Membrane technology revolutionizes water treatment

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Abstract Membranes play a crucial role in living cells, plants and animals. They not only serve as barriers between the inside and outside world of cells and organs. More importantly, they are means of selective transport of materials and host for biochemical conversion. Natural membrane systems have demonstrated efficiency and reliability for millions of years and it is remarkable that most of these systems are small, efficient and highly reliable even under rapidly changing ambient conditions. Thus, it appears to be advisable for technology developers to keep a close eye on Mother Nature. By doing so it is most likely that ideas for novel technical solutions are born. Following the concept of natural systems it is hypothesized that the Millennium Development Goals can be best met when counting on small water and wastewater treatment systems. The core of such systems could be membranes in which chemical reactions are integrated allowing recovery and direct utilization of valuable substances.

Keywords Active transport; anaerobic conversion; biofilm; biomimetics; cell membrane; embedded biochemical reactions; green refinery; Millennium Development Goals; natural membrane systems

Water Science & Technology **Vol 55 No 7 pp 11–20** © IWA Publishing 2007

Introduction

When browsing through the literature of the past 15 years one gets the impression that membrane technology constitutes the most important invention man has ever made. Application of membranes for the purpose of water and wastewater treatment is certainly a respectable demonstration of human ingenuity, however, membrane processes are not at all inventions of man. An even superficial investigation of natural biological systems reveals that membranes are widely used in nature for a multitude of purposes and have been for billions of years. As a matter of fact, membrane processes play an essential role in cell metabolism as well as in the metabolism of animals and plants. It can be hypothesized that membrane systems are the main reason why small systems like a cell, the lung, the kidney or the rumen of a cow function so effectively. It may be a good idea, therefore, to study the function of membranes as they are integrated in living systems and use the information gained for further development of membrane technology.

Learning from nature is the concept of a relatively new branch of science called “biomimetics” or “bionics”. Attempts to use natural systems as a model have already led to a variety of innovative technical solutions. In this context, it should be noticed that living systems – a cell, an organ, a plant, an animal – are relatively small in size. Nevertheless, these systems are apparently highly efficient, flexible and adaptable to changing ambient conditions. Taking this into account, it is fair to assume that membrane technology derived from natural systems provides specific advantages to small systems. We could even go a step further by hypothesizing that membrane technology allows development and implementation of a new generation of small on site water supply and sanitation systems with re-use of the valuable substances, the purified wastewater for instance, as an integral part – often referred to as “Decentralized Sanitation and Re-use” (DeSa/R).

doi: 10.2166/wst.2007.121

DeSa/R sytems are considered highly important in the process of meeting the Millennium Development Goals (MDGs) because they allow rapid while stepwise installation of water infrastructure especially in newly built residential areas of the fast growing cities, where the demand of water supply and sanitation is of utmost importance for social stability. The key component in this concept is most probably membrane technology.

In the following, membrane processes as they occur in living systems are briefly described, followed by a chapter in which current applications of membrane technology are summarized. Finally, some ideas are presented on how to translate natural membrane systems into advanced membrane technology.

Membrane systems on duty in nature

It is worth noticing that membranes (Latin: membrana = cuticle) play a very important, even crucial role in natural systems. In lungs, for instance, membranes serve as an interface between a gaseous phase (air) and a liquid phase (blood). They separate both phases from each other, but – importantly – they allow transfer to and dissolution of oxygen in the blood flowing along the membrane, and transfer of carbon dioxide from the blood stream into the atmosphere. Similarly, membranes exposed to the anaerobic atmosphere in the rumen of a cow allow transfer to and dissolution of hydrolysis products (e.g. fatty acids and amino-acids) in the blood. Cell membranes are not only barriers and transfer units but provide a structure within which chemical processes are executed, electron transfer processes for instance (respiration chain), and enzymatically catalyzed binding and transport processes.

Cell membranes

Membranes are vital for all living entities. They separate the cell from the outside world, and they also separate compartments inside the cell to protect important processes and events. In addition to their separation function, membranes have diverse other functions in the different regions and organelles of a cell (Alberts *et al.*, 1994). In particular, they allow communication of the cells with the outside world by controlling selective transfer of materials into and from the cell. Some of the most important physical, chemical and physiological functions of cells occur in or on the membrane.

Membranes contain proteins and lipids. However, the proportion of each varies depending on the membrane. Myelin, for instance, insulating nerve fibers, contains only 18% protein and 76% lipid. Mitochondrial inner membranes contain 76% protein and only 24% lipid. Plasma membranes of human red blood cells and mouse liver contain nearly equal amounts of proteins (44 and 49% respectively) and lipids (43 and 52% respectively).

The lipids are arranged in the form of a lipid bilayer. Proteins are embedded in this structure. They pass through the bilayer and are called transmembrane proteins, therefore. These proteins mainly function as enzymes allowing selective transport of chemical substances including electrons. Within the cell membrane (or the inner mitochondrial membrane in eukaryotic cells) the electron transport chain is embedded by means of which the cell gains energy (Figure 1).

Membranes of the respiratory tract

The lung is an organ designed to bring blood into close contact with the air. This is to allow oxygen to be dissolved in the blood; and carbon dioxide to be discharged into the atmosphere.

Air is pumped down into the lungs through the muscular action of the chest, a combination of activity of the diaphragm and the muscles between the ribs. By the time air reaches the alveoli (Figure 2) it has become warmed and been filtered of particulate materials by hairs.

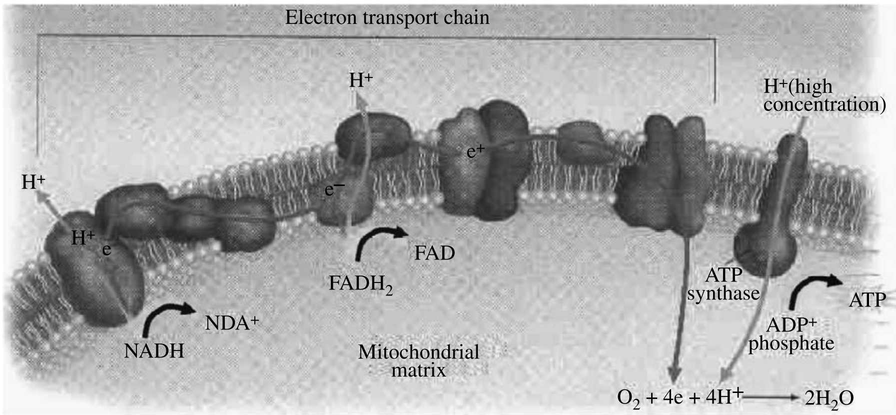

Figure 1 Schematic representation of the electron transport chain embedded in the inner mitochondrial membrane of eukaryotic cells (source: Johnson, 2005)

The gas exchange takes place within the alveoli where air is separated from blood by a membrane, just two cells in thickness. In the lungs of an adult, about three hundred million alveoli provide a surface area of sixty to eighty square metres. The alveoli constitute a membrane system. It separates the gas space filled with air from the blood flowing by.

Oxygen travels through the membrane by force of a concentration gradient, dissolves in the blood and is taken up by the red blood corpuscles. Carbon dioxide in turn travels towards the gas space – by force of a concentration gradient – transforms into its gaseous form, and is blown into the atmosphere as the lungs are emptied.

Membranes of the intestinal tract

The intestinal tract of animals and man is to be understood as an anaerobic reactor in which the organic material contained in the feed is gradually converted through chemical reactions and by the aid of microorganisms into small size molecules. This process is

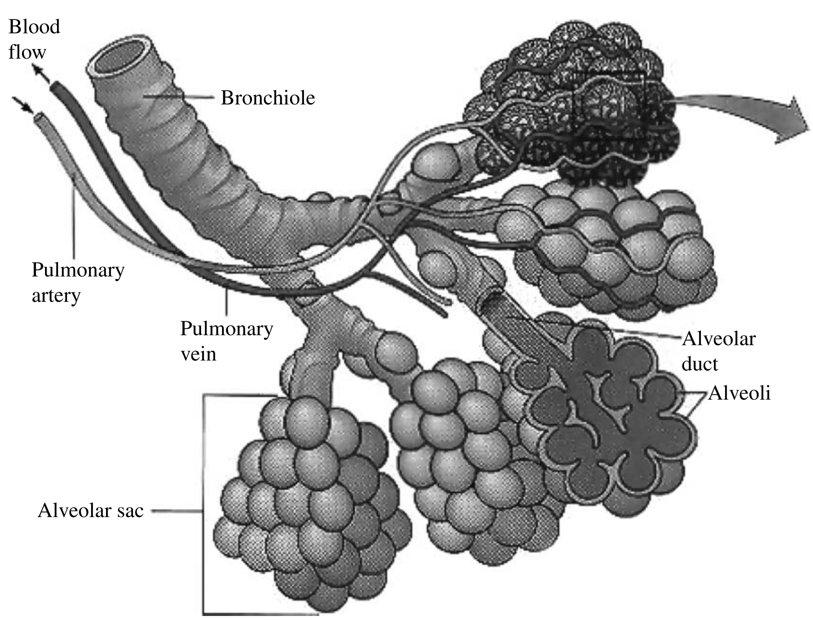

Figure 2 Schematic representation of the gas exchange systems in lungs (source: Johnson, 2005)

referred to as hydrolysis and acidification. The walls of the intestinal tract constitute a membrane system separating the anaerobic reactor from the blood stream, and it serves, in many cases at least, as an adhesion site for microorganisms, forming a biofilm there.

Hydrolytic reactions are most effectively performed by ruminant organisms (e.g. cows, goats and sheep). Again, the rumen is to be understood as a fermentation reactor providing an anaerobic environment, constant temperature and pH, and good mixing. Well masticated substrates are delivered through the esophagus, and fermentation products are either transferred into the blood stream through the wall of the rumen, more precisely through the membrane which separates the rumen environment from the blood stream, or flow out for further digestion in the intestinal tract. Figure 3 shows the membrane module as it typically exists in the rumen.

Organic molecules are transferred through the membranes by force of concentration gradients (diffusive mass transport) or actively and selectively by the aid of specific transmembrane proteins.

Membrane systems in the root zone of aquatic plants

It is worth noticing that roots, in particular roots of aquatic plants form symbiotic associations with soil microbes (Hook and Crawford, 1978). Aquatic plants which typically grow in an anaerobic environment developed a specific form of symbiosis involving ammonia and nitrite oxidizing bacteria (nitrifiers) in particular. Nitrifiers together with other microorganisms grow in the form of a biofilm at the surface of the roots (Figure 4).

Ammonia present in the bulk liquid is transformed into nitrite and nitrate which diffuses into the roots by force of a concentration gradient and is used as a source of nitrogen. In turn, the water plants support nitrifiers and other aerobic microorganisms with oxygen.

Oxygen is required by the root cells anyway. To support the root cells with oxygen, the plants have developed a unique ventilation system. By means of a tubular system within the stems and roots air is "blown" down to the root zone. Excess oxygen not

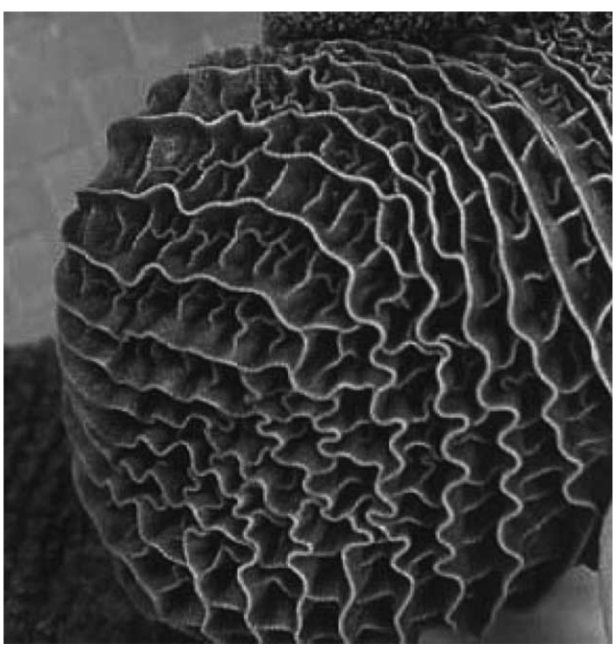

Figure 3 Photographic representation of the membrane system in the rumen of a calf (source: Penn State University, USA, www.das.psu.edu)

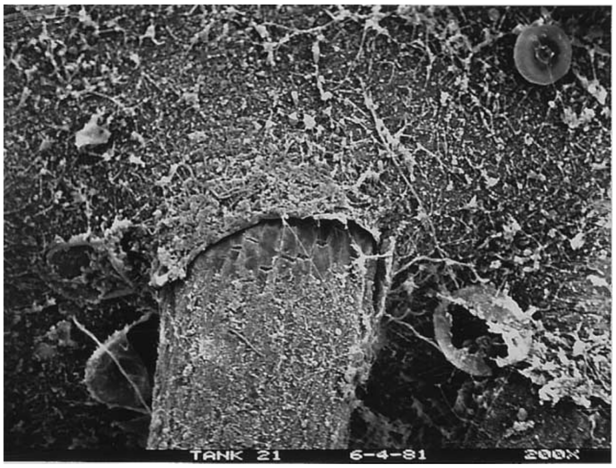

Figure 4 Electron scanning micrograph of a biofilm growing at a root of a water hyacinth plant

utilized by the root cells diffuses through the root structure into the biofilm which adheres to the surface of the roots.

Take home message

- Membranes play a very important role in the metabolism of organisms.
- Mass transport through the membranes is accomplished by development and maintenance of concentration gradients.
- At both sides of the membrane, diffusive mass transfer limitations are minimized by gentle force of either contraction or squeezing or by advection (e.g. flow of blood).
- Selective mass transport is actively controlled by enzymes embedded in the membranes.
- Bio-chemical conversion processes are performed within membranes.
- In many cases membranes are used by microorganisms as an adhesion site (substratum).The biofilms which develop at the surface of the membranes do not inhibit transmembrane flow of material but as representation of symbiosis.
- In natural membrane systems, cross flow is not applied to keep membranes from fouling. Neither pressure nor suction is applied to facilitate transfer of materials through the membranes. Relatively low transfer rates are compensated by provision of large membrane surfaces.

Contemporary membrane technology

Comparison of technical and natural application of membranes reveals some similarities but differences as well. For instance, membranes have been in use for millions of years in organisms whereas man made membrane technology is relatively new.

Currently, application of membrane technology is mainly focused on removal of particulate material from water (micro-, ultra-, nano-filtration) and removal of dissolved material (reverse osmosis). The opposite process, i.e. transfer of material into water is an option which is discussed but rarely applied in the field of water and wastewater treatment. For instance, membrane systems have been investigated for bubble-free transfer of oxygen into water (Wilderer *et al.*, 1985; Lee and Rittmann, 2000), and for bubble-free transfer of ozone into water as well (Picard *et al.*, 2001). In resemblance of root systems, membranes were proposed as a substratum for biofilms (Rothemund *et al.*, 1996; Lee and Rittmann, 2000).

In the uppermost cases, plastic materials (mainly polymers) are used as membrane material. Experiments have also been conducted, however, with sintered materials (ceramics, metals). Membranes applied for desalination (reverse osmosis) or for bubble-free oxygenation do not contain pores, whereas membranes for solid–liquid separation do. In the latter case, we talk about filtration membranes. The membranes are manufactured either as flat sheets or as capillaries. To provide maximum membrane surface per unit volume of the reactor the membranes are arranged in various ways. Pressure or suction is applied to maximize flow of permeate or filtrate, respectively.

During the in-service time the surface of the membranes may get coated with a layer of inorganic or organic material. In this case we are talking about scaling effects. When biofilms grow at the surface we are talking about bio-fouling. In either case, flow through the membrane gets reduced and the efficiency of the membrane module deteriorates. To remove scales and biofilms the membranes are to be backwashed – if possible – or cleaned, mechanically or chemically. The resulting out-of-service time diminishes the efficiency of the membrane system, and additional costs are generated. Keeping membranes from rapid scaling and fouling is therefore of major interest.

Experience shows that fouling can be minimized by exposing the membranes to hydrodynamic shear. Shear can be conveniently generated by letting gas bubbles pass along the membrane surface, perpendicular to the direction of the trans-membrane flow. This option is referred to as "cross flow" operation. Another way of producing a cross flow is shown in Figure 5. Here a stack of ceramic membranes is brought into rotation by which centrifugal forces add to the cross flow effects.

In wastewater treatment plants, membrane modules are mainly used as a substitute for sedimentation tanks. A prominent example of this approach is the so called "Membrane Bio-Reactor" (MBR). Membrane modules are submerged in the activated sludge tank. By sucking the wastewater through the membranes a particle-free, hygienically safe effluent can be produced ready for various re-use purposes such as toilet flushing, watering lawns or crop fields.

Figure 5 Stacks of flat ceramic membranes brought into rotation to control fouling (source: www.kerafol.com)

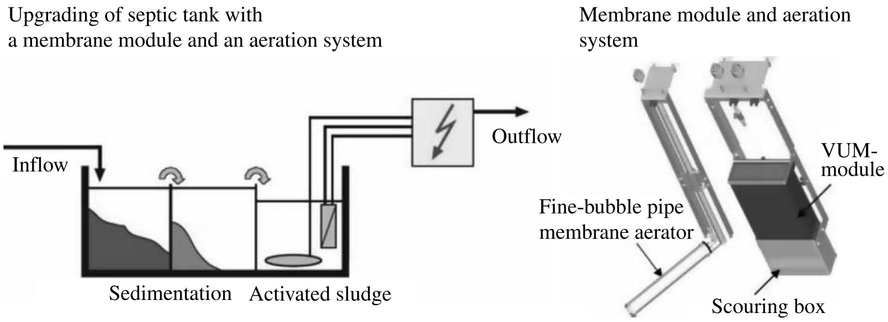

Figure 6 Upgrading of a septic tank with a submerged membrane module (HUBER-VUM-module; VUM = Vacuum Upstream Membrane)

Advanced concepts of membrane application

As mentioned above, particle-free, hygienically safe effluents can be achieved by driving wastewater through membranes. This concept is not only applicable for activated sludge plants. It could also be applied to treat the effluent of septic tanks. Figure 6 shows a configuration as it has been applied at several locations in Germany. Table 1 summarizes the effluent quality obtained.

The quality of the filtrate matches the requirements of the EU bathing water directive. In addition micro-pollutants such as pharmaceutics, hormones and alkyl phenols can be eliminated more efficiently than in conventional wastewater treatment plants by using membrane processes (Meuler *et al.*, 2006).

Membrane modules could also be used as a substitute for primary sedimentation tanks. This concept is visualized in Figure 7. Again, the basic idea is to generate an effluent which is free of particulate matter, free of pathogenic organisms and viruses, in particular. Thus, the permeate can be safely used for toilet flushing, cleaning, watering lawns or for irrigation of agricultural land. Hygienic safety is a must in all these cases. Expensive treatment operations such as nitrification and denitrification are unnecessary, particularly if the permeate is used for irrigation

On first glance, application of membrane separation technology to treat raw wastewater appears impossible because of rapid fouling of the membranes. To counteract fouling processes, removal of readily biodegradable substances is assumed to be necessary. As sketched in Figure 7, this could be achieved by adding precipitants and adsorbents (Teleman *et al.*, 2005) after the wastewater has passed a sequence of mechanical treatment steps.

The results of field tests proved that the addition of precipitants and coagulants increase the separation efficiency by means of a fine screen (Table 2). It appears to be worthwhile to further investigate the concept with membrane separation modules following fine screens.

Table 1 Quality of the water obtained by membrane ultra filtration (source: Meuler *et al.*, 2006)

Parameter	Filtrate*		Treatment efficiency
BOD_5	2	mg/l	99.1%
COD	23.7	mg/l	95.5%
NH_4-N	1.2	mg/l	81.9%
N_{anorg}	24.2	mg/l	
TSS	2.3	mg/l	99.3%
Faecal coliforms	45.8	1/100 ml	99.9%

*mean value

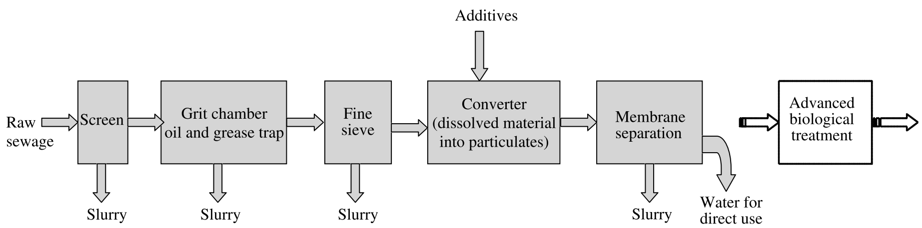

Figure 7 Schematic of an advanced pre-treatment train based on physico-chemical conversion and membrane separation

The same concept could also be applied to treat grey water. In this case, detergents are most probably the main component of organic pollutants. Because detergents are designed to adsorb to surfaces, removal of COD and BOD should be effectively accomplishable by adding powdered activated carbon to the effluent of showers or bath tubs. The loaded activated carbon particles together with other particulate matter (e.g. hair) can be effectively removed by micro- or ultra-filtration. The treated effluent could be directly re-used for showering as has been demonstrated by Leonhard *et al.* (2004).

Various trials have been made to use membrane biofilm systems for the treatment of wastewater. Kolb and Wilderer (1995), for instance, demonstrated the applicability of such a system to aerobically treat process wastewaters containing volatile organic substances (benzene, toluene, xylene and 3-chloro-ethylene) without running the risk of stripping of such problematic substances into the atmosphere.

Mimicking nature: an example

The idea of considering natural membrane systems as a model for technical solutions links directly to the discussion on decentralization of water and sanitation systems and on the idea of replacing the concept of degradation and discharge by recovery and re-use. The technologies briefly described above may be understood as a first step in this direction. We could take a step further, however, in the attempt to take advantage of the experience of Mother Nature. The process schematic of anaerobic treatment of organic matter presented in Figure 8 is just an example of such an approach.

In contrast to the current technical treatment concept, anaerobic processes in nature are not directed to maximizing generation of methane gas. In focus are the generation of building materials for cell synthesis and release of electrons for energy generation.

Anaerobic reactors operated to produce methane gas for energy generation must have a significant size in term of loading to be cost efficient. The amount of gas produced in small reactors is too little to make profitable use of it. In contrast, anaerobic "reactors" in nature are very small in comparison. They can be small and still be efficient because the

Table 2 Comparison of the removal efficiency by means of fine screening of raw municipal wastewater with and without addition of chemicals (source: Fromman *et al.*, 2005)

Treatment	Filterable solids	BOD_5	COD	P_{tot}	Unit
Fine screening	32.5	12–18	24–36	0.04	[g/(E·d)]
	50	20–30	20–30	2.5	[%]
Addition of coagulants +fine screening	62.0	30	60	1.1	[g/(E·d)]
	95	50	50	60	[%]
Addition of precipitants and coagulants + fine screening	62.0	39	78	1.6	[g/(E·d)]
	95	65	65	90	[%]

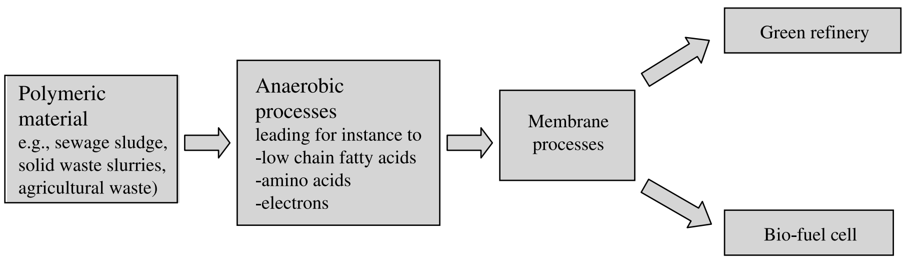

Figure 8 Anaerobic treatment of wastewater involving innovative membrane applications

efficiency is not dictated by amount and value of gas produced but by the value of a variety of materials produced, fatty acids, amino acids and electrons, in particular.

The new generation of anaerobic treatment systems for decentralized application should be based on membrane processes. As in the intestine, membranes should be applied to harvest from the anaerobic environment fatty acids, amino acids and electrons immediately after their release to avoid local accumulation and subsequent inhibitory effects. The membrane system should be designed so that it can be effectively operated at low pressure. Biofilms should be allowed to grow at the surface of the membrane facing the anaerobic reactor but microorganisms should not be driven into the pores of the membrane by force of pressure or suction.

To enhance the flux of anaerobic products, the transmembrane concentration gradient should be kept at a high level. In resemblance of the blood circulation this could be achieved by circulating water along the membrane surface – opposite to the anaerobic zone. The water would serve as a temporary sink. It would be pumped to a secondary "sink" where the picked up materials are harvested from the water for any further use ("green refinery approach"). Electrons could be separately harvested and converted into electrical energy in a bio-fuel cell implemented in the reactor system. Alternatively, it may be possible in future to implement energy generation processes in the membrane as is the case in cell membranes (see Figure 1).

The concept described above may sound futuristic. But this is not the case, actually. First trials have already been made, for instance in the framework of the MELISSA project (www.esa.int/esaCP/ESA9CV0VMOC_life_0.html) conducted by the European Space Agency.

Conclusions

The following list of statements may be treated as incentives for further consideration:

- Membrane systems are very common in nature. Cell metabolism and the metabolism of higher organisms including man are based on membrane processes.
- In organisms, membranes are to be understood as interfaces between the inside and the outside world and as an instrument to transfer substrates, metabolites and gases.
- In most cases, transfer of materials is actively controlled by molecules embedded in the membrane. These substances, mostly enzymes, allow selective mass transfer at high rate.
- In comparison, membrane systems applied in water and wastewater treatment plants are passive and appear rather low in sophistication. Here the mass transfer is performed by a driving force applied from outside (pressure, suction).
- Mostly, membranes are used for solid–liquid separation. Nowadays, the main purpose of technical membrane systems is to gain water free of particulate material and salt. Ultra-filtration allows generation of hygienically safe water for further use, including irrigation.

- Application of this type of membrane system is not limited to biological wastewater treatment schemes (e.g. membrane bio-reactor). Membrane separation of raw wastewater in combination with precipitation and adsorption may produce water ready for irrigation of agricultural land.
- Membrane separation applied to small systems such as septic tanks are worth to considering. Small systems could be effectively upgraded to the advantage of communities in water scarce areas.
- Special attention should be paid to anaerobic processes. The intestine should be treated as a model for innovative solutions, specifically with respect to miniaturization of wastewater treatment plants. If generation of fermentation products for further use is considered as the target – instead of biogas – anaerobic treatment would become applicable even at household level.

In either case, it appears to be of advantage for technology developers to keep a close eye on Mother Nature. There, a great variety of solutions have been tested over millions of years. It is most likely that novel technical solutions will be developed by taking advantage of the "experience" accumulated in the course of evolution.

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