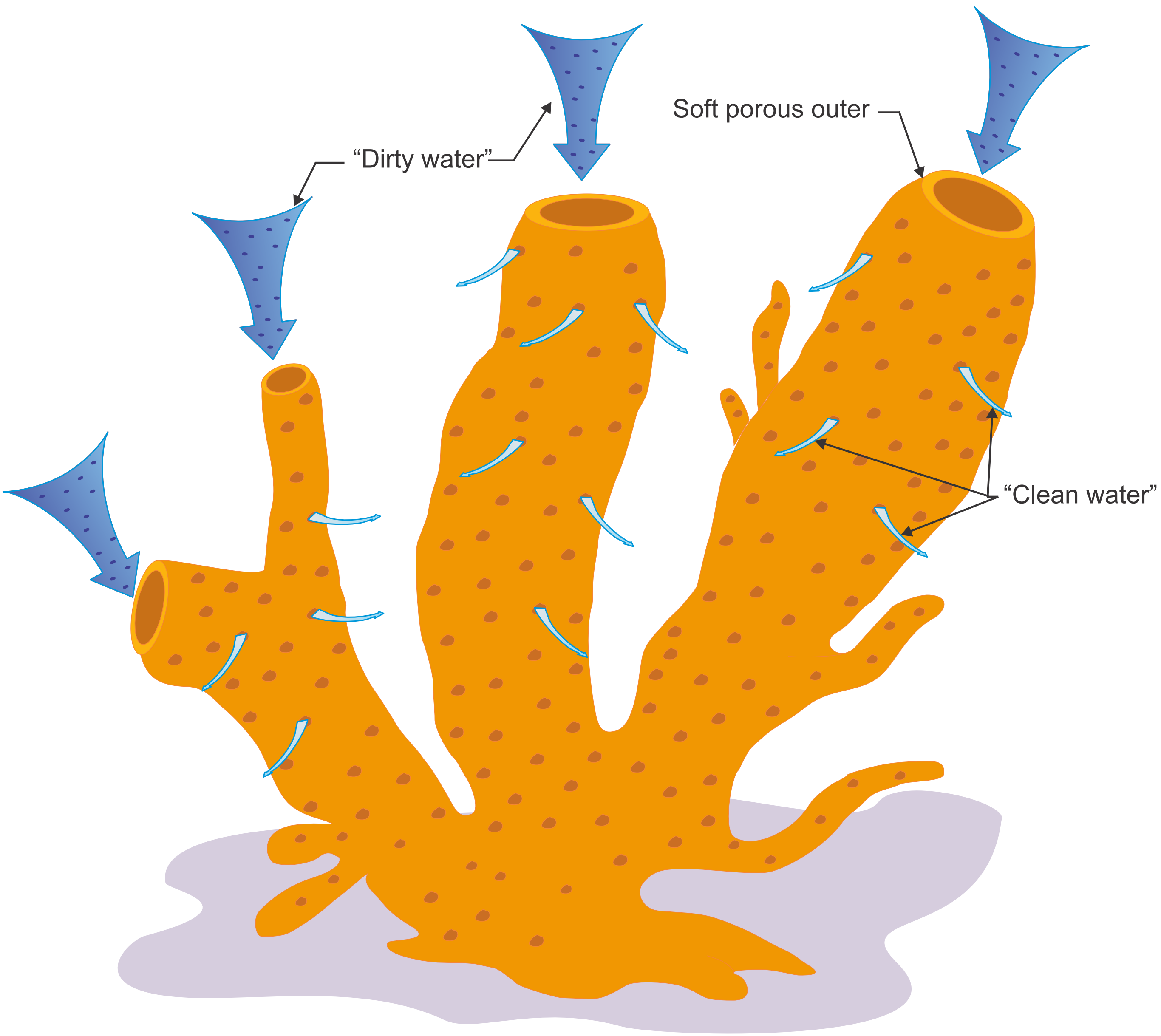
DEEP SEA SPONGES



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Human Liver

Removal of toxins and pathogens in a multi-functional (bio) chemical reactor

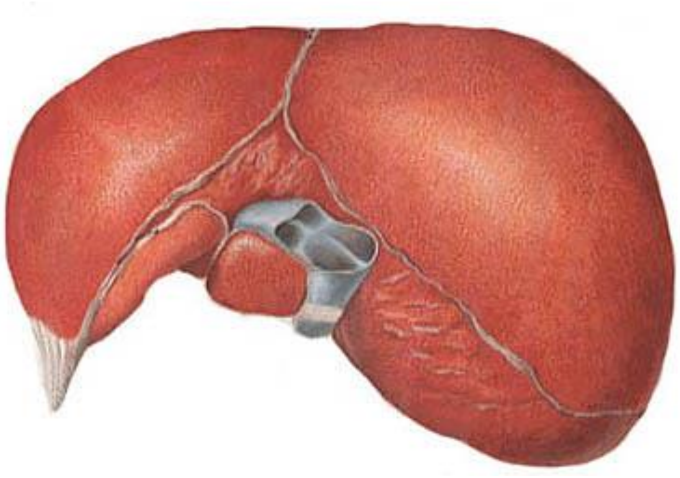


Figure 1: Image of a liver

Biomimicry Innovation:

Waste-streams from mixed industrial and domestic origin can contain organic and inorganic nutrients and toxins as well as pathogens. Effective remediation of variable waste streams is achieved in one integrated system, by utilizing physical and biological processes, balanced with life-friendly chemical processes.

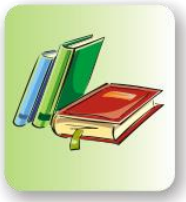
Design principles

Possible applications

Biological Foundation

Context

Case studies



References

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Human Liver

Design Principles

Process: When the cells (units) come into contact with bacteria, the receptors on their surface will bind to the pathogen (the pathogen is identified based on the roughness of the unwanted material, or previous identification by the scanning system). This binding will lead to the engulfing of the bacteria by the cell (unit). The sides of the membrane then join together so that the engulfed material is localized inside a vesicle within the cell. The unit will then oxidize the ingested pathogen using chemical oxidants.

Within each cell (unit), conditions are created to maintain effluent standards within set parameters, even when the wastewater differs in composition. To achieve this goal, certain functions are prioritized over others, so that the biological milieu of the system is maintained within optimal parameters.

Chemistry: Powerful oxidizing agents, including superoxide, hydrogen peroxide, hypochlorite and hydroxyl ions are released into specific treatment areas, to oxidize bacteria and to remove drugs and toxins.

Structure: The outer membranes of cells (units) can change their shape to engulf unwanted material.

Back

Human Liver

Possible Applications

The biochemistry can be applied as green chemistry to bio convert toxins into less toxic molecules and produce oxidizing agents capable of killing pathogens. If the source material is inconsistent, a hierarchal homeostatic-type system can be used to maintain the most important parameters within a specified range.

Back

Human Liver

Biological Foundation

Biological Strategy

The human liver is a vital, multi-functional organ that stores and filters blood, and is the major metabolic and secretory site of the body (Guyton & Hall, 1996). About 29% of the resting cardiac blood output flows through the liver each minute. This blood contains microorganisms from the gastrointestinal tract. Specialized phagocytic cells (Kupffer cells) recognize, engulf, and destroy dead tissues and foreign bodies entering the liver in the blood (phagocytosis, Figure 1). The Kupffer cells thus protect the body from pathogenic invasion (Guyton & Hall, 1996).

Biological Mechanism

Pathogen removal by phagocytosis:

Phagocytes are the cells that protect the body by ingesting (phagocytosing) harmful foreign particles, bacteria, and dead or dying cells. Their name comes from the Greek phagein, "to eat" or "devour", and "-cyte", the suffix in biology denoting "cell".

Phagocytes like Kupffer Cells can distinguish between cells and materials which need to be destroyed, and healthy tissue. Sometimes it is because of the roughness of unwanted material, and sometimes because the material has been ‘tagged’ for phagocytosis by the immune system. The cell membrane changes shape to engulf the unwanted material. The sides of the membrane then join together so that the engulfed material is localized inside a vesicle inside the cell called a phagosome. In Kupffer Cells, powerful oxidizing agents, including superoxide, hydrogen peroxide, hypochlorite and hydroxyl ions are produced by the phagosome membrane and specialized organelles. These chemicals are released into the phagosome where they are lethal to most bacteria.

Back

Human Liver

Detoxification: In the liver cells, a large, chemically reactant pool exists, that processes and synthesizes multiple substances, including removal and excretion of drugs and toxins (Guyton & Hall, 1996). An example is the conversion of toxic ammonia to urea; ammonia is formed from the degradation of amino acids in tissues where it is converted to non-toxic, electrically neutral glutamine, for transport to the liver in the bloodstream. In the liver, glutamine is hydrolyzed back to glutamate and ammonia and urea are formed from the ammonia. Urea is released into the bloodstream and excreted by the kidneys (Guyton & Hall, 1996).

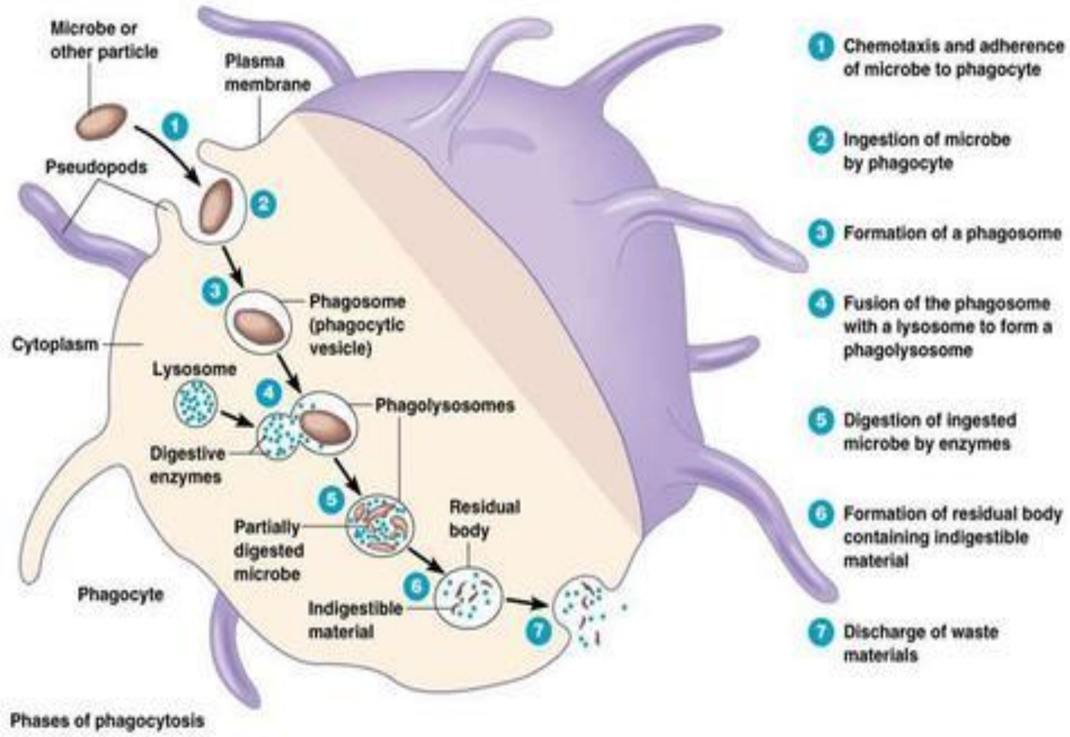

Figure 2: Phases of phagocytis – fundamentals of physiology (http://fundamentalsofphysiology.wikispaces.com/Cells+Interaction+with+Environment)

Back

Human Liver

Context/Working Conditions

The human liver operates best under homeostatic conditions (regulated, stable fluid) that provide optimal conditions for the metabolic reactions reliant on enzyme systems (Guyton & Hall, 1996). The driver of homeostasis is the homeostatic control system of the body, which is “a collection of interconnected components that keeps a physical or chemical parameter of internal environment relatively constant within a predetermined range of variables” (Vander, Sherman, & Luciano, 2001). For example, under most conditions, the internal body temperature is kept at around 37°C using complicated feed-back loops and reflexes, irrespective of external conditions (Vander, Luciano, & Sherman, 2001). It is however not always possible to maintain all parameters within specific optima, so homeostasis is hierarchal i.e. the most important parameters may be maintained by markedly altering other less-important parameters (Vander, Sherman, & Luciano, 2001).

Back

Human Liver

Existing Biomimicry: Case Study

The liver has not yet been mimicked for these applications at the time of compilation of this document.

Back

Human Liver

References

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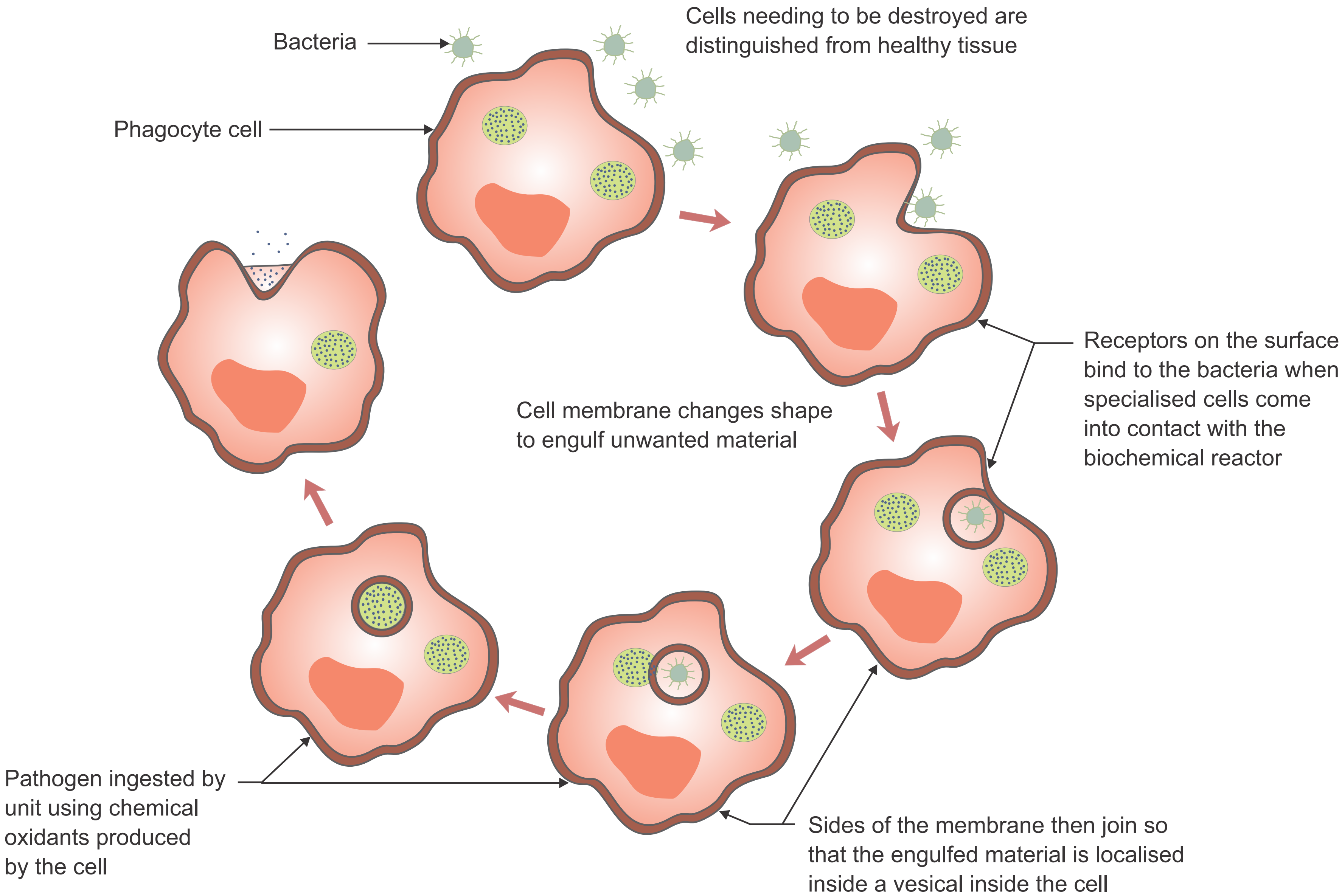
LIVER

(Pathogen removal by phagocytosis)



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Oxidising and Reducing Bacteria

Removal of toxins by enhancing desirable redox reactions

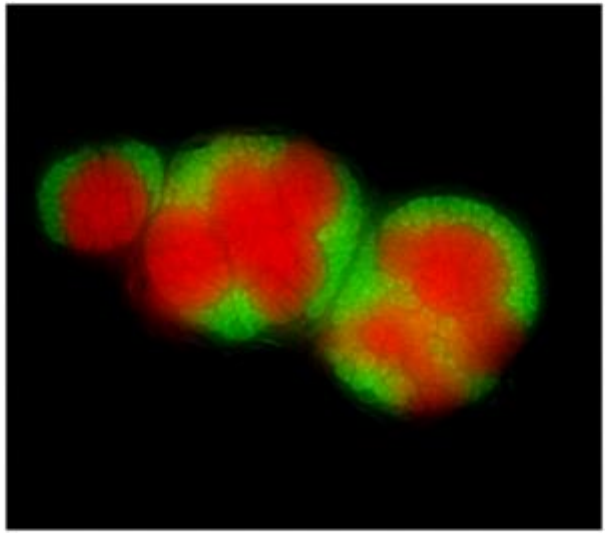

Figure 1: Anaerobic methane oxidising Archea with sulphate reducing bacteria (Wendeberg, 2013)

Biomimicry Innovation:

Microorganisms can be utilized to deliberately change the oxidation status of chemicals to detoxify or neutralize wastewaters. Microorganisms derive electrons for metabolic reactions from organic molecules (organotrophic organisms), or inorganic molecules (lithotrophic organisms). The source of energy for these reactions may be light (phototrophic organisms), inorganic molecules (chemolithotrophic organisms), or organic molecules (chemoorganotrophic/heterotrophic organisms) (Atlas, 1997). Chemolithotrophic and chemoorganotrophic reactions can have a profound effect on the geochemistry of the environment (Morrison & Aplin, 2009). The toxic effects of many metal(loids) and inorganic compounds is reliant on the oxidation status of the particular chemical. Bioutilisation of this organism could be expanded to biomimicry, if included in larger biomimetic systems such as eco-machines.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

Back

Oxidising and Reducing Bacteria

Design Principles

Process/Chemistry: The correct environmental conditions (nutrients, redox) must be present or created in an aquatic environment to sustain the growth of desirable microorganisms. The redox conditions can be manipulated by the addition or exclusion of oxygen, or other terminal electron acceptors. Under the correct conditions, oxidation and reduction can convert metal(loid)s from toxic to non-toxic species (e.g. chromium(VI) to chromium(III)).

It could be considered a biomimetic approach if the desirable conditions are established to promote growth of specific micro-organisms. Just simply adding them to a system would be bioutilisation.

Back

Oxidising and Reducing Bacteria

Possible Applications

This type of “technology’ could be applied for detoxification and/or decontamination of toxins from domestic, industrial, and agri-industrial wastewaters. Oxidation and precipitation of heavy metals for removal from wastewater. Biotransformation of organic pollutants coupled with metal/metalloid oxidation-reduction reactions. Neutralization of acid mine drainage. These are mostly biotechnology or bioutilisation applications. If included in a larger eco-machine type of biomimicry system, then it could potentially be considered biomimicry. In any case, the value of these organisms is worth considering.

Back

Oxidising and Reducing Bacteria

Biological Foundation

Biological Strategy

In natural environment, the major elemental biogeochemical cycles that occur are the sulphur cycle, the nitrogen cycle and the carbon cycle (Atlas, 1997). The redox status of the particular environment and the microbial interactions are intrinsically involved in these cycles.

Biological Mechanism

Sulphate-reducing bacteria are heterotrophic bacteria that utilize sulphate as an electron acceptor, thereby reducing sulphate to sulphide (Morrison & Aplin, 2009). During this reaction, carbonate is formed as a co-product, enabling remediation (neutralization) of highly acidic sulphur-rich water such as acid mine drainage (Morrison & Aplin, 2009).

Chromium reducing bacteria are heterotrophs that reduce soluble chromium (VI), a potent mutagen and carcinogen, to chromium (III). The reduced form has a high affinity for organics and precipitates as amorphous hydroxides allowing remediation of wastewater high in chromium (VI). This includes effluent from tanneries and chromite mines (Samuel, Paul, Pulimi, Nirmala, Chandrasekran, & Mukherjee, 2012).

Geobacter metallireducens is a bacterium that has been shown to couple the biodegradation of an organic pollutant, toluene, to the reduction of Fe (III) and As (V) to Fe (II) and As (III) (Lee, Bosch, & Meckenstock, 2012).

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Oxidising and Reducing Bacteria

Context/Working Conditions

Temperature ranges at which microbial reproduction is fastest vary widely: psychrophiles grow best at low temperatures (<20°C), mesophiles grow best at moderate temperatures (20°C-40°C) and thermophiles grow best at high temperatures (>40°C). For example *Vibrio marinus* grows between -15°C and 25°C, while *Pyrococcus occultum* grows between 55°C and 105°C (Atlas, 1997). To limit energy requirements for heating, industrial biocatalysts that are effective at room temperature are often the microbes of choice for synthetic reactions.

Some microorganisms need oxygen to grow (obligate aerobes, aerobic metabolism), some die in the presence of oxygen (obligate anaerobes, fermentative metabolism), and others can grow with or without oxygen and are termed "facultative" (Atlas, 1997). Some microorganisms, such as marine bacteria, require NaCl for growth and are known as halophiles. Extreme halophiles require NaCl concentrations as high as 25% in order to grow (Atlas, 1997). Some acidophilic fungi can grow at a pH of 0, while pH 11 is the upper limit for alkaliphilic microbes (Atlas, 1997).

For efficient, cost-effective, sustainable bioremediation, a balance must be struck between the functional capabilities and the ability to provide optimal nutritional growth requirements for microbial consortia or pure cultures of microorganisms.

Back

Oxidising and Reducing Bacteria

Existing Biomimicry: Case Studies

These are bioutilisation case studies but may inspire future biomimicry applications:

Bioremediation utilizes the biogeochemical cycles present in nature and has been used extensively to detoxify and decontaminate wastewater for decades. There are many literature reports where conventional suspended and attached growth wastewater treatment options, especially activated sludge systems, have been used to detoxify metal and metalloid-laden wastewaters (Stasinakis & Thomaidis, 2010). Passive treatment systems, including successive alkalinity producing systems, have also been described for the treatment of acid mine drainage (Riefler, Krohn, Stuart, & Socotch, 2008).

Back

Oxidising and Reducing Bacteria

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Surface Protection

Surface protection is conventionally achieved through coatings, materials selection and chemical dosing.

Biomimicry research has revealed a number of innovations for surface protection. The innovations are inspired by natural organisms and systems that are specialists in surface protection from bacterial colony build-up. These innovations are based on millions of years of natural selection of organisms which have evolved highly efficient and effective sustainable solutions in each case. The following subsections summarise the key innovations from natural “champion” or specialists in each case. They are classified as champions in this context based on the fact that of the many organisms that perform this particular function, these organisms are the specialists identified in each case.

Surface protection through combined hydrophilic patches and hydrophobic layers (Salvina)

Prevention of biofilm formation through release of chemical furanones that disrupt bacterial communication (Red Algae)

Prevention of biofilm formation through diamond-shaped microscopic surface ridges (Shark Skin)

Back

Salvina

Surface protection to prevent corrosion and abrasion through combined hydrophilic patches and hydrophobic layers

Figure 1 *Salvina molesta*

Biomimicry Innovation:

Conventionally, corrosion protection of piping surfaces is achieved through chemical means or the selection of corrosion resistant materials. Surfaces less prone to corrosion are often more expensive. This innovation is enabled through a surface layer that can be applied to e.g. the walls of piping to maintain a distinct separation between air and water layers, even under turbulent conditions. The innovation is inspired by the combined hydrophilic and hydrophobic layers on salvina plants that include tiny egg-beater shaped hairs, covered with microscopic wax crystals.

Salvina

Design Principles

Structure: A fine layer of microscopic egg beater-shaped fibres (see Figure 2 for shape) coated in microscopic wax crystals. The cells on the uppermost layer of the fibres, approximately 2% of the total are not coated with the wax. These hydrophilic patches act as stabilisers at the air-water interface, especially under turbulent conditions.

The combination of their shape and orientation, together with the hydrophilic patches and hydrophobic layer results in the ability to maintain a distinct separation between the air layer and water, even under turbulent conditions. The following factors contribute to the effect:

- The arrangement of the multicellular fibers
- The variations in size and orientation of the fibers
- The convex shape of the fibers
- The wax crystals which have two different sizes and shapes
- The last 2% of the egg beater shaped fibers do not have the wax layer

Back

Salvina

Possible Applications

The surface can be applied to piping for corrosion protection, by preventing contact between fluid and pipe wall. Reduced drag effects would also be beneficial in piping, as this will in turn reduce energy required for pumping. Aquatic vehicles will also benefit from reduced drag effects.

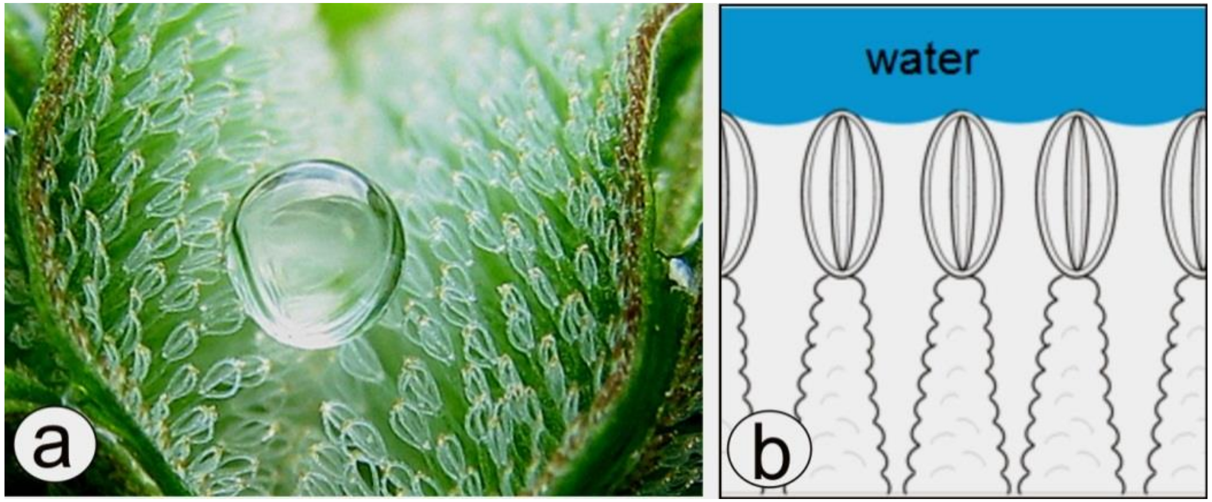

Figure 2: a) illustrates the hydrophobic effect resulting from the egg beater shaped hairs,
b) a schematic showing egg beater shaped hairs. (Koch, 2010).

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Salvina

Biological Foundation

Biological Strategy

The Floating Water Fern, *Salvina molesta*, which is considered a serious pest in most tropical countries, is able to keep its leaves dry by means of maintaining a thin layer of air on the leaf surface.

Biological Mechanism

The surface of the *S. molesta* leaf is coated with egg beater-shaped hairs, and is covered with nanoscopic wax crystals. The cells on the uppermost layer of the hairs, approximately 2% of the total, however, are not coated with the wax. These hydrophilic patches act as a stabiliser at the air-water interface, especially under turbulent conditions. The combination of super hydrophobic surfaces with hydrophilic patches is referred to as the “Salvina Effect” (Barthlott, et al., 2010). It is thought that the Salvina Effect is caused by to the following:

- The arrangement of the multicellular hairs
- The variations in size and orientation of the hairs
- The convex epidermis on the cells of the hairs
- The wax crystals which have two different sizes and shapes
- Terminal cells of the egg beater shaped hairs do not have the wax layer

Back

Salvina

Context/Working Conditions

The hairs and wax crystals are on a nano-scale. The properties of the wax crystals need to be understood, as these may be soluble in certain liquids.

Back

Salvina

Existing Biomimicry: Case Study

The surface is currently being investigated by the Ohio State University scientists, as a material for use in the manufacture of boats and other aquatic vehicles.

Back

Salvina

References

Barthlott, W., Schimmel, T., Wiersch, S., Koch, K., Brede, M., Barczewski, M., et al. (2010). The Salvina Paradox: Superhydrophobic surfaces with hydrophylic pins for air retention under water. *Andvanced Materials*, 2325 - 2328.

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Red Algae

Prevention of biofilm formation through release of chemical furanones that disrupt bacterial communication.

Biomimicry Innovation:

Conventionally, surface protection from bacterial biofilms is achieved through chemical means (antibiotics, sterilisers, etc.). These chemicals can pollute water systems, and have negative health effects on humans and the aquatic environment. If used prolifically, bacteria can become resistant to the action of these chemicals. This innovation enables an eco-friendly bacterial prevention, without the creation of bacterial resistance.

Figure 1: Red Algae (Ask Nature, 2012)

Design principles

Possible applications

Biological Foundation

Context

Case studies

References

Back

Red Algae

Design Principles

Process: The release of a furanone chemical inhibits the communication between bacteria, and hence inhibits the formation of biofilm on surfaces by preventing the building of matrix-like structures between bacteria.

Back

Red Algae

Possible Applications

The addition of the halogenated furanones can be useful in the prevention of biofilm formation on piping or aquatic vehicles. For example, furanones could be added to paints to prevent the formation of mildew on walls in humid environments.

Back

Red Algae

Biological Foundation

Biological Strategy

The red algae, *Delisea pulchra*, effectively prevents bacteria from forming colonies, through the release of halogenated furanones, thus reducing the risk of infections and preventing the formation of biofilms.

Biological Mechanism

Bacteria adhere to surfaces and organise themselves in matrix-like structures to form biofilms. Studies indicate that the biofilm patterns increase resistance to antibacterial agents (Rasmussen, et al., 2000). The process whereby the biofilm structure is formed is referred to as swarming. Swarming requires both environmental as well as intercellular signals. Red Algae release halogenated furanones which affect bacterial characteristics, such as swarming and bioluminescence (Maximelien, et al., 1998). Studies indicate that furanones are bacteriostatic. *D. pulchra* effectively avoids a broad spectrum of bacterial infections, without creating bacterial resistance to its defensive chemistry. Molecules known as furanones, produced by the seaweed, bind readily to the specific protein-covered bacterial receptor sites that receive the bacterial signalling molecules (N-acyl homoserine lactone) which normally induce surface colonization. This method of blocking bacterial communication effectively prevents bacteria from forming groups and becoming virulent, but does not physically kill them. Over 80% of bacterial infections in humans are estimated to involve the formation of bacterial colonies or biofilms, while numerous other potential applications for this completely novel anti-bacterial technology exist.

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Red Algae

Context/Working Conditions

Red algae can be found in a variety of habitats and on a variety of hosts or on rock substrates. A liquid media is required in order for the furanones to remain mobile and avoid clumping.

Back

Red Algae

Existing Biomimicry: Case Study

A company called Biosignal Biofilm Control Technology (Biosignal Ltd.) has been created, using the principle displayed by red algae to reduce biofilm formation. BioSignal Ltd. is now testing and/or already applying synthetic furanones based on those produced by *D. pulchra* in a variety of applications, including medical treatment and devices, pipelines, heating, ventilating, and air conditioning systems, cleaning products, and water treatment.

Back

Red Algae

References

Ask Nature. (2012, May). *Biofilm-inhibiting chemical protects surfaces: red alga*. Retrieved November 2012, from Ask Nature: http://www.asknature.org/strategy/b5fc580c4821fb11d9264adcfec126aa

Maximelien, R., de Nys, R., Holmstrom, C., Gram, L., Givskov, M., Crass, K., et al. (1998). Chemical mediation of bacterial surface colonisation by secondary metabolites from red alga Delisea pulchra. *Aquatic microbial ecology*, 233 - 246.

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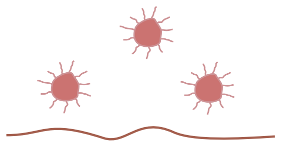
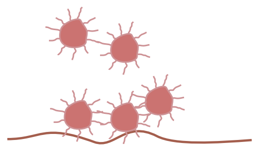
RED ALGAE

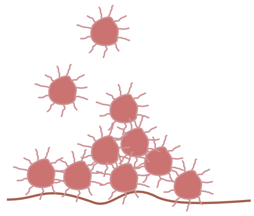
Surface without red algae



- Bacteria communicating using signals

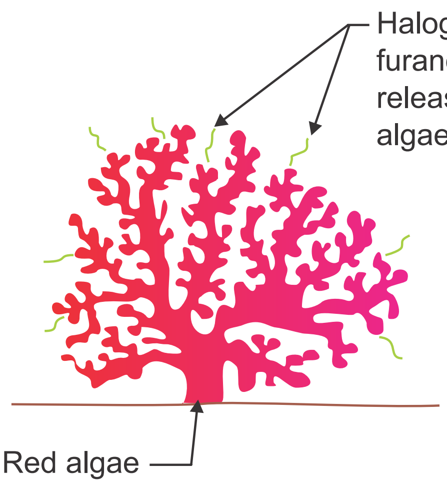


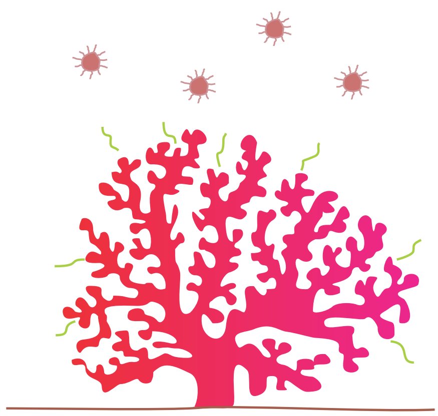
- Adherence of bacteria to surface



Swarming:
- Signals used by bacteria to organise into matrix-like structure forming biofilms

Surface with red algae





- Communication between bacteria inhibited by furanones
  Bacteria blocked from releasing signals
- Formation of bacterial groups (biofilms) prevented

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Shark Skin

Prevention of biofilm formation through diamond-shaped microscopic surface ridges

Figure 1: Great White Shark (Bondy, 2007)

Biomimicry Innovation:

Conventionally, surface protection from biofilms is achieved through chemical means (antibiotics, sterilisers, *inter alia*). These chemicals can pollute water systems, and have negative health effects on humans and the aquatic environment, and lead to bacterial resistance over time. This innovation is enabled through a surface layer that can be applied to e.g. piping walls, for example where the surface structure prevents bacteria from establishing a biofilm without the need for chemical addition. This innovation is inspired by the denticles on shark skin. The same surface has reduced drag effects that could have additional energy benefits for moving water over surfaces (e.g. through piping systems).

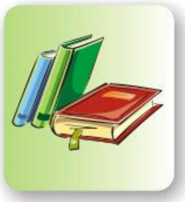
Design principles

Possible applications

Biological Foundation

Context

Case studies



References

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Shark Skin

Design Principles

Structure: The raised and lowered surfaces on the diamond-shape microscopic surface ridges prevent bacteria from establishing matrix-like formations. These formations prevent bacteria from adhering to the surface, thus reducing biofilm growth.

Materials: The ridges could be made of apatite, and surrounded by collagen. The hard centres, surrounded by a flexible material, make them extremely durable. The helical arrangement of the cells enables them to bend easily.

Back

Shark Skin

Possible Applications

Prevention of biofilm formation on piping, boats, ships, *inter alia*. by coating the outer surface with this formulation. In addition to anti-fouling, the coating will also reduce drag, thereby providing a dual benefit. The technology has the potential to reducing biofouling in nanofiltration processes. The structure could also be mimicked for the manufacture of strong and flexible hosing.

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Shark Skin

Biological Foundation

Biological Strategy

Elasmobranchs are a subclass of cartilaginous fish, which includes sharks and rays. They have a natural ability to resist biofouling through non-toxic, and physical mechanisms.

Biological Mechanism

On a microscopic level, the surface of shark skin is not smooth. Instead, there are microscopic placoid scales that have been termed dermal denticles (Sullivan & Regan, 2011). The denticles have both a drag reducing effect as well as an antifouling effect.

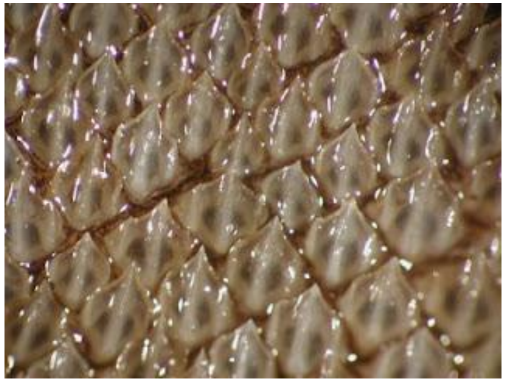

Figure 2: Scales of a Great White Shark (Molly, 2009).

The denticles are elongated with a central riblet (raised surface) and riblets on either side converging to a point. Whilst the number of riblets varies between denticles, they are generally found in odd numbers. The scales are made of apatite and surrounded by collagen. The hard centres, surrounded by a flexible material make them extremely durable. The helical arrangement of the cells enables the sharks and rays to bend and twist easily, as they swim (Molly, 2009).

In the initial stages of biofilm formation, bacteria colonize independently or in small groups. The micro pattern of shark skin disrupts several critical microbial colonizing processes that are necessary for the formation of biofilm. For example, on rough surfaces such as shark skin, the energy required for attachment of bacteria and/or algae may be too high and the organisms either localize on a more suitable surface or die. It has been shown that the roughness (width to height ratio) of the denticles corresponds to the mathematical model for the prevention of microbial settling (Sharklet Technologies, 2012).

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Shark Skin

Context/Working Conditions

The principle has been mimicked successfully in both water and air.

Back

Shark Skin

Existing Biomimicry: Case Study

Sharklet Technologies™ have successfully mimicked the structure of the shark skin, and developed a material which inhibits bacterial growth. (Sharklet Technologies, 2012).

The coating has been used on Airbus aeroplanes, in hospitals, on workstation mats, skins for benches, counters and locker rooms, and applied in numerous services that are at high risk from biofilm formation.

Refer to (Sharklet Technologies, 2012) for additional information.

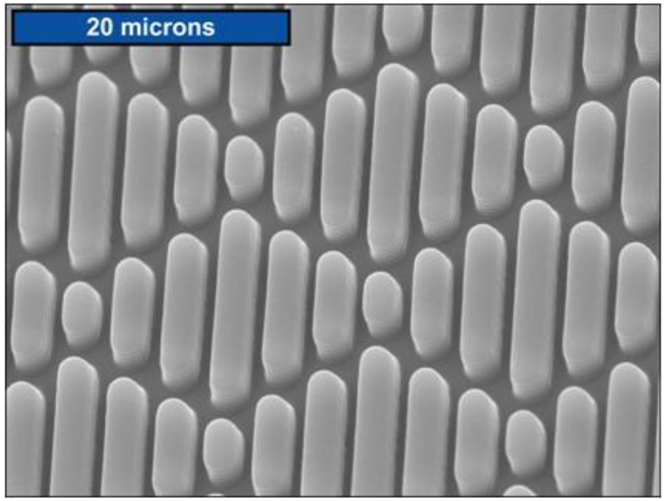

Figure 3: Sharklet membrane (Sharklet Technologies, 2012)

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Shark skin

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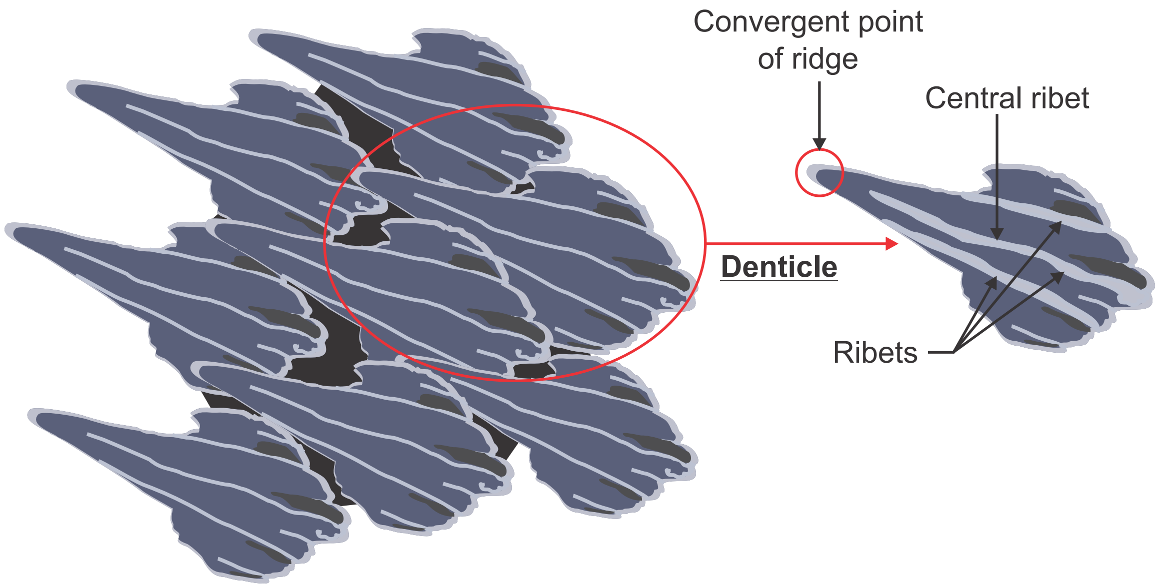
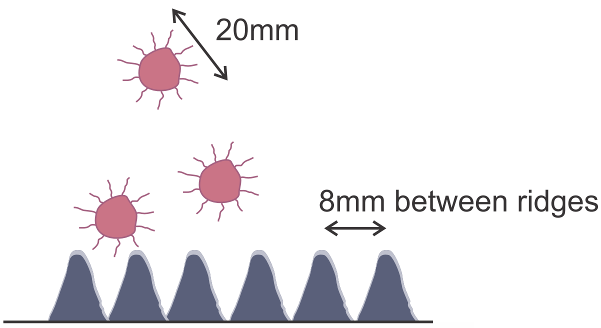
SHARK SKIN



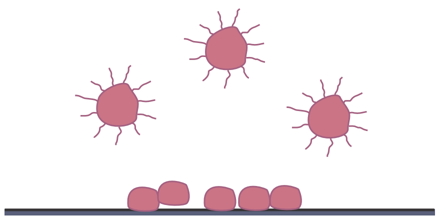
Side View of Denticle

Shark skin:



Biofilm Prevention

Flat Surface:



- Attachment of bacteria to surface

- Ridges disrupt bacterial colonisation
- Biofilms not formed as no initial colonisation can occur

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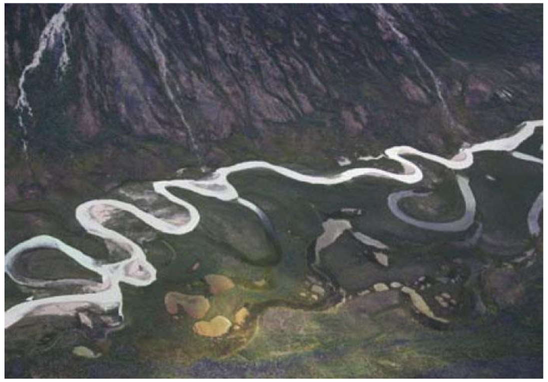
Flow Management

Numerous techniques are used to manage and dissipate high flows conventionally. This includes:

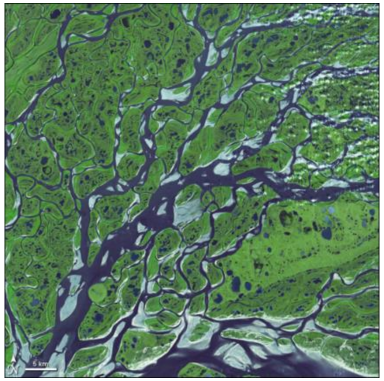
- Inserting dams;
- Weirs/Baffles;
- Cascades;
- Distributed inlet pipes;
- Porous berms.

In natural systems, water follows the path of least resistance.

Reducing flow and increasing surface area for micro-organisms treating water to adhere to.
(Gravel Beds)



Managing flow and dissipating peak flows through meandering.
(Meanders)



Dissipating flow and managing sediment by means of splitting flow into branches.
(Deltas)

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Deltas

Dissipating flow and managing sedimentation by means of splitting into branching.

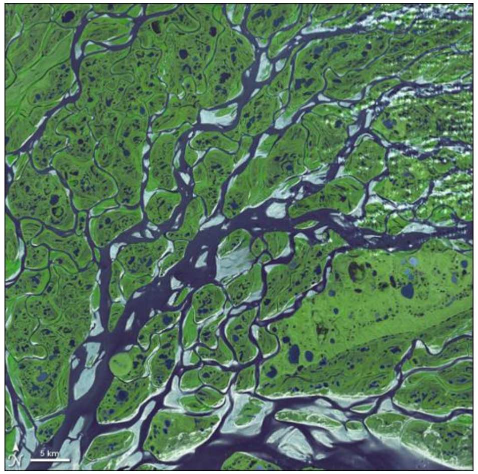

Figure 1: River Delta

Biomimicry Innovation:

This innovation is inspired by the flow patterns of river deltas. This principle could be applied as a flow dissipation mechanism, to minimize erosion as well as the impact on a receiving body of water. It could also be an innovation for removal of suspended solids from a carrier stream. It could also improve the design of open ended pipe tailings deposition. Delta formation could be applied to induce stream channel braiding, and to prevent single preferential flow path formation, thus improving reaction time, velocity, energy, preventing 'cutting' down in the channel, or eroding the channel base.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

Back

Deltas

Design Principles

Flow Mechanism: A reduction in flow by hindering/obstructing a straight single flow path, thus splitting the flow into smaller meandering flows, and inducing stream channel braiding.

Sedimentation Mechanism: Large liquid flow meets a stationary body of flow. As flow velocity reduces, its ability to carry particles reduces and the heavier particles settle out first. Finer particles are carried further, resulting in a grading of particle sedimentation. As the sediment builds up, it will become the primary reason for the dissipation of the fluid energy, and cause the flow to split (channel braiding). This further enhances the function of sedimentation build-up and as a result the system will keep increasing in size.

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Deltas

Possible Applications

This principle can be applied as a flow dissipation mechanism to minimise the impact on the receiving body of water (not creating a plume profile or embankment erosion). In certain areas, erosion can be sufficiently reduced as the flow velocity is reduced.

Such a system may also be employed as a distribution system that self regulates over an area. The removal of suspended solids from a carrier stream could also be an application.

The above can be induced by constructing ponds and gravel beds in succession, such that velocity is reduced, and deltas are formed. With the layering and segregation of the deltas into the ponds, natural systems are mimicked, and the deltas can be populated with wetland vegetation, and used to braid the channels.

Open ended pipe tailings deposition could be studied and compared to natural deltas. Small scale deltas from natural examples could be mimicked and manipulated, and responses documented and applied.

Delta formation could be applied to induce stream channel braiding, and to prevent single preferential flow path formation. Preferential flow paths cause lower reaction times, higher velocities and energy, and potentially ‘cutting’ down in the channel or eroding of the channel base.

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Deltas

Biological Foundation

Biological Strategy

A delta is a landform that is shaped at the mouth of a river over time. The formation happens as a result of sedimentation build-up, forcing the river to divide and dissipate the flow energy.

Biological Mechanism

Deltas form as a result of a river losing some of its capacity to keep heavier suspended solids in suspension, resulting in these particles settling out. This dissipation of energy is initially due to the river meeting a large “stationary” body of water, such as a lake or ocean. The immediate contact with such a body of water causes the river to slow down, thus facilitating the sedimentation and delta formation. As stream velocity reduces, its ability to carry sediment (eroded) reduces, and the heavier particles settle out first. Finer particles are carried (eroded) further and this results in a grading of sediment in the delta.

Over time, as sediment accumulates, it will become the primary reason for the dissipation of the river’s energy, and cause the flow to split (channel braiding and island formation). This further enhances the function of sedimentation build-up and as a result the delta system will keep increasing in size (Discovery, 2011).

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Deltas

Context/Working Conditions

These systems occur under all conditions across the planet. The natural system will however only apply to systems with a large sediment or particulate load of heavier particles, that settle out due to gravitational force. Colloidal problems will not apply.

To apply these principals the following is needed:

- Liquid
- Seed structures to enable the initial formation of the delta
- Suspended material to allow for growth of the delta.

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Deltas

Existing Biomimicry: Case Study

A large number of case studies have been conducted on delta systems, but none have been for the direct implementation as a biomimicry tool.

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Deltas

References

Discovery. (2011). *Ecosystems*. Retrieved 08 22, 2012, from Curiosity.com: http://curiosity.discovery.com/question/how-do-river-deltas-form

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Gravel Beds

Reducing flow and increasing surface area for micro-organisms treating water to adhere to.

Figure 1: White River gravel bed (M-J Milloy, 2007)

Biomimicry Innovation:

Gravel beds occur naturally in all aquatic systems. These beds have multiple benefits for the aquatic system. The water that flows through it slows down around the particles thus dissipating the energy of the flow and increasing retention times. The probability of preferential flow paths forming is often reduced by the coarse particle size. Gravel beds also form a suitable media for micro-organisms to adhere to, resulting in biological water purification, as water slowly trickles through the bed. Many existing and future applications could be improved with continued study of these natural systems.


Design principles


Possible applications


Biological Foundation


Context


Case studies


References

Back

Gravel Beds

Design Principles

A gravel bed designed so that liquid flowing through it is forced to slow down and take longer pathways to reach its end destination over the same length of bed. This allows for longer contact time between the liquid and the bed media.

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Gravel Beds

Possible Applications

The use of gravel beds to for the following applications are common and widely implemented:

- Prevention of erosion of the bottom of waterways;
- Prevention of preferential flow path formation;
- Allowance of bacterial growth for nutrient removal;
- Attenuation of flow in a system;
- Distribution of water in an up-flow system (where the water comes in contact with the gravel bed from the bottom);
- Use in oxidation cascade systems to introduce oxygen into the water;
- Coarse filter systems.

Gravel beds also allow for the establishment of certain types of vegetation, which may further influence flow patterns in a system. Gravel beds occur naturally in all aquatic systems depending on the system's history.

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Gravel Beds

Biological Foundation

Biological Strategy

Gravel beds are a continuous layer of mixed rock and debris fragments, coarser than sand. Typically diameters of these fragments will range from 2mm – 4mm. Gravel beds form due to erosion and deposition that takes place within the water system over time. These beds will typically contain a mixture of rock fragments and some sand of varying sizes (Lisle & Hilton, 1999), and reduce the flow of water.

Biological Mechanism

The gravel beds force any water that flows through it to slow down, by causing it to flow around the particles, thus eliminating the possibility for the water to flow in a straight line, and subsequently causing a loss of energy and increase in retention time. The probability of preferential flow paths forming is often reduced by coarse particle sizes. Gravel beds also form a suitable media for micro-organisms to adhere to, resulting in biological water purification as water slowly trickles through the bed.

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Gravel Beds

Context/Working Conditions

Gravel beds work in various aquatic systems and fulfil a number of roles. These systems form parts of rivers, wetlands, lakes and pool systems. They are likely to be found where there is a regular change in flows within a system, as this would allow for the erosion and deposition action to take place - actions that are essential for the formation of these systems.

Implementation of gravel beds for any of the above applications is possible with a minimal amount of effort, or regard for climatic parameters. These systems can be made by layering any available coarse rock material in the required setup. The applications of these principles are not bound to any specific climatic conditions.

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Gravel Beds

Existing Biomimicry: Case Study

Gravel beds are mimicked in constructed wetlands and packed bed reactors. These systems have been in existence long before the biomimicry process has been formalised.

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Gravel Beds

References

Lisle, T. E., & Hilton, S. (1999). Fine bed material in pools of natural gravel bed channels. *WATER RESOURCES RESEARCH, VOL. 35, NO. 4*, 1291–1304, .

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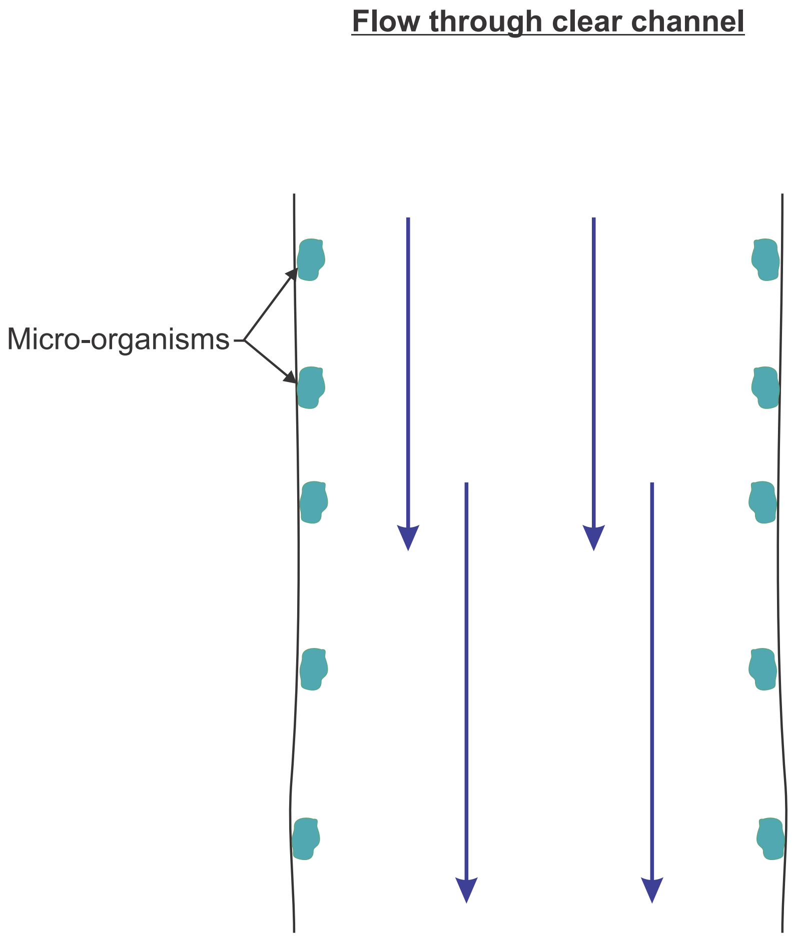
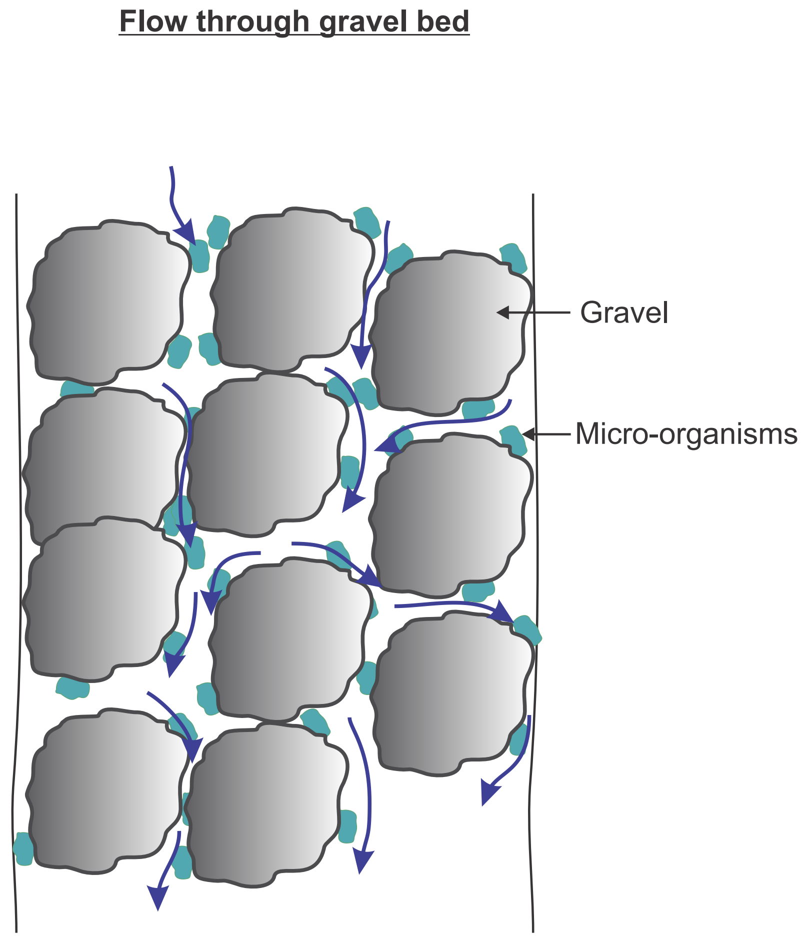
GRAVEL BED





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Meanders

Managing flow and dissipating peak flows through meandering.

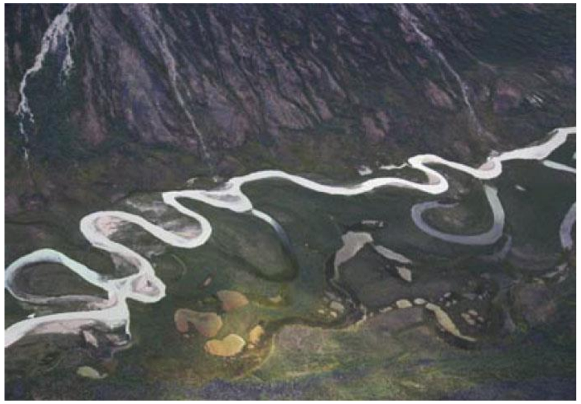


Figure 1: Meandering stream

Biomimicry Innovation:

One can reduce the velocity at which water flows and manage sediment deposition by mimicking the way natural systems develop meandering pathways. Meandering enables reduction in flow velocity of a liquid along a path and can minimise the impact of flooding or dissipate the energy flow of the fluid. This can also be a mechanism to manage sediment through mimicking the vortical flow pathways that enable sediment deposition separate from or in combination with flow management. Meandering flows also increases contact time for reactions.

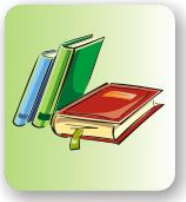

Design principles


Possible applications


Biological Foundation


Context


Case studies


References

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Meanders

Design Principles

Mechanism: The reduction in flow velocity of a liquid along a path is created by the balance between erosion and deposition of sediment, resulting in the formation of bends. This may be designed into an engineered system – either by creating vortical fluid flow pathways for balanced erosion and deposition of sediment, or by enabling meandering fluid flows to dissipate the energy of the fluid, and increase contact times if any reactions require it.

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Meanders

Possible Applications

A meandering flow design can adequately address the issue for the dissipation of energy in a water system, by slowing the water flow down sufficiently. The use of meandering designs will also increase contact time within a system, thus allowing for reactions and interactions between the water and the intended reagents or entities to be more efficient. It is possible to retrofit existing water canals or similar straight flow paths to induce a meandering flow. This has been done in some canals in Europe to help manage flooding and sediment accumulation, by adding subsurface rock/cement layers at angles in the canal.

Numerous river diversions are constructed on a regular basis, and water courses and wetlands are often altered. Costs generally are reduced by incorporating a straight line design, but energy build up could result in downstream impacts. There is a need for the offsetting of construction costs of dissipation systems against meandering to be investigated.

The system may also be applied for the removal of unwanted suspended solids in a system, as the reduced flow velocities will improve settlement.

If meandering is built into a system, it can provide for effective management of base flow, and high flow or flood conditions. During base flow, water remains in the meandering channel, allows sufficient reaction time, and deposition where required. If a flood peak is experienced, the water 'bursts the banks' of the meandering channel, and flows more directly along the broader, straighter channel. In this way, base flows can be treated, while diluted high flows can be allowed to pass through without causing significant damage or impacting on the efficiency of the process.

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Meanders

Biological Foundation

Biological Strategy

Meanders are a series of bends and curves in a water course. These are formed over time as a result of alternating erosion and deposition actions in the water course.

Biological Mechanism

In the juvenile stages of a river, stream or lotic wetland system, energy is often used for, or often leads to the widening of channels or cutting of channels deeper into the substrate. In the mature sections, energy is dissipated by previous alluvial deposition or reduction in flow is achieved as the result of flatter slopes. Energy could however still be high in larger floodplain systems. Meandering is one of the dissipating mechanisms whereby a stream will flow through a series of curved channels, rather than flow in a direct line. (Chambers, 2006)

Erosion and deposition are balanced in this way to reach a state of equilibrium.

Meandering takes on a serpentine moving method, but with the opposite purpose of reducing velocity and not for accelerating positively. There is an action-reaction mechanism whereby meanders cut off to form oxbows. An increase in energy and meandering starts again, thus giving some interdependence.

Biotic factors of ecosystems can adapt, and can affect the process.

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Meanders

Context/Working Conditions

In ideal conditions, fluvial equilibrium exists between erosional forces and depositional forces. The balance does sway over time, as not all systems are in perfect state of equilibrium all the time. Some systems, like endorheic pans, are by their nature depositional systems, though erosion could take place in their catchments. Studying both erosional and depositional systems, and applying it to a specific condition with wetland vegetation can be used to stabilise or move specific material.

No natural formation of meandering or limitations on the working conditions will be applicable in terms of balance between erosion and deposition, when mimicking the technology.

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Meanders

Existing Biomimicry: Case Study

Meanders have been studied extensively and are well documented. The following are examples of such studies.

The hydro-electric scheme near Ladysmith is an example where a depositional system was partially flooded for use as a buffer dam, to release water through tunnels (very high energy systems), to lower lying systems. The new dynamics in the system could be studied and compared to the Wakkerstroom systems and applied elsewhere.

The white paper on channel design published by the Washington Department of Fish and Wildlife (Miller, 2001) shows how to incorporate meandering into a design, and how to take sedimentation and flow energy dissipation into account.

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Meanders

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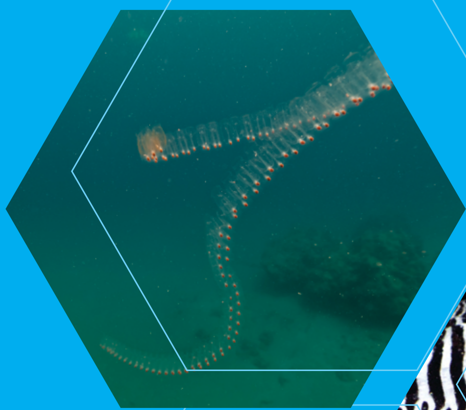

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