

Ceramic as a Potential Tool for Water Reclamation: A Concise Review

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Abstract

An awful consequence of technology's recent fast progress is the immense deterioration of precious and essential water resources. As water quality becomes increasingly inferior, a successful alternative treatment measure is urgently required, in addition to available traditional methods. The present review aims to draw a significant account of the water reclamation proficiency of ceramic, which substantially contributes to improving water quality. Incorporation and application of ceramics in the form of filter, macro and microfilter, hybrid and composite membrane filter, and adsorbent using filtration, adsorption, absorption and ion-exchange mechanisms has opened a new approach in the field of drinking water purification, wastewater treatment, removal of aquatic pollutants, and de-eutrophication of water. The promising effectiveness of different modified forms of ceramics in the purification and treatment of freshwater and wastewater would significantly contribute to providing organic, inorganic, and microbial hazards-free qualitatively and quantitatively improved reclaimed water to our present and forthcoming generations at a low cost without any environmental negative impacts. Due to having several significant properties, it may, therefore, be concluded that ceramic is an important natural resource that can be generated through the waste recycling process and may be used as a potential tool for water reclamation.

Keywords: ceramic, drinking and waste water treatment, removal of pollutants, waste recycling, reclamation.

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Introduction

Water is undoubtedly the most precious natural resource, comprising over 70% of the earth's surface. Nonetheless, demand for clean water is worldwide, whether it is for human consumption, agricultural application, or industrial use [1]. Rapid and continuous economic development and growth in developed and developing countries around the world has also led to a considerable increase in water demand. The worldwide demand for high quality water resources will be difficult to meet in the foreseeable future. The supply is dwindling because the aquatic environment is continuously contaminated by a massive volume of hazardous and toxic substances generated by anthropogenic activities. Surface and groundwater pollution has been recognized as an alarming threat to the whole world, especially developing countries. In the recent past,

expanding human population, intensive agricultural practices, and industrialization has discharged massive amounts of wastewater containing toxic and hazardous substances including heavy metals into the water, tremendously contaminating the aquatic environment [2,3]. As runoff moves downslope, sediments and other pollutant particles are transported to perennial surface water bodies affecting the water quality and biodiversity [4]. Herbicides used in agriculture can also be transported to surface or ground waters [5], causing adverse ecotoxicological effects on aquatic life [6,7] and also degrading drinking water quality [8].

Globally, more than 3 billion people live in proximity to the marine coast and are directly polluting coastal water bodies. Apart from that, wastes from both industrial and domestic sources as well as habitat destruction have a substantial impact on the coastal environment. Due to these reasons, the oceans were previously considered to be

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a vast reservoir for the safe disposal of pollutants. Many chemical contaminants, including organochlorine compounds, herbicides, domestic and municipal wastes, petroleum products and heavy metals are now recognized to have adverse effects on ocean environments, even when released at low levels. The accumulation of heavy metals in estuarine, nearshore, and marine sediments from both natural causes [9] and human activity [10,11] has also been identified. This has been of considerable concern due to apparent degradation of the marine environment and, in particular, to its effect on marine life and its potential health-hazard to the human population.

The consequences of pollution of all types of water resources are associated with an increase in the concentration of toxics in drinking water, which is also responsible for the high cost of water potabilisation [12,13]. In addition, most of the pollutants (non degradable) accumulate in different trophic levels of the environment through the natural processes of bioaccumulation and biomagnification. This results in various costs to the environment, principally the loss of biodiversity that leads to the present global concern – loss of ecosystem stability. Very little attention had been given to this problem until shortly before the 19th century. Nowadays, the conservation of water resources by preventing their pollution by hazardous and toxic elements is one of the most important challenges to the human race. All of the above concerning information is the primary driving force for the present review on the significance as well as technological application of ceramic for aquatic environment conservation.

Traditional water pollution control measures

Various measures are adopted to control the indiscriminate pollution of water. In recent decades, a number of legislations have also been imposed to control water pollution in different countries. In 1970, the Clean Water Act provided 50 billion dollars to cities and states to build wastewater treatment facilities for controlling surface water pollution generated from industrial and municipal sources throughout the United States. Despite legislation measures, numerous techniques have evolved to remove toxic compounds from the soil, air or water by either of the following two ways: (i) by breaking down the chemical(s) into a less toxic chemical, such as enhanced bioremediation and thermal oxidation; or (ii) by reducing the concentration of the chemical(s) to a level that is not considered toxic to humans or the environment, such as pump-treat methods, soil-vapor extraction, air stripping, etc.

Though complexation, adsorption, precipitation, and diagenesis, particularly in sediments, are the major natural processes that control pollutants in the aquatic environment, enormous overgeneration of hazards has led to the failure of a complete natural breakdown of all

harmful compounds. Therefore, several techniques have been developed and are described below.

Bioremediation

Bioremediation is the most important eco-friendly technique to reclaim polluted water using different biological components of the environment. The preliminary idea behind biological methods of wastewater treatment is the introduction of bacteria, which feed on organic materials in wastewater, thereby reducing its biochemical oxygen demand (BOD) content. Various biological agents, such as aquatic vegetation and animals, also play a significant role in reclaiming polluted and heavy metal contaminated water. Ecosystem components show variable performance, and we found that the aquatic plant *pistia* was the efficient component in cadmium (Cd) removal from the aquatic ecosystem [14].

Mechanical and physical

The mechanical treatment process also plays a crucial role in removing large particles in the wastewater treatment process. This treatment technology involves physical and mechanical wastewater treatment resulting in the decantation of effluent and separation of sludge. Mechanical processes are also used in combination with biological for advanced unit operations including the processes of sedimentation and flotation.

Chemical

Chemical disinfection of water depends on the killing of Protozoa (*Giardia* and *Amoeba* cysts), bacterial, and viral pathogens through chemical means. In most wastewater and drinking water treatment plants, chemical treatment plays a vital role in removing the pathogenic load. Killing effectiveness of chemicals is greatly dependant on the chemical concentration, temperature of water, and contact time. Halazone (chlorine and iodine) are convenient and inexpensive, but have several disadvantages in drinking water treatment because reliable disinfection in all conditions requires a sufficient amount per liter with long enough contact periods, which results in poor flavor.

Objectives

It is clear that scientists have evolved several biological, physical, mechanical, and chemical devices and natural processes to reclaim polluted water. Among various treatment measures, ceramic is one of the unmasked and important natural resources that opened a new approach of drinking water purification and wastewater reclamation through the removal of health hazardous compounds and microbes. Application of ceramics in water purification and reclamation has been an emerging and new concern in recent years. Therefore, the objective of the present review aims to draw a vivid account of the potential pollutant removal aspects of ceramics, which substantially

contribute to treating and purifying water resources by providing pollution-free reclaimed water to our present and forthcoming generations at a low cost without any negative environmental impacts.

Background of ceramic

Before an elaborate discussion about the water reclamation proficiency of ceramic, following is a short general account. The word ceramic is derived from the Greek word *keramikos* (κεραμικός). Ceramic was most importantly known as traditional clays until the 1950s. It is considered the most ancient and manmade non-metallic material composed of clay – plastic material, silica (quartz and sand) – nonplastic properties, and feldspar ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$, $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$, and $CaO \cdot Al_2O_3 \cdot 6SiO_2$) – fluxes or mineralizers as principal raw ingredients and is hardened by firing at a high temperature varying from 600 to 1400°C [15]. Ceramics are familiar materials that can be transformed into objects having a wide range of useful properties – not conducting electricity, resisting corrosion, and being hard, durable, and waterproof. Traditional ceramics, such as brick, tile, stonewares, earthenwares, vitreous china, and porcelain products are indispensable for commonplace activities, and newer varieties of ceramics have enabled dramatic improvements in communications and computer technologies. Recently, (Ca,Sr) (Zr,Ti)O₃-based, MgO-TiO₂-based, BaO-TiO₂-based, and BaO-TiO₂-based dielectric ceramic compositions, which can be used for multilayer ceramic chip capacitors.

Most ceramics consist of one or more varieties of a metal oxide in different proportions to accentuate the strengths of the materials in which the atoms of metal and oxygen usually form a crystal, where the positions of the atoms are very regular, producing edges and facets. In traditional ceramics, generally, small and variously-sized metal oxide crystals containing alumina and silica (the oxide of silicon) exist in clays. Ceramics are usually ionic or covalent bonded materials, and can be crystalline or amorphous. A material held together by either type of bond will tend to fracture before any plastic deformation takes place, which results in poor toughness. Additionally, because these materials tend to be porous, the pores and other microscopic imperfections act as stress concentrators, decreasing toughness further and reducing tensile strength.

Functional mechanism of ceramic

From the water reclamation point of view, the basic functional mechanism of ceramic is governed by various intrinsic fundamental chemical properties of constituting materials responsible for filtration, ion exchange mechanism, and the physical property of porosity, which

helps in adsorption as well as the absorption process. Porosity is a fundamental requirement for the good performance of ceramic substrates for solid–gas reactions operating at high temperatures; it should be as stable as possible on use so that, even after several treatments at high temperature, densification is minimized [16,17]. Porous ceramic materials actually adsorb substances into their porous space, and for that reason they are widely used in industrial fields. In fact, due to their good mechanical properties at high temperatures and their chemical inertness, they can be used as filters for hot exhaust gases, catalytic supports, and separation membranes [18,19]. The general interest devoted to porous ceramic materials has recently increased and many researchers, on the grounds of studies regarding natural biomaterials and novel production strategies for new materials having a biomimetic approach, have prepared porous ceramics by adapting biological principles, which in nature govern the production of biocomposites, to laboratory production, in order to prepare new materials and/or find new preparation techniques [20,21]. Presently, monolithic ceramic substrates, prepared for application as catalytic supports, have porosity of two different sizes: macroporosity and microporosity. The former has dimensions of some tens of microns (0.1µm), the latter is roughly ten times smaller, being directly determined by grain size which, in turn, is function of thermal treatments adopted during the production of materials. Microporosity mainly depends on powder characteristics such as composition and particle size distribution. It follows that powders' thermal history plays an important role on the resulting porosity of sintered material. Macroporosity, on the other hand, depends on the preparation procedure of the ceramic substrates and may be obtained by introducing, in the starting green compacts, some substances that, upon thermal sinterization, can evaporate or burn, leaving place to the equivalent porosity. These substrates have a higher proportion of metal oxides, which are supposed to play a pivotal role in the exchange of ions in the aqueous phase. Apart from the above intrinsic properties, various environmental factors such as temperature, pH, ionic strength of the aqueous phase, etc., are responsible to a great extent in the functional mechanism of ceramic. The Cd adsorption capacity of ceramic increased with increasing temperature [22] and adsorption of thorium(IV) on bentonite was influenced by pH, ionic strength and temperature [23].

Ceramic as an environmental tool for water reclamation

Ceramic tool for drinking water purification

One of the targets established in the millennium development goals is to halve the proportion of people who do not have sustainable access to safe water and basic sanitation [24]. The majority of related deaths are associated with diarrhea among children under 5 years old

suffering the effects of malnutrition, dehydration, or other secondary health effects related to waterborne infections in developing countries. An estimated 1.8 million people die every year [25]; 4.0% of all deaths and 5.7% of the global disease burden are largely due to diarrheal diseases [26] related to inadequate water, sanitation, and hygiene. An unknown percentage of the diarrheal disease burden is due solely to unsafe drinking water containing viral, bacterial, and parasitic microbial pathogens. WHO and UNICEF assessed that 1.1 billion people do not have access to improved drinking water sources [27]. This is undeniably a major task for policy-makers, engineers, and researchers, among many others. Pioneers have come up with smart solutions to treat water in the tropics – often adaptations of conventional techniques for local use. Many technologies

focus on water treatment at the point-of-use, which is often done within the household, as household drinking water treatment has been shown to be an effective intervention to reduce diarrheal diseases in developing countries. Improvements in household drinking water quality and associated health impacts by low-cost ceramic water filters, a promising technology for point-of-use water treatment, have not been adequately characterized. Now it has been proved that the ceramic filter has substantial dysentery (61%) and diarrheal (> 40%) disease reduction ability. Therefore, various types of experimentally proved ceramic balls and filters have been developed recently to treat the drinking water, as described in Table 1.

Table 1. Application of different forms of ceramic for various purposes of drinking water treatment

Types of ceramic ball and filter	Composition and application
Negative Potential Ceramic Ball	It is made from natural non-metal mineral tourmaline, high-grade clay added with other natural negative ion powder and germanium powder and mainly used for reducing ORP of water and adjusting PH.
Magnetization ball	It is also composed of natural non-metal mineral tourmaline, kaolin and high-grade clay and used for improving water quality.
Alkaline ceramic ball	Natural nonmetal mineral tourmaline, kaolin and high-grade clay are mixed by special techniques mainly used for adjusting water PH and making water present alkalescence, and accelerating human body metabolism.
Energy ceramic ball	The energy ceramic ball is prepared by natural nonmetal mineral tourmaline, kaolin and high-grade and used for activating, purifying, and mineralizing drinking water.
Negative ion ceramic ball	It is mainly formed by mixing natural nonmetal mineral tourmaline, kaolin and high-grade clay with a specific ration and applied as water purifiers and in textile and health care products.
Antibacterial ceramic ball	Natural nonmetal mineral tourmaline, porcelain clay and high-grade clay are mixed very well by a special technique and used for eliminating bacteria from water.
Mineral ceramic ball	It is also made by natural nonmetal mineral tourmaline, a special type of stone, porcelain clay and calcium carbonate with specific techniques and used for activating, purifying, and mineralizing drinking water.
Kitchen water purifier R-600	It is produced by mineral tourmaline, porcelain clay, and high-grade clay, and can be installed inside the cabinet in the kitchen for kitchen water filtration and purification, such as removal of heavy metal, sediment, rust, protozoa, and bacteria.
Ceramic water softener	Ceramic water softener is made by tourmaline ceramic ball, ion exchange resin, ceramic hemisphere, and activated carbon. It removes calcium and magnesium ions from the water and softens water quality.
Nano filter	The nano filter is constructed by tourmaline ceramic ball, ceramic hemisphere, nanofiltration membranes, and coconut shell activated charcoal. It helps to retain nano material and removes bacteria, viruses, colors, hardness, organic material, carcinogen chloroform and heavy metal ions, etc.

Low cost ceramic pot

A widely used silver-impregnated ceramic pot filter (Figure 1) is one example of a low-cost technology to treat drinking water at the household level [28]. It consists of a pot-shaped filter element that is placed in a plastic receptacle. The ceramic filter element is manufactured with local materials and skills with a mixture of clay, sawdust, and water and is pressed into a pot shape with press moulds. Once the filter element has its shape, it is fired in a kiln and the sawdust is combusted to leave porous material. The filter element is impregnated with a mixture of colloidal silver, for assumed disinfection purposes. During manufacture, the only energy consumption is the firing of the kiln; the environmental impact depends on the energy source used by the manufacturers. Apart from the kiln, the manufacturing method and natural sources needed for this treatment system are very environmentally-friendly. It is a promising treatment system to supply safe drinking water, especially to people living in rural areas. The main criterion of such a pot for household drinking water treatment is sustainability of a system based on five properties: (i) accessibility, (ii) water quality, (iii) water production, (iv) functionality, and (v) environmental footprint. The removal of fecal *coliforms*, *E. coli* K12, and protozoan oocysts was found to be significant, which was supported by the reduction in diarrhea cases observed in users in a recent field study [29,30]. Retention of MS2 bacteriophages as an indicator for virus removal was, however, found to be unsatisfactory. Therefore, further research is recommended on virus removal by this ceramic pot, especially in relation to the colloidal silver application and other potential additives. The criterion of water production was shown to be the limiting factor, because it is reduced substantially during treatment of surface water. The silver-impregnated ceramic pot filter has been indicated to have a lifespan of over five years [31,32] but implementers recommend a life of one to two years [33].

Ceramic tool for wastewater treatment

Researchers have proposed a variety of technologies for the treatment of wastewater generated by indiscriminate human activities. Ceramics play a substantial role among these technologies. After finishing the first step of traditional wastewater treatment, the next step, the secondary treatment process, takes place in aeration tanks where compressed air is bubbled through thousands of ceramic domes located on the bottom of the tanks. In this biological process, air provides the mixing and oxygen for particles teeming with bacteria, fungi, and protozoa. These particles (called activated sludge) consume the organic material (pollutional load) in the wastewater, converting it to carbon dioxide, water, and new cells. Furthermore, in many treatment processes, ceramics are also used as a filtering unit in the form of small bricks and as coparticles

for the development of a microbial colony (population) to decompose the organic matter [34]. In addition, a number of modified forms of ceramic have also been developed to mitigate the treatment requirement as described below:

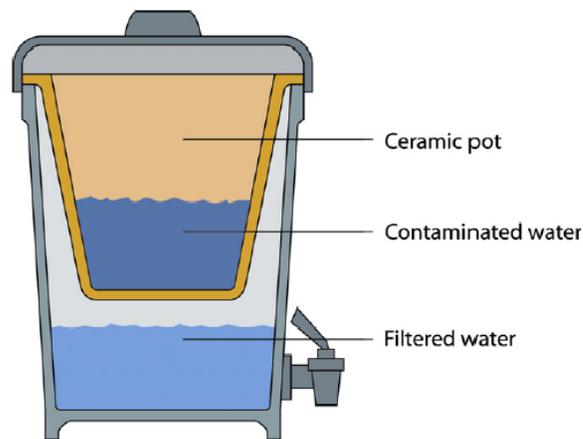


Figure 1. Ceramic silver-impregnated pot filter (Van Halem et al., 2008).

Simple ceramic membrane

The importance of membrane technologies for wastewater treatment has increased in recent years and emerged as an important separation and purification method in various process industries to prevent pollution of water resources caused by toxic elements (such as Pb, Cd, Hg) and dyes [12] and to obtain effluents without contaminants. They recycle process water and recover valuable products, which can be reused in the process itself or in other applications [35,36]. Inorganic membranes (oxide-based membranes such as Al_2O_3 , ZrO_2 , TiO_2 , and hyperpolysiloxanes) have attracted more attention due to high mechanical, chemical, and thermal resistance, which can be potentially applied in liquid separation, gas separation, and pervaporation. Nowadays the ceramic membrane has developed based on clay, which is abundant and requires a lower firing temperature in comparison with metal oxide materials. Clay minerals have a well-known structural adsorption, rheological, and thermal properties [37]. Messaoudi et al. suggested that membranes can be prepared entirely from natural clay [38].

Recently, the prepared microfiltration membranes based on ceramic materials are being used for wastewater effluent treatment because of their mechanical resistance, chemical inertia, long working life, thermal stability, and low cost. To make the process profitable, a specific type of ceramic microfilter membrane can be obtained with high separation coefficients and high permeate fluxes [39,40] (Figure 2). Natural barbotine consisting of clay, various kinds of kaoline, feldspath, and sand is used as a constituting ingredient of this membrane. Four different

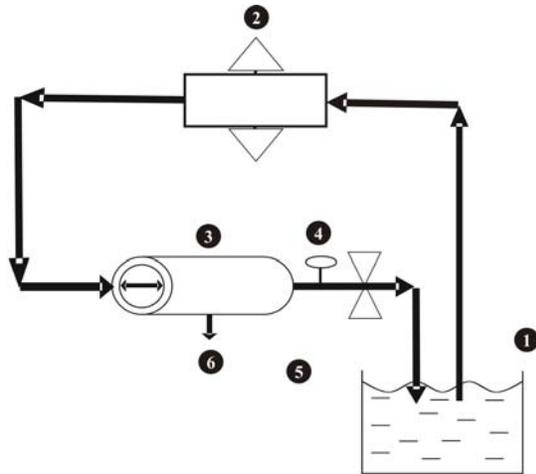


Figure 2. Figure representing the filtration flow diagram using the barbotine membrane prepared by mixing Hycast clay (21% w/w), KR-Kaoline 7%, LPC-Kaoline (20%), Tamazirt Kaoline (8%), Incusa-Feldspath (13%), NM-feldspath (7%) and sand (24%) from the Sig area with water (Belouatek, 2005, 2008). 1. Feed tank; 2. Feed pump; 3. Tubular barbotine membrane; 4. Manometer; 5. Pressure valve; 6. Filtrate recovery.

tubular membrane supports are prepared by mixing barbotine with activated carbon (1%), then with alumina-c(3%), and finally with oxide titanium “anatase variety” (3%). The supports are thermally treated at a heating rate of 10 °C/h up to 1,100 °C. The anatase-containing support gives a 70% retention rate for Evans blue and flux of 33 l/m² h, while the double layer support results in a 98% retention rate and a flux of 8 l/m² h for the same solution. Advantages of inorganic membranes are their chemical, thermal, and pH properties. Efficiency of these membrane supports for distilled water flow has also been studied. For the 3.5 bar pressure, an almost steady state is observed for the supports versus time. On the other hand, the increase of pressure to 5.5 bar results in an unsteady increase of the permeate flux, that is a flux decrease with time. Generally, though the flux increases with pressure, when the flux reaches a fixed value, it does not affect the pressure. Thus, limiting flux is defined as the flux independence of pressure increase at steady state.

Oil is a common hydrocarbon pollutant of wastewater and it can be found in a wide range of industries, such as general metal-working, food processing, textile, leather, etc. Onshore and offshore industries and engine rooms of ships (bilge waters) have effluents with higher oil levels. These pollutants must be reduced to acceptable levels before discharge into waterbodies by microfiltration ceramic membrane. Bilge waters with different oil-emulsion droplet sizes can be treated successfully using

ultrafiltration processes with ceramic membranes [41]. These membranes are a multi-layer asymmetric system, which consists of a tubular cordierite support where an α -Al₂O₃ layer has been deposited on its outer surface (Figure 3). The structure of these membranes with very high porosity (about 70%) has been designed to obtain high permeate fluxes and increase the efficiency of the process.

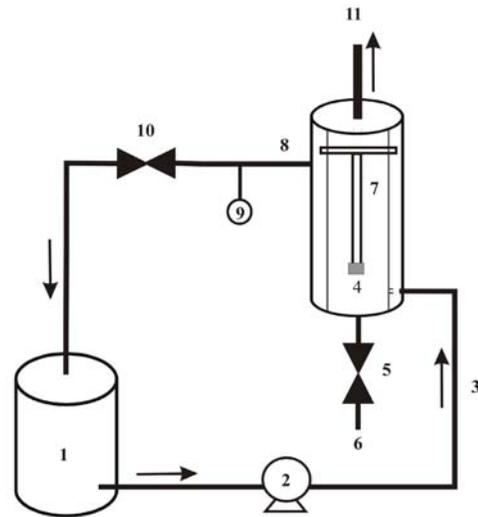


Figure 3. Figure showing the application of ceramic membrane in filtration equipment (Benito, et al., 2007). (1) feed tank, (2) centrifugal pump, (3) feed line, (4) membrane module, (5) valve 1, (6) drainage, (7) tubular membrane, (8) retentate line, (9) pressure transducer, (10) valve 2, (11) permeate line.

Composite ceramic membrane

Baus et al. described a new technique of the novel composite ceramic treatment process combining membrane technology with advanced oxidation to treat problematic pollutants [48]. Membrane pervaporation was employed to separate pollutants from wastewater [49]. This composite membrane was prepared by coating high surface area γ -Al₂O₃ on the porous ceramic membrane. A thin layer of γ -Al₂O₃ is coated on the surface of the individual ceramic particles to increase the contact surface by about 50 m². Ozone treatment of contaminated water showed that ozonization with traditional sparger in a batch reactor yielded a 1.1% decrease in total organic carbon (TOC), and simply replacing the sparger with a membrane distributor gave a 20% TOC removal. Providing a membrane contactor increased this value to 25%, while simultaneous membrane pervaporation of water resulted in 40% TOC degradation. This shows that it is possible to achieved enhanced ozone water treatment from a compact membrane reactor unit that uses the combined function of membrane as distributor, contactor, and separator.

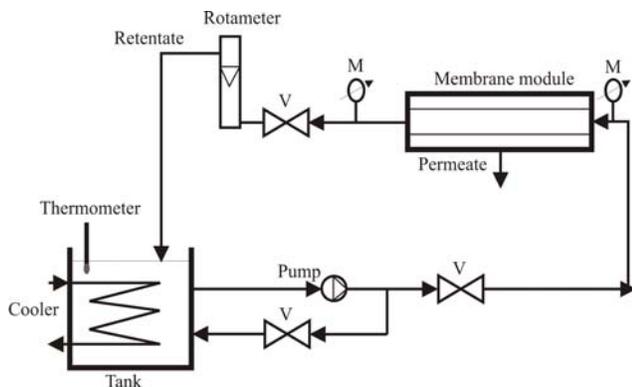


Figure 4. Figure representing the membrane filtration process was carried out using the apparatus where the membrane module microfilter ceramic membranes (M, manometer; V, valve) were installed (Konieczny et al., 2006).

With application of the hybrid process of coagulation–membrane filtration, organic or inorganic pollution can also be removed more effectively. Introductory studies have shown that, with respect to surface water treatment, coagulation may contribute to ensuring a high permeate flux of membrane filtration ceramic membranes and to lowering the frequency of their hydraulic or chemical washing (50,51). The implication of the hybrid process offers better water treatment than a unit process of coagulation or microfilter carried out separately. Konieczny et al. successfully developed a high performance hybrid system combining coagulation and membrane filtration that offers better removal of organic pollution about 100% for TOC (52) (Figure 4). The hybrid system uses coagulants (aluminium sulphate, polyaluminium chloride, ferric chloride, and ferric sulphate) in the ceramic membrane filter, which play a significant role to optimize the effects of coagulation and formation of cake of organic and inorganic pollutants in the membrane. Experiments indicated slight differences in

Table 2. Results of physicochemical tests of raw water, water after coagulation and permeates in the unit and hybrid systems (Konieczny et al., 2006)

Parameter	Nominal TOC concentration in raw water (mg dm ⁻³)	Concentration in							
		Raw water	Water after coagulation			Permeate after coagulation–MF			Permeate after MF
			FeC ₁₃ ·6H ₂ O	Al ₂ (SO ₄) ₃ ·18H ₂ O	ALF	FeC ₁₃ ·6H ₂ O	Al ₂ (SO ₄) ₃ ·18H ₂ O	ALF	
Membrane: 0.1 µm	7	13	39	82	84	33	57	73	12.5
Conductivity(µS/cm)	10	13	49	79	76	32	56	71	13.2
Turbidity (NTU)	7	3.5	3.2	1.3	2.6	0.1	0	0	0
	10	3.5	1.7	2.4	3.2	0.2	0.1	0	0.05
Absorbance (1/cm)	7	0.3	0.1	0.2	0	0	0	0	0.02
	10	0.7	0	0.2	0.1	0	0	0	0.02
TOC (mg/dm ³)	7	7.2	2.3	1.7	2.9	0	0	0	0
	10	10	1	2.8	2	0	0	0	0
Iron (mg/dm ³)	7	0	1.5	-	1	0	-	0.2	-
	10	0	1.6	-	0.9	0.2	-	0	-
Aluminium (mg/dm ³)	7	0	-	3.9	3.3	-	2	2.8	-
	10	0	-	3.8	3.1	-	2.1	2.5	-
Membrane: 0.2 µm	7	10	44	73	65	45	67	60	10.1
Conductivity(µS/cm)	10	13	46	70	74	37	66	67	13
Turbidity (NTU)	7	2.4	1	1.5	1	0.1	0.1	0.1	0
	10	3.6	0.6	2.1	1.2	0.1	0.2	0	0.4
Absorbance (1/cm)	7	0.5	0	0.1	0	0	0	0	0
	10	0.6	0	0.2	0	0	0	0	0.03
TOC (mg/dm ³)	7	7.5	0.8	1.3	0.5	0	0	0	0
	10	11	1	1.2	0.5	0	0	0	0
Iron (mg/dm ³)	7	0	1.5	-	0.4	0.4	-	0.1	-
	10	0	1.6	-	0.6	0.6	-	0.6	-
Aluminum (mg/dm ³)	7	0	-	3.8	2.7	-	1.7	2.4	-
	10	0	-	3.3	3.1	-	2.3	3.1	-

cake formation trends between ferric- and aluminium-based coagulants and chloride and sulphate counterions, but that the range of measured specific cake resistance in each m^2 values was small (0.9 and $2.6 \times 10^{18} / m^2$) over the range of doses studied. Greater than 99% UV_{254} removal was achieved with every coagulant, whereas dissolved organic carbon (DOC) removal ranged from 78 to 88%. The main drawback of this hybrid process of coagulation is membrane fouling caused by an integrated effect of microorganisms, organic, and inorganic matters on the exterior surface, and bio-fouling on the inner surface examined through microcosmic observation using Scanning Electronic Microscope (SEM) combined with Energy Dispersive Spectrometer (EDS). Acidic and alkaline cleaning is the major device used to avoid fouling. The application of the hybrid system combining coagulation and microfiltration offers better removal of organic pollution (100% for TOC). Removal efficiency of organic compounds of this system is shown in Table 2, which presents values of the parameters of physicochemical studies of organic compounds for two concentrations of humic acids in simulated water (7 and 10 mg total organic carbon/dm³) in coagulation and membrane filtration unit processes and in the coagulation–membrane filtration hybrid process.

In this context, it should be mentioned that a number of methods, biological, chemical, electrochemical, chemical coagulation, and ion exchange are effectively employed for efficient treatment of food wastewater (53), sewage wastewater (54,55), phosphorus wastewater (56), oily wastewater (57), packing-house wastewater (58), and textile wastewater (59). Lin and Lin applied electrochemical, chemical coagulation, and ion exchange processes collectively for the treatment of wastewater and achieved a good reused standard of water shown in Table 3 (60). It is obvious that using all of these processes collectively is costly and involves high technology. This is not applicable in the practical field of developing countries and not suitable for large volumes of water. Apart from that, using all these devices itself leads to another water pollution under certain conditions, along with reclamation. Therefore, efficient and promising ceramic-based

wastewater treatment is easily available, lower technology, and gives results parallel to those of the other treatment methods. The water quality of the treated waste effluent was also excellent as discussed in this section.

Ceramic bioball in constructed wetland

From a wastewater treatment point of view, the wetland system acts as a kidney of a particular area that is energetically sustainable because it uses only natural energy to reduce hazards. The constructed wetland, known as a free water surface system, can mimic natural systems as the water flows over the bed surface and is filtered through a dense stand of aquatic plants [42]. Over the past decade, there has been a growing appreciation of the multiple values and functions of constructed wetlands, which are increasingly used for treating a variety of wastewaters [43]. Moreover, use of constructed wetlands is now recognized as an accepted eco-technology, especially beneficial to small towns or industries that cannot afford expensive conventional treatment systems [44,45]. Compared with the conventional wastewater treatment system currently used, it requires low construction and operational costs [46].

Incorporation of ceramic as a vesicle in the wetland treatment system is a new approach for wastewater reclamation. The emergent wetland plant *P. communis* has been shown to survive and reproduce well in a pilot-scale constructed wetland for receiving and treating a continuous industrial wastewater input from an industrial park in southern Taiwan. The use of vesicles ceramic bioballs as the media and *P. communis* as the wetland plant achieves the optimal results in the pilot-scale wetland system. The overall removal efficiencies are 61% for chemical oxygen demand (COD), 89% for BOD, 81% for suspended solid (SS), 35% for total phosphate (TP), and 56% for ammonia nitrogen (NH_3-N); wastewater treated this way meets the current industrial wastewater discharge standards in Taiwan [47]. With respect to system sustainability, the vesicles ceramic bioballs, which are made by recycled materials at a low cost, are especially desirable eco-friendly media to reclaim wastewater in similar constructed wetland systems.

	Original wastewater	Electrochemical process	Chemical coagulation	Ion exchange	Process reuse standard
COD (mg/l)	80-190	25-45	20-30	5-10	10
COD removal (%)	-	70-85	15-25	45-65	-
Turbidity, NTU	7.5-18.5	11-24	0.6--0.8	0.2-0.4	0.5
Conductivity(μmho/cm.)	1,150-1,750	1,400-1,950	1,800-2,200	0-10	50
Hardness (mg/l)	165-185	-	120-130	0-2	5
Alkalinity (mg/l)	350-460	-	140-160	0-2	5
Fe concentration (mg/l)	0.3-1.2	14-18	0.2-0.5	0-0.05	0.1
SS (mg/l)	45-85	-	1.0	0	0

Ceramic as a tool for the management of basic water quality parameters

Ceramics are also used for the management of water quality parameters. It was mentioned previously that ceramics are associated with the reduction of oxidation-reduction potential (ORP) and pH of the water. Excessive oxygen (O₂) and carbon dioxide (CO₂) in water have adverse effects on aquatic organisms; therefore, their removal is an important task. Though evidence regarding ceramic removal efficiency for O₂ and CO₂ from the aqueous phase is lacking, ceramics show a promising degree of performance in removing CO₂ from the atmosphere. Various separation technologies were considered for the purpose of CO₂ recovery from flue gases. Recently, a new lithium-silicate based ceramic material with exceptional CO₂ absorption characteristics, produced by Toshiba Corporation and Toshiba Ceramics Co. Ltd, Tokyo, Japan, has made a major step forward in environmental protection. This new material can absorb 400 times its own volume of CO₂ at an unmatched rate of absorption, and can do so at room temperature.

Ceramic and de-eutrophication of water

De-eutrophication efficiency of ceramic through the removal of nutrients has recently been documented by various researchers. Dissolved nutrients in water are efficiently removed by the ceramic, as described below.

Removal of NO₃ and NH₄

Nitrate is the most common groundwater contaminant worldwide because it is a stable and highly soluble nitrogen species, easily transported and accumulated in groundwater systems [61]. These properties, coupled with increased anthropogenic discharges of nitrogen-containing compounds from point and non-point sources, have resulted in elevated nitrate concentrations in ground and surface waters. Non-point sources may have a larger impact on groundwater and are associated with agricultural and livestock practices and residential septic tank effluents [61]. Nitrates can be removed either biologically or by physicochemical treatment techniques such as reverse osmosis, ion exchange, and electrodialysis. Conventional physicochemical treatment methods only concentrate nitrate into solutions that still require disposal.

It was observed that application of zeolite ceramic materials substantially reduces the NO₃ and NH₄ in water. Zeolite ceramic acts as a biocarrier and mediates the binding of nitrate and ammonia, which also serves as a source of reserve nitrogen to the immobilized microorganisms [34]. It is interesting to note that the ion exchange and adsorptive properties were observed with this biocarrier when the matrices were heavily colonized with microorganisms or covered with biofilm for extended

periods. Durham et al. proposed Type Z (zeolite-based) biocarriers as having ion-exchange properties and possessing high porosity and a high level of surface area, which provide a suitable medium for microbial colonization (attainable viable cell population 10⁹/g) [34]. Collectively, the surfaces of such a bioreactor provide a suitable matrix for colonization, resulting in proficient volumetric productivities and unparalleled protection of immobilized microorganisms from adverse operating conditions. Novel biocarriers that combine the adsorptive properties of activated carbon with the ion-exchange properties of zeolite-based type Z inorganic oxide biocarriers [62] were developed. These biocarriers, designated Type CZ, possess fundamental properties that heretofore have not been described for available microbial immobilization matrices. Type CZ biocarriers provide an environment that promotes dense microbial colonization and maintains bioreactor productivity by buffering immobilized microorganisms from unfavorable operating conditions. Data demonstrating protection of immobilized bacteria from organic shock loads and extended pH shocks are presented. In addition, bioreactors containing the composite Type CZ biocarriers continue to remove waste stream contaminants during periods of oxygen deprivation and nutrient limitation. Thus, these new zeolite-ceramic biocarriers may represent a major advancement for the full-scale biotreatment of aqueous wastes to remove nitrate and ammonia in industrial applications. The data indicated that biocarriers are also proficient in removing phenol (1,000 ppm) from contaminated water.

Removal of PO₄

Ceramic is similar in the removal process of PO₄ as that of NO₃ and NH₄. It has been proposed that addition of natural zeolite in wastewater treatment evidently reduces the final concentration of phosphate [63,64], but little is known about this mechanism. Here ceramic serves as a support material showing promising effects for the immobilization of microorganisms [65]. The main functions of the support material in removing phosphate are the increase of biomass, and to a lesser extent, the adsorption of phosphate on the material particles. The amount of phosphate removal depended on particle size and type of material used [66]. Hrenovic et al. suggested that the phosphate adsorption capacity of magnesium-exchanged natural zeolite (NZMg) exhibited a higher value than that of the natural zeolite (NZ) and quartz sand (QS), and showed an increasing response with the decreasing of particle size [67] (Table 4). The estimated phosphate adsorption capacity of NZ is in the range of 2 to 15 mg/kg as reported by Lopez-Ruiz et al. [68], and 48.5 mg/kg according to Hrenoviæ et al. [69]. The notably higher potential of phosphate sorption for NZMg is consistent with results reported by Lopez-Ruiz et al. [68]. The absence of exchangeable cations and sorption sites on QS results in a poor phosphate sorption

Table 4. Phosphorus adsorption capacity for different fractions of natural zeolite (NZ), magnesium-exchanged natural zeolite (NZMg), and quartz sand (QS) (Hrenovic et al, 2005).

Material, fraction	Capacity (mg/kg)
NZ	
1) < 0.125 mm	30.0
2) 0.125-0.25 mm	27.5
3) 0.25-0.5 mm	22.5
4) 0.5-1.0 mm	20.0
NZMg	
1) < 0.125 mm	37.5
2) 0.125-0.25 mm	32.5
3) 0.25-0.5 mm	27.5
4) 0.5-1.0 mm	22.5
QS	
1) < 0.125 mm	37.5
2) 0.125-0.25 mm	12.5
3) 0.25-0.5 mm	5.0
4) 0.5-1.0 mm	2.5

capacity (20 mg/kg for Danish QS) compared to those with exchangeable cations [70]. The clinoptilolite material (zeolite) is used to remove ammonium and phosphate ion

from wastewater. However, naturally occurring ceramic materials are a cheaper alternative, have a high phosphate removal capacity, and can be used in many wastewater treatment plants.

Ceramic as a tool for the removal of metals and heavy metals

Conventional methods for removing toxic metal ions from wastewater include chemical reduction, reverse osmosis, co-precipitation, coagulation, complexation, electrodeposition, solvent extraction, and electrochemical treatment. Such processes may be less effective or extremely expensive for the treatment of effluents with low heavy metal concentrations ranging from 10 to 100 g/m³ [71]. Adsorption has been shown to be an economically feasible alternative method for removing heavy metals from wastewater and water supplies [72]. Durham et al. [34] suggested that zeolite has adsorptive and ion exchange properties and serves as a biocarrier. According to Bhattacharyya and Gupta, kaolinite and montmorillonite are efficient adsorbents capable of removing Fe(III), Co(II), and Ni(II) from aqueous solutions [73]. The inorganic sorbents are commonly iron hydroxides and oxyhydroxides [74], aluminium hydroxides and oxides [75], clays, zeolite, calcite, manganese nodule residue [76], perlite [77], peat [78], and activated carbon [79] and are suitable for Cd adsorption. Xu et al. proposed that aluminum-loaded Shirasu-zeolite is

an effective adsorbent for the removal of As(V) from aqueous systems such as drinking water [80]. Recent research has also revealed that different types of ceramics have the promising ability to remove As(III) [81] and Cd [22] from contaminated water. It has been found that 96% of As(III) from an initial concentration of 0.5 mg/l can be effectively removed by a silica ceramic (S-K) adsorbent dose at 90 g/l within 3 h [81]. It was also revealed that As(III) uptake increased with increasing contact time and adsorbent dosage. It was observed that As(III) removal is relatively dependent on pH and temperature variations. High adsorption of As(III) was found at pH 7.5 and at 25 °C. The results suggest that silica ceramic (S-K) is a potential adsorbent for effective removal of As(III) ions from contaminated water. This may be attributed to increased sorbent surface area and availability of more sorption sites resulting from the increased mass of the sorbent, but the amount of metal adsorbed per unit mass of sorbent decreases with increase in sorbent amount [82 – 84]. Particle size also played a significant role in the metal removal process of silica ceramic along with temperature, pH, and contact time. It has also been reported that ground pine cone [85], chitin [82], and manganese nodule residue [76] adsorb Cd from aqueous solutions.

A new high performance adsorbent has been synthesized by a sol-gel processing technique to treat aqueous streams contaminated by Cd and mercury ions [86]. In order to synthesize this adsorbent, the functional precursor (3-mercaptopropyltrimethoxysilane) and the cross-linking agent (tetraethoxysilane) are hydrolyzed and co-condensed in an acidic water and ethanol mixture followed by gelation in a basic solution. This organo-ceramic adsorbent has a high uptake capacity for Cd and mercury ions. This high performance adsorbent synthesized at optimal conditions has uptake capacities of 222 and 1,284 mg/g for Cd and mercury ions, respectively. These uptake capacities are considerably higher than those of covalently functionalized ceramic adsorbents and other functionalized polymeric resins. In addition, the beneficial properties of ceramic adsorbents, such as strong mechanical, thermal, and chemical stabilities have been previously maintained.

On account of the metal removal efficiency of ceramic, it can be emphasized that though metal removal kinetics of ceramic are largely influenced by different intrinsic and extrinsic parameters, ceramic is a potential low-cost, easily available adsorbent for the removal of different metals from contaminated water compared to above-mentioned organic and inorganic materials.

Re-removal of antibiotics and organochlorine pesticide compounds from the aqueous phase

Presently, the information concerning the removal of antibiotics and organochlorine pesticide by ceramic is limited. Our study reported that a 10 g/l ceramic dose

removes 100% and 60% of antibiotics and organochlorine pesticide from the initial concentration of 1 mg/l and 10 mg/l, respectively (unpublished data). Importantly, however, it is unknown which process is responsible for removing these compounds. Until now, we concluded that absorption was the main mechanism, but our research group is conducting further studies to determine the other basic reasons the removal process correlates with the physical and chemical properties of ceramic. A novel nanoparticle-based drug carrier for photodynamic therapy can provide stable aqueous dispersion of hydrophobic photosensitizers, yet preserve the key step of photogeneration of singlet oxygen, necessary for photodynamic action. The potential of using ceramic-based nanoparticles as drug carriers for photodynamic therapy has been demonstrated [87].

Ceramic as a leach resistant

Presently, scientists are able to develop leach-resistant material using hexagonal tungsten bronze as an ingredient, applying hydrothermal methods useful for selective separation of Cs^+ and Sr^{2+} from acidic solutions [88]. It has been demonstrated that such compounds can potentially be converted into leach-resistant ceramics [89]. The conversion of a saturated adsorbent into a leach-resistant ceramic has been termed the ‘cradle-to-grave’ approach in which separation and immobilization are carried out on the same chemical system. This strategy has many attractive aspects for nuclear waste management, including waste volume reduction and simplification of processing since there is no need to undertake combination of a liquid radioactive feed stream with oxide components [90].

Removal of aquatic microbes

Another significant aspect of ceramic is the filtration of microbes in the aqueous phase, discussed previously. Ceramic microfiltration combined with the powdered activated carbon (PAC-MF) technique was tested for organic and microbial control using river water laden with sewerage effluents [91]. It compactly held two filtration zones: (i) the PAC adsorption zone (PAZ); and (ii) the ceramic microfiltration zone in one reactor (Figure 5). Different types of MF modules (Kubota Co., Japan) with a nominal pore size of 0.1 μm were installed in each membrane reactor. One of the modules (denoted hereafter as R1) had 120 ceramic tubes with an outer diameter of 3.3 mm, and the other module (denoted hereafter as R2) had 11 ceramic tubes with an outer diameter of 13 mm. About 20 g/l of PAC with a mean diameter of 151.2 μm (Shirasagi S1, Japan Environmental Chemicals Co., Japan) was put into the PAZ at the beginning of operation. Carbon concentration was naturally balanced between PAZ and MFZ, since PAC in MFZ settled and moved back to the PAZ during the filtration cycle when no aeration was done in MFZ. This system with no PAC drain can supply a high buffering capacity to the micropollutant load fluctuation. Fluxes of R1 and R2 were 1.99 and 2.61 m/day, respectively. Hydraulic retention times (HRT) were 67 and 53 min, respectively, in PAZ and MFZ of R1, and HRTs of PAZ and MFZ in R2 were 60 and 48 min, respectively. The aeration rate of PAZ was 60 l/min throughout the MF filtration, and 50 l/min of aeration rate was applied only during the backwash operation. Selective adsorption of hydrophobic organic compounds onto PAC resulted in

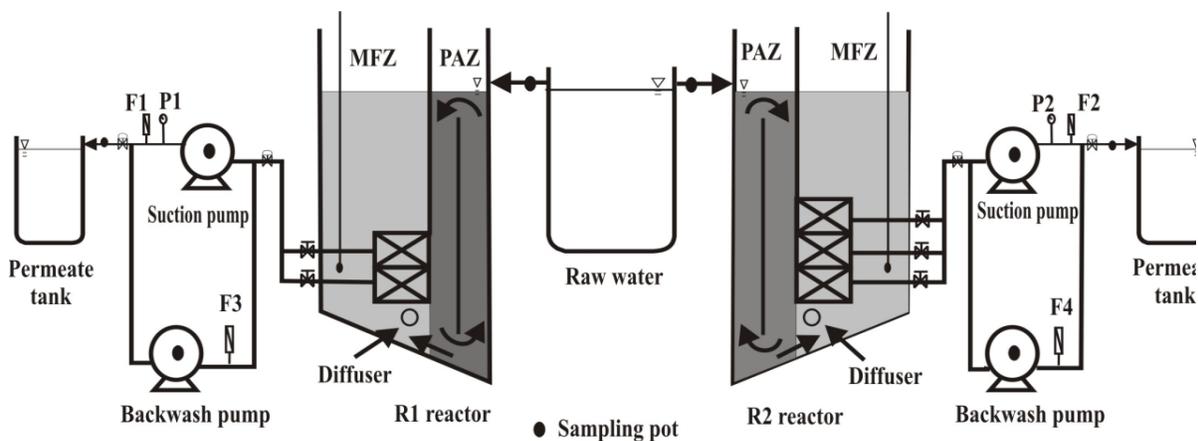


Figure 5. Schematic diagram of PAC-MF [Ceramic microfiltration (MF) combined with powdered activated carbon (PAC)] using two different kinds of ceramic module tubes (Oh et al., 2007).

greater UV₂₆₀ removal of 90.3±3.3 than DOC removal of 80.2±8.6%. Efficient organic control of the PAC-MF considerably decreased chlorine consumption to less than 0.5±0.08 mg/l, and thus THMFP was brought down to less than 8.8±2.2 µg/l in permeate. Furthermore, adsorption or attraction potential of microorganisms by the PAC zone, as well as virus capture in the PAC cake layer, also assisted ceramic microfiltration to remove viruses to less than the detection limit after 60 days of operation. Therefore, the hybrid ceramic microfiltration combined with PAC is a prospective advanced water treatment process capable of simultaneous organic and microbial removal by adsorption and filtration mechanisms (Table 5).

Ceramic: A waste recycling product

Nowadays, without using or using a very small percentage of the principal raw materials general clay and silica, scientists are capable of producing ceramic to apply to waste materials. The term “waste into wealth” is appropriate for ceramic, because it may be produced from the vast amount of sludge generated every day in wastewater treatment plants and can be applied for aquatic environment purification. Sludge disposal by land filling may no longer be appropriated due to the scarcity of land and increasingly stringent environmental controls; incineration may be an alternative solution, but substantial amounts of ash are produced after the firing process, and must be disposed by other means [92]. From these concepts, ceramic materials have recently been produced using ash generated from the combustion of wastewater sludge [93,94]. The production of tiles [95] and bricks by mixing sludge ash and clay has also been studied [96]. Glass-ceramic has been prepared by melting a blend of limestone and ash and further reheating at lower temperatures [97]. When mixed with ashes and/or clay minerals, finely ground glass may act as a flux lowering the firing temperature during the ceramic-making process [98] and reducing leaching by inertization of hazardous constituents [99]. The influence of sewage sludge ashes on the strength of cement mortars has been studied [100], with an enhancement of compressive strength attributed to the pozzolanic properties of the ashes. Ashes can be converted into lightweight aggregates after being

pelletized and fired [101] into asphaltic paving mixes or into water permeable paving bricks like ceramic [102].

Presently, various investigators are trying to deepen the preparation of ceramic products using sludge ashes with several additives after thermal treatment, with the following aims: (i) characterization of ashes and additives by physicochemical methods; (ii) characterization of prepared test probes of ceramic products by density, compressive strength, and water absorption to evaluate their quality; (iii) comparative analysis of the ceramic products prepared taking into account the composition, treatment temperature, and type of additive; and (iv) finding a use of sludge ashes avoiding both the transfer to landfill and the environmental problems derived from the leaching because of the inertization of the more soluble constituents during the thermal treatment.

Conclusion

The 20th century brought unprecedented developments in human history, with major breakthroughs in all scientific and technical fields and a fourfold increase in human population (from 1.6 billion people in 1900 to over 6 billion at present). Therefore, water consumption has multiplied by nine in the same period with significant degradation of aquatic resources. In this context, conservation of aquatic resources is one of the most critical challenges to scientists. As the present discussion concludes, it is obvious that ceramic has potential wide ranging applications for aquatic environment reclamation. It cleans drinking water by removing hazardous compounds and microbial pathogens, and it can also be applied for more effective wastewater treatment. Its endless significance promotes scientists to further research its unrevealed aspects. From an environmental point of view, ceramic contributes a high degree of impacts because it has numerous possible applications. Evolution of ceramic technology has led to the development of a lower-cost, eco-friendly ceramic composition. This attributes to a critical level of conservation to the aquatic environment in various ways. Recently, a number of methods using ceramic have been adopted to treat drinking water. Low-cost ceramic water filters in the form of “ceramic balls” and “ceramic pots” improve drinking water quality at the household level. In addition, ceramic

Table 5. Results of bacteria and viruses removals (Oh et al., 2007)

Samples	Bacteria (CFU/ml)				Viruses (PDU 100/ml)					
	<i>E. coli</i>		TCs		NV-G1		NV-G2		AdV	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Raw water	0.5	0.7	10	13	1.0	9.36	34.7	465	116	371
PAC-MF	ND*		ND		ND	0.29	ND		ND	
Sand filter	0.1	0.2	ND		0.20	9.36	ND	5.78	ND	3.75
O3 BAC	ND		ND		ND		ND		ND	

proves an effective intervention to reduce waterborne diseases [dysentery (61%) and diarrheal disease (>40%)] in developing countries. Ceramics can also potentially contribute to treating wastewater in the modified forms, “bioball of ceramic” and “ceramic membranes,” which are also cost-effective environmental products. New ceramic membrane processes are now used to obtain effluents without contaminants; they recycle process water and recover valuable products, which can be reused in the process itself or in other applications [35,36]. Microfiltration and ultrafiltration membrane technology of ceramic is a recent advanced water treatment approach. The water produced by this advanced water treatment process should be free from microbial pathogens, contain low concentrations of synthetic organic compounds or small amounts of disinfection by-products precursor, and have no harmful heavy metals. As discussed previously, the hybrid membrane system with addition of PAC in ceramic membranes works as a successful final barrier against particles and protozoa, bacteria, and virus-like microbial contaminants. Virus removal could be enhanced through mechanical sieving by membrane or adsorption onto the membrane, as well as by cake layer during microfiltration [103]. The hybrid membrane system of ceramic using coagulation or adsorption is capable of enhancing virus removal [104]. Ceramic membranes can be significantly resistant to membrane deterioration by microbes and surface abrasion by coarse particles circulation. Ceramics significantly remove heavy metals and other toxic metals (Pb, Cd, Hg, As, etc.) from contaminated water bodies. Excess nutrients, as well as antibiotics and organochlorine pesticides of the eutrophicated water in fish and shrimp farming water bodies, are removed by means of the de-eutrophication process of special types of ceramic. Moreover, microwave absorbent ceramics represent a breakthrough in ceramic technology having ability to absorb microwave radiation. These materials have thermal properties unlike conventional ceramic materials. When exposed to microwave radiation, microwave absorbent ceramics heat quickly and predictably.

From the environmental perspective but also directly from the human health perspective, ceramic water treatment is going to occupy a significant part in medical science. Most recently, it has been a matter of research aimed to reproduce the ceramic structure of human bones, where the inorganic part is mainly constituted of porous hydroxyapatite [105 – 107]. In addition, the potential use of ceramic-based nanoparticles as drug carriers for photodynamic therapy has been demonstrated [87].

Due to the above several properties of multipurpose applications and low product cost, we can conclude from the present review that ceramic is an important resource for water purification. Moreover, it plays a significant role in providing a promisingly clean and hazard-free aquatic environment at a low cost without any negative feedback,

along with the other adopted devices and biological components of the environment.

References

1. Cicek N (2003). A review of membrane bioreactors and their potential application in the treatment of agricultural wastewater. *Canadian Biosystems Engineering/Le génie des biosystèmes au Canada*; 45: 6.37-6.49.
2. Gbem TT, Balogun JK, Lawal FA, Annune PA (2001) Trace metal accumulation in *Clarias gariepinus* Teugules exposed to sublethal levels of tannery effluent. *Sci Total Environ*; 271: 1–9.
3. Woodling JD, Brinkman SF, Horn BJ, et al. (2001) Non uniform accumulation of cadmium and copper in kidney's of wild brown trout *Salmo trutta* populations. *Arch Environ Contam Toxicol*; 40: 381–85.
4. USEPA (1997) Non-point pointer No. 7: Fact Sheet (EPA841-F-S-00-001). U.S. Environmental Protection Agency, Office of Science and Technology, Washington, DC.
5. Larson SJ, Capel PD, Majewski MS (1997). Pesticides in Surface Waters. Ann Arbor Press. Chelsea, MI.
6. Liess M, Von Der Ohe PC (2005) Analyzing effects of pesticides on invertebrate communities in streams. *Environmental Toxicology and Chem*; 24: 954–65.
7. Probst M, Berenzen N, Lentzen-Godding A, Schulz R, Liess M (2005) Linking land use variables and invertebrate taxon richness in small and medium-sized agricultural streams on a landscape level. *Ecotoxicology and Env Safety*; 60: 140–46.
8. Tesfamichael AA, Caplan AJ, Kaluarachchi JJ (2005) Risk-cost-benefit analysis of atrazine in drinking water from agricultural activities and policy implications. *Water Resour Res*; 41: W05015, doi:10.1029/2004WR003497.
9. Angelidis MO, Aloupi M (2004) Geochemical study of coastal sediments influenced by river transported pollution: Southern Evoikos Gulf, Greece. *Mar Pollut Bull*; 40: 77– 82.
10. Bowen R, Sandu N (2000) Heavy metal accumulation and anthropogenic impacts on Tolo Harbour, Hong Kong. *Mar Pollut Bull*; 40: 174– 80.
11. Ruiz F (2001) Trace metals in estuarine sediments from southwestern Spanish Coast. *Mar Pollut Bull*; 42: 482–90.
12. Hestekin JA, Bhattacharyya D, Sikdarand SK, Kim BM. Membranes for treatment of hazardous wastewater. (1998) In: Meyers RA, ed. *Encyclopedia of Environmental Analysis and Premeditation*. John Wiley and Sons Inc.
13. Burggraaf AJ, Keizer K. Synthesis of inorganic membranes. (1991) In: Bhave RR, ed. *Inorganic Membranes*. Von Nostrand Reinhold, New York, NY, 10– 63.
14. Bhakta JN, Muneke Y (2008) Role of ecosystem components in Cd removal process of aquatic ecosystem. *Ecol Eng*; 32: 274–80.

15. Sharma BK (2004) *Industrial Chemistry*. Goel Publishing House, Meerut, India.
16. Kainer H, Reh H (1991) High-performance ceramics. III. The products: catalysts (part II), *Interceramics*; 40: 99–108.
17. Church JS, Trimm LD, Cant NW (1993) Stabilization of aluminas by rare earth and alkaline earth ions. *Appl Catal*; 101: 105–16.
18. Kaneko S, Tsukagoshi K, Uchida S, Kinoshita M, Tokuda K (1998) Development of PFBC commercial plant with high temperature ceramic filters. *Mitsubishi Heavy Ind Tech Rev (English translation)*; 35: 48–51 (Original in Japanese).
19. Zhang G, Yang J, Ohji T (2001) Fabrication of porous ceramics with unidirectionally aligned continuous pores. *J Am Ceram Soc*; 84: 1395–97.
20. Ota T, Imaeda M, Takase T, Kobayashi K, Kinoshita N, Hirashita T, Miyazaki H, Hikiki Y, et al. (2000) Porous titania ceramic prepared by mimicking silicified wood. *J Am Ceram Soc*; 83: 1521–32.
21. Suzuki Y, Morgan PED, Ohji T (2000) New uniformly porous CeZrO₃/MgO composites with three-dimensional network structure from natural dolomite, *J Am Ceram Soc*; 83: 2091–93.
22. Salim M, Son LT, Munekage Y (2008) Silica ceramic as potential absorbent of cadmium removal from aqueous solutions. *Res J of Env Sci*; 2: 185 – 96.
23. Zhao DL, Feng SJ, Chen CL, Chen SH, Xu D, Wang XK (2008) Adsorption of thorium(IV) on MX-80 bentonite: Effect of pH, ionic strength and temperature. *Appl C Sci*; 41: 17–23.
24. United Nations Millennium Project (2006) at <http://www.unmillenniumproject.org/goals>.
25. WHO (2004) Water, Sanitation and Hygiene Links to Health: Facts and Figures at <http://www.who.int>.
26. Prüss A, Kay D, Fewtrell L, Bartram J (2002) Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Env H Persp*; 110: 537–42.
27. WHO/UNICEF (2000) *Global Water Supply and Sanitation Assessment Report*, Geneva.
28. Van Halem D, van der Laan H, Heijman SGJ, van Dijk JC, Amy GL (2008) Assessing the sustainability of the silver-impregnated ceramic pot filter for low-cost household drinking water treatment. *Phy and Chem of the Earth*. (In press).
29. Lantagne DS (2001a) Investigation of the potters for peace colloidal silver impregnated ceramic filter, Report 1: Intrinsic Effectiveness. Alethia Environmental, Allston.
30. Van Halem SGJ, Heijman H, Soppe AIA, van Dijk JC, Amy GL (2007) Ceramic silver-impregnated pot filters for household drinking water treatment in developing countries: material characterization and performance study. *W Sci and Tech: W Sup*; 7: 9–17.
31. Lantagne DS (2001b) Investigation of the potters for peace colloidal silver impregnated ceramic filter, Report 2: Field Investigations. Alethia Environmental, Allston.
32. Campbell E (2005) Study on Life Span of Ceramic Filter Colloidal Silver Pot Shaped (CSP) Model, Managua, Nicaragua.
33. UNICEF/WSP (2007) *Improving Household Drinking Water Quality: Use of Ceramic Water Filters in Cambodia*. Water and Sanitation Program (WSP).
34. Durham DR, Marshall LC, Miller JG, Chmurny AB (1994a) Characterization of inorganic biocarriers that moderate system upsets during fixed-film biotreatment processes. *Appl Environ Microbiol*; 60: 3329–35.
35. Scott ICS, Hughes R (1996) *Industrial Membrane Separation Technology*. Kluwer Academic Publishers.
36. Uhlhorn RJ, Keizer K, Burggraaf AJ (1992) Synthesis and gas separation properties of microporous membranes. *J Membr Sci*; 66: 271.
37. Jones BF, Galan E. Sepiolite and palygorskite. (1998) In: Bailey SW, ed. *Reviews in Mineralogy, Hydrous Phyllosilicates (Vol. 19)*. Mineralogical Society of America, Washington, 631–74.
38. Messaoudi L, Larbot A, Rafiq M, Cot L (1995) Mise au point d'une membrane de microfiltration sur supports tubulaires à base d'une argile marocaine. *Ind Ceram Ver*; 12: 831–35.
39. Belouatek A, Benderdouche N, Addou A, Ouagued A, Bettahar N (2005) Preparation of inorganic supports for liquid waste treatment. *J Micro Meso Mate*; 85: 163–68.
40. Belouatek A, Ouagued A, Belhakem M, Addou A (2008) Filtration performance of microporous ceramic supports. *J Biochem Biophys Methods*; 70: 1174–79.
41. Benito JM, Sánchez MJ, Pena P, Rodríguez MA (2007) Development of a new high porosity ceramic membrane for the treatment of bilge water. *Desalination*; 214: 91–101.
42. Jing SR, Lin YF, Lee DY, Wang TW (2002) Microcosm wetland for wastewater treatment with different hydraulic loading rates and macrophytes. *J Environ Qual*; 31: 690–96.
43. Kadlec RH, Reddy KR (2001) Temperature effects in treatment wetlands. *W Environ Res*; 73: 543–57.
44. Karathanasis A, Potter C, Coyne M (2004) Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. *Ecol En*; 20: 157–69.
45. Karim M, Manshadi F, Karpiscak M, Gerba C (2004) The persistence and removal of enteric pathogens in constructed wetlands. *Water Res*; 38: 1831–37.
46. Ran N, Agami M, Oron G (2004) A pilot study of constructed wetlands using duckweed for treatment of domestic primary effluent in Israel. *Water Res*; 38: 2241–48.
47. Chen TY, Kao CM, Yeh TY, Chien HY, Chao AC (2006) Application of a constructed wetland for industrial wastewater treatment: A pilot-scale study. *Chemosphere*; 64: 497–502.
48. Baus C, Schaber K, Gassiot-Pintori I, Braun A (2002) Separation degradation of organic pollutants in aqueous

- system by pervaporation vacuum-ultraviolet-photolysis. *Sep Puri Technol*; 28: 125–140.
49. Heng S, Yeung KL, Julbe A, Ayril A, Schrotter J-C (2008) Preparation of composite zeolite membrane separator/contactor for ozone water treatment. *Micro and Meso Mate*; 115: 137–46.
50. Pikkarainen AT, Judd SJ, Jokela J, Gillberg L (2003) Pre-coagulation for microfiltration of an upland surface water. *Water Res*; 38: 455–65.
51. Mo L, Huang X (2003) Fouling characteristics and cleaning strategies in a coagulation–microfiltration combination process for water purification. *Desalination*; 159: 1–9.
52. Konieczny K, Bodzek M, Rajca M (2006) A coagulation–MF system for water treatment using ceramic membranes. *Desalination*; 198: 92–101.
53. Beck EC, Giannini AP, Ramirez ER (1974) Electrocoagulation clarifies food wastewater. *Food Technol.*; 28 (2) 18
54. Biwyk A (1980) Electrocoagulation of biologically treated sewage. In: 35th Purdue Indust. Waste Conf., Lafayette, Indiana.
55. Horan NJ (1990) *Biological Wastewater Treatment Systems: Theory and Operation* John Wiley & Sons, New York. 310p.
56. Groterud O, Smoczynski L (1986) Phosphorus removal from water by means of electrolysis. *Water Research*; 20: 667–669.
57. Weintraub MH, Gealer R, Golovoy LA, Dzieciuch MA, Durham H (2006) Development of electrolytic treatment of oily wastewater. *Environmental Progress*; 2: 32 – 37.
58. Ramirez ER (1981) Ramirez, Physicochemical treatment of rendering wastewater by electrocoagulation. In: 36th Purdue Indust. Waste Conf., Lafayette, Indiana.
59. Sheng H Lin, Chi F Peng (1996) Continuous treatment of textile wastewater by combined coagulation, electrochemical oxidation and activated sludge. *Water Research*; 30: 587–592.
60. Lin SH, Lin CS (1998) Reclamation of wastewater effluent from a chemical fiber plant. *Desalination*; 120: 185–195.
61. Kapoor A, Viraraghavan T (1997) Nitrate removal from drinking water - Review. *J of Env Eng-ASCE*; 123: 371–80.
62. Durham DR, Marshall LC, Miller JG, Chmurny AB (1994b) New composite biocarriers engineered to contain adsorptive and ion-exchange properties improve immobilized-cell bioreactor process dependability. *Appl and Env Micro*; 60: 4178–81.
63. Sakadevan K, Bavor HJ (1998) Phosphate adsorption characteristics of soils, slags and zeolite. *W Res*; 32: 393–99.
64. Venglovsky J, Pacajova Z, Sasakova N, Vucemilo M, Tofant A (1999) Adsorption properties of natural zeolite and bentonite in pig slurry from the microbiological point of view. *Vet Med*; 44: 339–44.
65. Shindo S, Takata S, Taguchi H, Yoshimura N (2001) Development of novel carriers using zeolite and continuous ethanol fermentation with immobilized *Saccharomyces cerevisiae* in a bioreactor. *Biotechnol Lett*; 23: 2001–4.
66. Hrenoviae J, Tibljaš D, Büyüküngör H, Orhan Y (2003a) Influence of support materials on phosphate removal by the pure culture of *Acinetobacter calcoaceticus*. *F Tech Biotech*; 41(4): 331–38.
67. Hrenoviae J, Tibljaš D, Orhan Y, Büyüküngör H (2005) Immobilisation of *Acinetobacter calcoaceticus* using natural carriers. *Water SA*; 31: 261–66.
68. Lopez-Ruiz JL, Lopez-Alcala JM, Torres-Fernandez JCG, Rodriguez-Fuentes. Elimination of phosphates by natural zeolites. (1997) In: Colella C, Mumpton FA, eds. 5th Int. Conf. on the Occurrence, Properties, and Utilization of Natural Zeolites – Ischia. De Frede, Napoli, 209–11.
69. Hrenoviae J, Büyüküngör H, Orhan Y (2003b) Use of natural zeolite to upgrade activated sludge process. *Food Technol. Biotechnol*; 41: 157–65.
70. Arias CA, Del Bubba M, Brix H (2001) Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. *W Res*; 35: 1159–68.
71. Poon CPC. Removal of Cadmium from Waste Waters. (1986) In: Mislin H, Ravera O, eds. *Cadmium in the Environment*. Birkha User, Basel, Switzerland, 46–55.
72. Dakiky M, Khamis M, Manassra A, Mer'eb M, (2002) Selective adsorption of chromium(VI) in industrial wastewater using low-cost abundantly available adsorbents. *Adv Environ Res*; 6: 533–40.
73. Bhattacharyya KG, Gupta SS, (2008) Kaolinite and montmorillonite as adsorbents for Fe(III), Co(II) and Ni(II) in aqueous medium. *Appl C Sci*; 41: 1–9.
74. Mustafa G, Singh B, Kookana RS, (2004) Cadmium adsorption and desorption behaviour on goethite at low equilibrium concentrations: effects of pH and index cations. *Chemosphere*; 57: 1325–33.
75. Bell RR, Saunders GC (2005) Cadmium adsorption on hydrous aluminium (III) oxide: Effect of adsorbed polyelectrolyte. *Appl Geochem*; 20: 529–36.
76. Agrawal A, Sahu KK (2006) Kinetic and isotherm studies of cadmium adsorption on manganese nodule residue. *J Hazard Mater*; B137: 915–24.
77. Hasan S, Krishnaiah S, Ghosh TK, Viswanath DS, Boddu VM (2006) Adsorption of divalent cadmium (Cd(II)) from aqueous solutions onto chitosan-coated perlite beads, *Ind Eng Chem Res*; 45: 5066–77.
78. Gabaldon C, Marzal P, Alvarez-Hornos FJ (2006) Modelling Cd(II) removal from aqueous solutions by adsorption on a highly mineralized peat. Batch and fixed-bed column experiments. *J Chem Technol Biotechnol*; 81: 1107–12.
79. Jusoh A, Shiung LS, Ali N, Noor MJMM (2007) A simulation study of the removal efficiency of granular

- activated carbon on cadmium and lead. *Desalination*; 206: 9-16.
80. Xu YH, Nakajima T, Ohki A (2002) Adsorption and removal of arsenic from drinking water by aluminum loaded Shirasu-zeolite. *J Hazard Mat*; B92: 275-87.
81. Salim M, Munekage Y, Naing KM (2007) Arsenic(III) Removal from contaminated water using silica ceramic: A Batch Adsorption Study. *J of Appl Sci*; 7: 2314 -20.
82. Benaissa H (2006) Screening of New Sorbent Materials for Cadmium Removal from Aqueous Solutions. *J of Hazard Mate*; B132: 189-95.
83. Nouri L, Ghodbane I, Hamdaoui O, Chiha M (2007) Batch sorption dynamics and equilibrium for the removal of cadmium ions from aqueous phase using wheat Bran. *J Hazard Mate*; 149: 115-25.
84. Ghodbane I, Nouri L, Hamdaoui O, Chiha M (2008) kinetic and equilibrium study for the sorption of cadmium(II) ions from aqueous phase by eucalyptus bark. *J Hazard Mate*; 152: 148-58.
85. Izanloo H, Nasser S (2005) Cadmium removal from aqueous solutions by ground pine cone. *Iran J Env Health Sci Eng*; 2: 33-42.
86. Lee JS, Gomez-Salazar S, Tavlarides LL (2001) Synthesis of thiol functionalized organo-ceramic adsorbent by sol-gel technology. *Reac and Funct Poly*; 49: 159-72.
87. Roy I, Ohulchanskyy TY, Pudavar HE, Bergey EJ, Oseroff AR, Morgan J, Dougherty TJ, Prasad PN, et al. (2003) Ceramic-based nanoparticles entrapping water-insoluble photosensitizing anticancer drugs: A Novel Drug-Carrier System for Photodynamic Therapy. *Am Chem Soc*; 125: 7860-65.
88. Luca V, Griffith CS, Chronis H, Widjaja J, Li H, Scales N (2004a) Cs^+ and Sr^{2+} ion-exchange properties of microporous tungstates. *Mate Res Society Symp Pro*; 807: 309-14.
89. Luca V, Drabarek E, Griffith CS, Chronis H, Foy J (2004b) The immobilization of cesium and strontium in ceramic materials derived from tungstate sorbents. *Mate Res Society Symp Pro*; 807: 303-8.
90. Griffith CS, Sebesta F, Hanna JV, Yee P, Drabarek E, Smith ME, Luca V (2006) Tungsten bronze-based nuclear waste form ceramics. Part 2: Conversion of granular microporous tungstate-polyacrylonitrile (PAN) composite adsorbents to leach resistant ceramics. *J of Nu Mate*; 358: 151-63.
91. Oh HK, Takizawa S, Ohgaki S, Katayama H, Oguma K, Yu MJ (2007) Removal of organics and viruses using hybrid ceramic MF system without draining PAC. *Desalination*; 202: 191-98.
92. Tay JH (1987) Bricks manufactured from sludge. *J of Env Eng*; 113: 278-84.
93. Endo H, Nagayoshi Y, Suzuki K (1997) Production of glass ceramics from sewage sludge, *W Sci and Tech*; 36: 235-41.
94. Merino I, Arévalo LF, Romero F (2007) Preparation and characterization of ceramic products by thermal treatment of sewage sludge ashes mixed with different additives. *Waste Man*; 27: 1829-44.
95. Lin DF, Luo HL, Sheen YN (2005) Glazed tiles manufactured from incinerated sewage sludge ash and clay. *J of the Air and Waste Man Ass*; 55: 163-72.
96. Anderson M (2002). Encouraging prospects for recycling incinerated sewage sludge ash (ISSA) into clay-based building products. *J of Che Tech and Biot*; 77: 352-60.
97. Suzuki S, Tanaka M, Kaneko T, et al. (1997) Glass-ceramic from sewage sludge ash. *J of Mate Sci*; 32: 1775-79.
98. Smith AS (2004) To demonstrate commercial viability of incorporating ground glass in bricks with reduced emissions and energy savings. *The Waste & Res Act Progr*; ISBN: 1-84405-101-3.
99. Li ChT, Huang YJ, Huang KL, Lee WJ (2003) Characterization of slags and ingots from the vitrification of municipal solid waste incineration ashes. *Ind & Eng Chem Res*; 42: 2306-13.
100. Monzó J, Payá J, Borrachero MV, Peris-Mora E, (1999) Mechanical behavior of mortars containing sewage sludge ash (SSA) and Portland cements with different tricalcium aluminate content. *Cem and Concre Res*; 29: 87-94.
101. Kato H, Takesue M (1984) Manufacture of artificial fine lightweight aggregate from sewage by multi-stage stream kiln. *Int Conf of Recycling*, Berlin, Germany, 459.
102. Al Sayed MH, Madany IM, Buali ARM (1995) Use of sewage sludge ash in asphaltic paving mixes in hot regions. *Constr and Buil Mate*; 9: 19-23.
103. Jacangelo JG, Adham SS, Laine JM (1995) Mechanism of *Cryptosporidium*, *Giardia*, and MS2 virus removal by MF and UF. *Am W Wor Ass*; 87: 107-21.
104. Matsushita T, Matsui Y, Shirasaki N, Kato Y (2004) Effect of membrane pore size, coagulation time, and coagulant dose on virus removal by a coagulation-ceramic microfiltration hybrid system. *Proc. EDS Conf. on MDIW Production*. L'aquila, Italy, 15-17.
105. Engin NO, Tas AC (2000) Preparation of porous $Ca_{10}(PO_4)_6(OH)_2$ and $\beta-Ca_3(PO_4)_2$ bioceramics. *J Am Ceram Soc*; 83: 1581-84.
106. Slosarczyk A (1989) Highly porous hydroxyapatite material. *Powder Metall Int*; 21: 24-25.
107. Byrd HS, Hoba PC, Shewmake K (1996) Augmentation of the craniofacial skeleton with porous HA granules. *Plast Reconstr Surg*; 97: 338-44.