Eliminating turbidity in drinking water using the mucilage of a common cactus

Thomas Pichler, Kevin Young and Norma Alcantar

ABSTRACT

Diced Nopal cladodes (pads) have been used for the treatment of turbid natural spring waters in Latin America. To investigate this phenomenon, the mucilage derived from the species *Opuntia ficus-indica* was investigated. Comparison against the commonly used synthetic flocculant, aluminium sulfate ($Al_2(SO_4)_3$) demonstrated the high efficiency of the cactus to eliminate turbidity. The mucilage extract increased particulate settling rates 330% compared with aluminium sulfate, at dosage concentrations of 3 mg L^{-1}, while its performance was equivalent at doses 0.3% of the required $Al_2(SO_4)_3$ concentration. The cactus mucilage, which consists of complex carbohydrates and sugars, has unique surface activity characteristics that make it an ideal candidate for enhancing dispersion properties, creating emulsifications, and for reducing the surface tension of high polarity liquids. These results indicated that the Nopal cactus mucilage has the potential to be the basis for a new 'green' technology, which is environmentally benign and cost-effective.

Key words | cactus, flocculant, green chemistry, natural material, Nopal, Opuntia, water remediation

Thomas Pichler
Geochemistry and Hydrogeology,
University of Bremen,
28359 Bremen,
Germany

Kevin Young
Norma Alcantar (corresponding author)
Department of Chemical and Biomedical Engineering,
University of South Florida,
Tampa, FL 33620,
USA
E-mail: *alcantar@eng.usf.edu*

INTRODUCTION

Turbidity, which is caused by fine suspended particles of clay, silt, organic and inorganic matter, plankton and other microscopic organisms, is an important indicator to evaluate the safe use of water for human consumption (Howard *et al.* 2001). It is more than an aesthetic concern because contaminants such as bacteria, viruses and parasites (e.g., *Giardia* and *Cryptosporidium*) can attach themselves to the suspended particles. Thus as turbidity rises, so does the risk of gastrointestinal illness and infectious diseases (Schwartz *et al.* 2000). Turbidities less than 5 NTU (nephelometer turbidity units) are considered to be 'safe' by most consumers (WHO 2008). However, the World Health Organization (WHO) unofficially considers 0.1 NTU to be the maximum turbidity allowed for disinfection (WHO 2008), because suspended particles promote the growth of microorganisms in water and therefore decrease the effectiveness of the disinfection procedure (Jakubowski *et al.* 1996). Thus, turbidity reduction can vastly improve the effectiveness of disinfection methods.

WHO currently recognizes four different categories of turbidity–reduction mechanisms for particulates and bacteria as potential areas for investigation (Sobsey 2006): (1) settling or plain sedimentation, (2) filtering with fibers, cloth, or membranes, (3) filtering with granular media, and (4) slow sand and biosand filters. The first process has the advantage of being a low-cost way to reduce suspended solids and some microbes, and is generally recommended as pre-treatment before disinfection. Unfortunately, sedimentation will not remove clays and smaller solid particles, nor will it remove smaller microbes (Howard *et al.* 2001). Also, the settling length for some solids can be as long as 2 days (Howard *et al.* 2001). The use of membrane filters, granular media, and slow sand and biosand filters includes filters made of compressed or cast fibers like cellulose papers or synthetic polymer filters, spun threads or woven fabrics. Generally, filters are placed over a water source and are used widely for point-of-use water supply systems. These filters do not always remove all suspended solids or all microbial contamination or may require

doi: 10.2166/ws.2012.126

fabrication by the user, initial education and training in fabrication, and frequent backwashing (Sobsey 2006). Another process to treat biological contamination of turbid water in the home may use inactivation mechanisms such as UV radiation from lamps or sunlight. However, this situation is considered a challenge due to the effect of turbidity in decreasing the access of UV radiation to microbes.

This study seeks to uncover an innovative new low-cost technology based on the mucilage extracted from a common cactus (*Opuntia ficus-indica (OFI)*) to be implemented for turbidity reduction in drinking water. While initially the focus was on its application in rural and underdeveloped areas, the results of this study indicate that this technology may have the potential to be implemented in large-scale water treatment systems, particularly when considering the trend towards 'green' chemistry solutions in chemical engineering (Anastas & Warner 1998). The cactus *OFI*, (commonly referred to as Nopal or prickly pear) is found in arid and semi-arid regions in multiple countries including Mexico and the USA. It owes its ability to store large amounts of water to its mucilage which swells when in contact with water (Sáenz 1997). The mucilage, which occurs in the cladode or cactus pad (Figure 1), was extracted and evaluated for uses including dietary fiber (Sáenz 1997), medicinal (Fernandez *et al.* 1994; Cardenas *et al.* 1998), digestive (El Kossori *et al.* 2000; Galati *et al.* 2002), lime mortar additive (Cárdenas *et al.* 1998), emulsifying agents (Garti 1999) and as a flocculant (McGarvie & Parolis 1979; Young *et al.* 2006). Diced Nopal cladodes have been used for centuries in Latin America as a natural technology for the rapid flocculation of turbid natural spring waters (Sáenz *et al.* 2004), but a scientific baseline was never provided for this phenomenon.

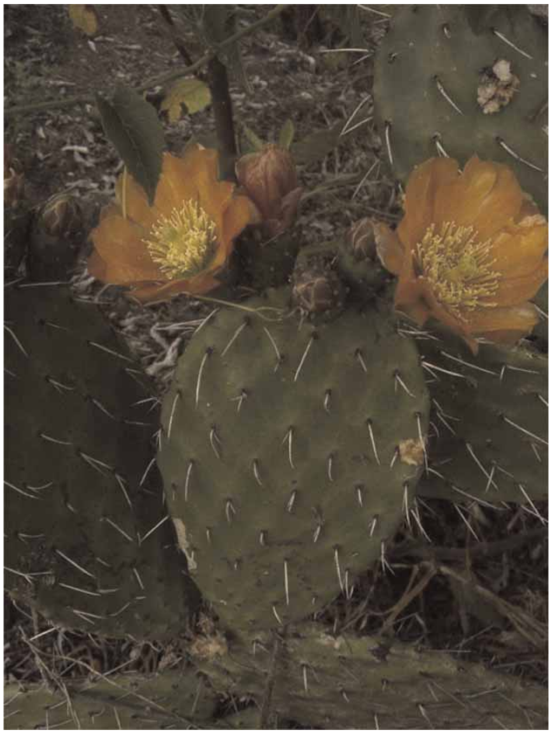

Figure 1 | Photograph of a *Opuntia ficus-indica* pad.

MATERIALS AND METHODS

The *OFI* mucilage (i.e., prickly pear or Nopal) is a thick substance, comprised of proteins, monosaccharides and polysaccharides, grows abundantly and is inexpensive and edible. Nopal pads are formed of complex carbohydrates that have the ability to store and retain water, allowing these plants to survive in extremely arid environments. Nopal mucilage is a neutral mixture of approximately 55 high-molecular weight sugar residues composed basically of arabinose (67.3%), galactose (6.3%), rhamnose (5.4%) and xylose (20.4%) (Techtenberc & Mayer 1981; Radia *et al.* 1988; Cardenas *et al.* 2008). Our chemical analysis is consistent with the aforementioned references. It also contains several ionic species (Radia *et al.* 1988). In fact, its composition gives the *OFI* the capacity to interact with metals, cations and biological substances (Benson 1982). Cactus mucilage swells but does not dissolve in water (McGarvie & Parolis 1979). Natural gums have unique surface activity characteristics which make them ideal candidates for enhancing dispersion properties, creating emulsifications and for reducing the surface tension of high polarity liquids.

Flocculation experiments

The following were used in the jar and cylinder tests: aluminium silicate (hydrated), also known as kaolin, (Fisher Scientific S71954), sodium hydroxide (Acros Organics 206060010), aluminium sulfate, $Al_2(SO_4)_3{\cdot}18H_2O$ (Fisher

Scientific S70495). Equipment included: Minimix Laboratory Mixer/Jar Test Apparatus manufactured by ECE Engineering (ECE MLM4) and a Micro 100 Turbidimeter (HF Scientific) able to measure 0 to 1000 NTU (accuracy: ± 2% and reading + 0.01 NTU). All chemicals used in this work were laboratory grade or higher. Kaolin suspensions were produced using milliQ water and allowed to sit for 24 h before use. The pH of the suspensions was adjusted to 7 with NaOH. A control sample was run in every experiment without the mucilage dosage and a sample dosed with aluminium sulfate, which is a commercial flocculant, for comparison (Bishop *et al.* 1991; Eyring *et al.* 2002).

For the cylinder tests, 5 g L^{-1} kaolin solutions were added to 100 mL graduated cylinders fitted with a glass stopper following common experimental procedures (Deng *et al.* 2003; Mishra *et al.* 2003). The pH of the kaolin slurries was kept neutral (pH = 7). The fall in liquid–solid interface was recorded with time, and rates were taken from the linear decay portion of settling. High concentrations of kaolin were chosen as they mimic mud-like conditions and make the interface visible. The cylinders were then capped and inverted 10 times to ensure uniform suspensions with the desired dose of flocculant (either alum or mucilage). Three cactus extracts (gelling extract (GE), non-gelling extract (NE), combined extract (GE + NE)) and aluminium sulfate (alum, $Al_2(SO_4)_3$) were dosed into kaolin slurries in triplicate sets at concentrations ranging from 0.01 to 10 mg L^{-1} of the flocculating agent. Those solutions were compared against control solutions of kaolin, which did not contain any flocculating agent. Each cylinder was placed on a level surface and flocs immediately began to form and settle. The height of the visible solid/liquid interface was then recorded with time until the flocs were fully settled. For the jar tests, 0.5 g L^{-1} kaolin suspensions were produced. Initially, identical volumes of control solutions and flocculant-free suspensions were quickly filled in each compartment. The experimental error for the cylinder tests is ± 2 cm min^{-1}.

Residual turbidity tests were carried out according to standard jar test procedures (Rath & Singh 1997; Kan *et al.* 2002; Singh *et al.* 2003). Mixing was started at 100 rpm while the desired flocculant dose was added to the jars and continued for approximately 2–5 min depending on the experiment. Subsequently the speed was reduced to 20 rpm for 5 min and then stopped. After a settling period of 30 min 30 mL-samples of the supernatant were collected from each compartment and poured into previously acid-cleaned turbidity meter cuvettes. Supernatant turbidity measurements were also recorded in triplicate.

Mucilage cactus extraction

Three types of mucilage were extracted. Cactus plants were purchased from Living Stones Nursery, Tucson, Arizona. Following a modified version of the method by Goycoolea & Cárdenas (2003), a GE and a NE were obtained. A combined version (CE) consisting of GE & NE was obtained using the method of Medina-Torres *et al.* (2000). All mucilage types extracted were stored dry and at room temperature. Changes to the above procedures were made in order to maximize mucilage extraction and chemical consumption as follows: for the extraction of NE and GE, cactus pads were cleaned and boiled in milliQ water until they became tender (approximately 20 min). The soft pads were then liquefied in a blender. The pH of the resulting suspension was then neutralized and the solids and liquid supernatant were separated in a centrifuge at 4,000 rpm. The supernatant was collected, mixed with 1M-NaCl solution (10:1 ratio), filtered and precipitated with 1:2 ratio of pulp to acetone to produce the NE extract. The acetone was then decanted and the precipitate washed with a 1:1 volume ratio of precipitate to isopropanol. The resulting NE precipitate was air dried on a watch glass at room temperature. In order to separate the gelling portion, the centrifuged precipitates were mixed with 50 mL of 50 mM NaOH. The suspension was stirred for 10 min and the pH adjusted with HCl to 2. The suspension was centrifuged and the solids again resuspended in water while the pH was adjusted to 8 with NaOH. The suspension was then filtered and the solids were washed following the same procedure as for the NE extract. For the combined extract, the initial blend was centrifuged and the supernatant was separated and pH adjusted to 8 with NaOH, washed with acetone and isopropanol as described above and finally air-dried. On average, for each pad of around 300 g wet weight, approximately 1.5–2 g of dry powder was obtained.

Mucilage characterization

Raman Spectroscopy (RS) is adept at determining functionalization of chemical structures, especially those of organic compounds, from their vibrational spectra. Samples analyzed with RS can exist in either the solid, liquid or gas states (Nyquist & Kagel 1977). The samples of GE, NE and CE analyzed were in the solid phase (powder form), a condition that RS is particularly suited for as conventional Infrared Spectroscopy (IR) provides water band interference (Nyquist & Kagel 1977). The mucilage samples were loaded in a capillary tube, inserted in the Raman Spectrometer, and their vibrational spectra were analyzed. The system was purged with nitrogen to reduce interference from ambient contaminants. The mucilage samples were loaded and sealed in 1 mm diameter capillary tubes and inserted into the Raman Spectrometer. Raman spectra were recorded with a computerized Jobin-Yvon Ramanor HG2S double monochromator with a Spectra Physics Model 2017 argon ion laser at 514.5 nm laser radiation. The power was 400 mW at the laser head and the spectral resolution was nearly 4 cm^{-1}. The scattered light, detected at a right-angle from the incident light, was collected on the photocathode of a cooled photomultiplier (EMI) and amplified by a DC operational amplifier.

RESULTS AND DISCUSSION

Mucilage flocculation efficiency

Three different extracts (GE, NE and CE) of mucilage from *OFI* were investigated to remove suspended solids (turbidity). The GE was found to be the best performer with respect to suspended solids removal as determined by standard cylinder tests with 5 g L^{-1} neutral kaolin slurries at flocculant doses of 3 mg L^{-1} (Figure 2). Flocculant doses of 3 mg L^{-1} were chosen because this concentration is comparable with the typical alum concentration used in water treatment applications (Trinh & Kang 2011). The slope of each curve gives the rate of settling. GE out-performed NE, CE and $Al_2(SO_4)_3$, a widely used chemical flocculant and benchmark for this study. The control (without a flocculant dose) settled at rates ranging from −0.53 to 0.57 cm min^{-1}.

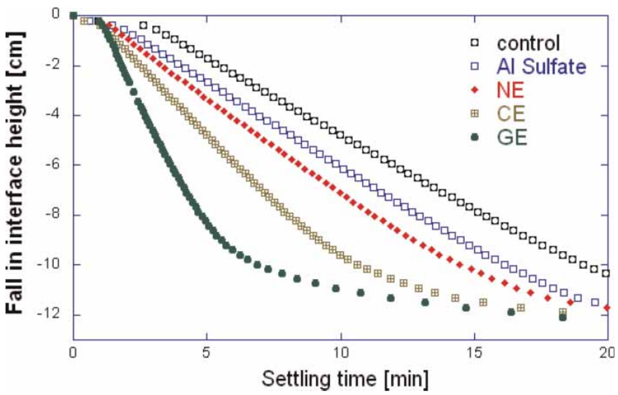

Figure 2 | Flocculation rates comparison at 3 mg L^{-1} flocculant dosages. The concentration of the kaolin solution is 5 g L^{-1}. Kaolin was used to mimic contaminated water containing a high concentration of particulates. The control refers to the settling of a solution without flocculant. A commercial flocculant was used to establish a base line ($Al_2(SO_4)_3$) and to compare the efficiencies of the three mucilage extracts, NE, CE and GE. The GE performed the best.

NE and CE settled at rates of −0.7 and −1.1 cm min^{-1}, respectively. GE performed at rates of approximately 2.2 cm min^{-1}, whereas the alum performed at rates close to 0.67 cm min^{-1}. Thus, the GE performed more than 3 times faster than the benchmark alum ($Al_2(SO_4)_3$).

The effectiveness of a flocculant is directly related to the size of the flocs formed. Larger flocs fall faster under the influence of gravity, leading to a faster settling rate. Larger flocs require more restructuring of the settled solids in the graduated cylinders, leading to a shorter linear settling portion. As the large flocs pile up they begin to rearrange, leading to an earlier removal from the linear settling scheme. Examining the data in Figure 2, it is obvious that GE performs as a faster flocculant due to its ability to form larger flocs than NE, CE and alum, as is evidenced by its relatively early departure from the linear scheme (5 min in comparison with the control's 21 min). Figure 3 shows the effect of GE dose from 0.01 to 4 g L^{-1} on the settling rates. The rates vary from −0.66 at low dose to −2.64 cm min^{-1}. That is, the GE dose of 0.01 mg L^{-1} performed at a rate equivalent to $Al_2(SO_4)_3$ dosed at 300 times that concentration (3 mg L^{-1}), proving that the GE is a more effective flocculant than the popular alum with respect to settling rate, and requiring the use of less material to obtain the same results (Figure 4).

Residual turbidity measurements of jar tests also showed that GE, CE and NE improved settling rates of

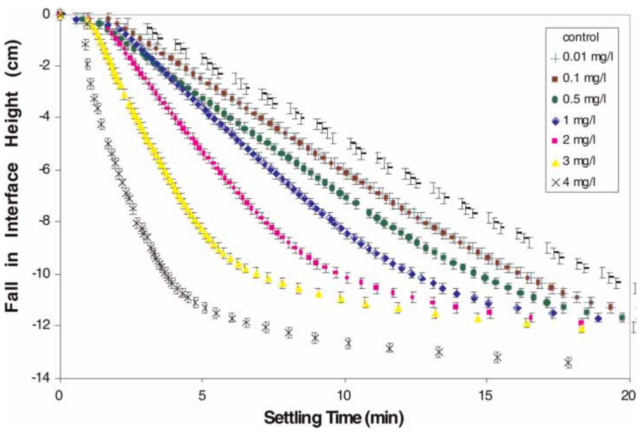

Figure 3 | The effect of dose on the settling rates of GE. The concentrations range from 0.01 to 4 mg L^{-1}. Kaolin is used to determine the performance of this flocculant against particulates. The control is the first curve on the right. The initial kaolin concentration is 5 g L^{-1}.

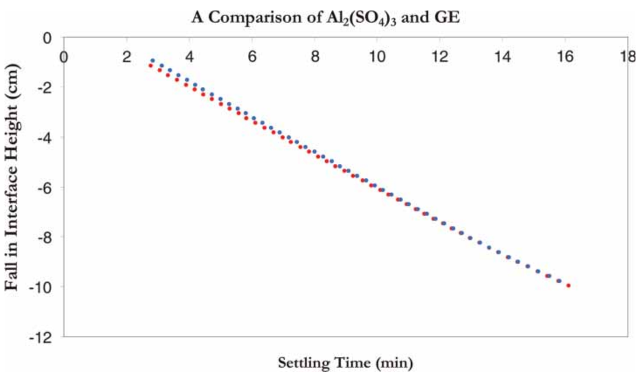

Figure 4 | Equivalent rate of performance between GE and alum shows that the GE is a more effective flocculent because it requires much less material to obtain the same settling rates. GE was dosed at 0.01 mg L^{-1}. $Al_2(SO_4)_3$ was dosed at 300 times that concentration (3 mg L^{-1}). Reprinted with permission (Young *et al.* 2006).

particulates. In addition, higher mucilage doses also increased the settling rates as attested in the cylinder tests from above. The turbidity values were similar to alum at low doses (0.01–0.1 mg L^{-1}) ranging from 30–45 NTU (Figure 5). However, at higher doses, the turbidity of the supernatants also increased (up to 250 NTU for concentrations of 10 mg L^{-1} of mucilage). In such cases, we found that the turbidity in the supernatants could be reduced to standards values by a coarse filter, as the mucilage forms much larger flocs that are easily caught by inexpensive secondary filtration devices such as cloths or colanders.

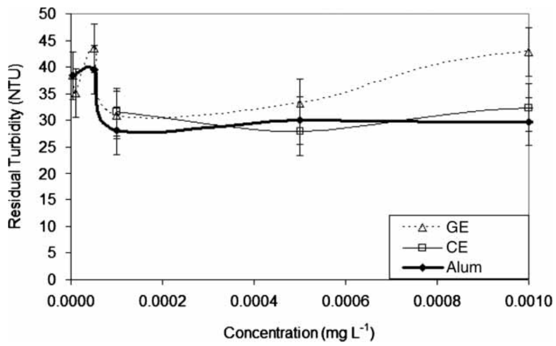

Figure 5 | Residual turbidity of GE, and CE and alum ($Al_2(SO_4)_3$) in the low dose region, where GE and CE are still better flocculants than alum. Reprinted with permission (Young *et al.* 2006).

Mucilage composition

Insight into the chemical structures of cactus mucilages in powder form was obtained using Raman IR spectroscopy (Figure 6). Our results on GE analysis confirm the presence of a glycosidic linkage as well as C-NH_2 bonds in aliphatic amines. This finding corroborates past characterization research which found the presence of glycoproteins in the *Opuntia* mucilage (Amin *et al.* 1970; Madjoub *et al.* 2001). Chemicals with similar structures have been characterized as viscous thickening agents, like the GE. The IR data also highlights the differences and similarities between the

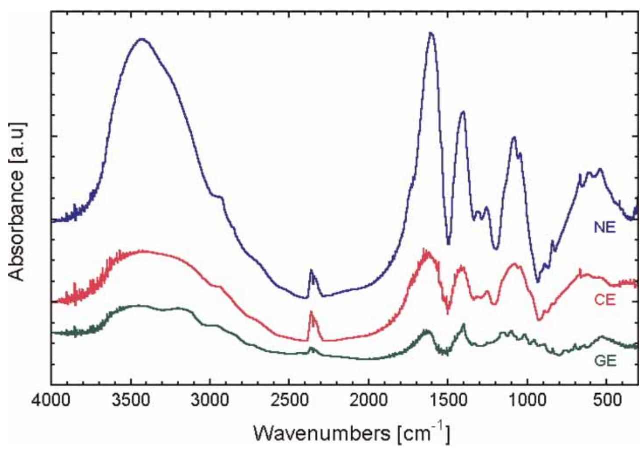

Figure 6 | Raman spectra for NE, CE and GE mucilage extracts showing different structures. The lower curve corresponds to GE extract, the upper curve corresponds to NE, and the intermediate curve corresponds to CE. As the concentration of GE and NE increases, the swirls formed by the mucilage complex are denser and bigger. As the most significant differences between the controls (C) and the GE (A) and NE (B) extracts occur at the highest concentration, we show the images for 100 mg L^{-1} only. The images for the other concentration follow the same trend.

three cactus derivatives. The spectrum for the CE is believed to be a combination of GE and NE. However, significant differences were found between GE and the other two extracts. The NE spectrum shows a broad peak in the isolated OH region (3,600–3,200 cm^{-1}) and peaks in the region suggesting liberation mode of residual water molecules (~800 cm^{-1}). They are both split in the GE spectrum, suggesting two types of O–H stretching, isolated OH species and residual water molecules attached to the complex structure of the mucilage with a combination of polyethers. However, the real differences occur in areas relating to ester bounding as small bands are observed in the absorptions at 890, 960 and 1,100 cm^{-1} ($\nu_{C\text{–}O\text{–}C}$) in the spectrum for GE. The broad band in all the spectra at 1,414 cm^{-1} (with two maximums at 1,402 and 1,450 cm^{-1}) is due to δ_{CH2} vibrations. An intense band in NE and CE at 1,630 and 1,610 cm^{-1}, with a shoulder at 1,730 cm^{-1} is attributed to $\delta_{H\text{–}O\text{–}H}$, $\delta_{C=C}$ and $\delta_{C=O}$ vibrations, respectively (Haxaire *et al*. 2003). The NE and CE spectra also show a broad peak in the region between 1,200 and 1,000 cm^{-1}. Two peaks on the same region but narrower and more defined are observed in the GE spectrum, which are generally attributed to C–N and C–O stretching vibration bonds. These peaks coincided with the bending vibration modes of amines and NH_2 scissoring (~1,650–1,550 cm^{-1}) and the α_{CH3} and α_{CH2} bending in aldehydes and ketones. These bands are assigned to vibrations of the glycosidic linkage (Tu 1982), as the structures of GE and NE/CE have similar properties of polymers that show the same functionality. For instance, poly(ethyl acrylamide), a polymer with similar structure to detailed peaks in GE and with the ability to form a gel, is used as a thickening agent and a colloidal carrier of drugs (Munk & Aminabhavi 2002).

Environmental sensitivity and applicability

Waterborne diseases from pathogens and contaminants afflict a majority of the world's population, especially in developing countries. A major victory in the battle against infectious and chronic diseases can be won if safe drinking water can be made available to people irrespective of their economic conditions (WHO 2008). While the developed world is willing to help, many projects have failed because of compatibility issues, ranging from technology to socio-economics, to customs and to religion (Ahmed *et al*. 2006). Often it is the fear of the unknown or unfamiliar which causes the failure (Ahmed *et al*. 2006). Because the Nopal cactus is well known to the indigenous population in Latin and Central America, a water treatment device based on its mucilage may be implemented successfully. Further investigation is required to review the feasibility of implementing this technology in a distributable or easy-to-assemble filter form for small-scale household removal. The implications of this project are exciting. We are currently investigating the possibility of using the cactus mucilage in emergency response packages that could be used in the aftermath of hurricanes and earthquakes. In addition, the use of mucilage as a non-toxic dispersant is also of interest to the authors for cleaning operations in the petroleum industry. The possibility of introducing a non-toxic, indigenous material as an improver of quality of life and health is attractive from a cultural sensitivity and sustainability standpoint.

CONCLUSIONS

This study has demonstrated that the mucilage extracted from *OFI* is a better flocculant than aluminium sulfate ($Al_2(SO_4)_3$) in all three of its forms. The ability of the GE to perform at the same efficiencies of $Al_2(SO_4)_3$, at doses 300 times smaller supports its use as an alternative. In addition GE is derived from a renewable resource and its disposal will involve simple organic degradation. This situation is a definite advantage compared with $Al_2(SO_4)_3$, which requires a chemical or mechanical recovery process to avoid further pollution problems, particularly if the mucilage was used in large-scale water treatment solutions.

ACKNOWLEDGEMENTS

Funding for this project was provided by NSF MUSES grant BES-0442977. Additionally, partial support was provided from NSF-Rapid grants CBET-1034849 and 1057897. Student funding was provided by USF STARS (Students, Teachers, and Resources in the Sciences) NSF Grant DGE-0139348. The authors would like to thank Dr Alessandro

Anzalone for his help collecting data. Our highest gratitude is also due to Dr Michel Picquart, from the Autonomous Metropolitan University of Mexico, for his valuable discussions involving the collection and interpretation of the Raman data.

REFERENCES

Ahmed, M. F., Ahuja, S., Alauddin, M., Hug, S. J., Lloyd, J. R., Pfaff, A., Pichler, T., Saltikov, C., Stute, M. & van Geen, A. 2006 Epidemiology: ensuring safe drinking water in Bangladesh. *Science* **314** (5806), 1687–1688.

Amin, E. S., Awad, O. M. & El-Sayed, M. M. 1970 The mucilage of *Opuntia ficus indica*. *Carbohydrate Research* **15**, 159–161.

Anastas, P. T. & Warner, J. C. 1998 *Green Chemistry Theory and Practice*. Oxford University Press, New York.

Benson, L. 1982 *The Cacti of the Unites States and Canada*. Stanford University Press, Stanford.

Bishop, M. M., Cornwell, D. A., Rolan, A. T. & Bailey, T. L. 1991 Mechanical dewatering of alum solids and acidified solids: an evaluation. *Journal – American Water Works Association* **83** (9), 50–55.

Cárdenas, A., Arguelles, W. M. & Goycoolea, F. M., 1998 On the possible role of *Opuntia ficus-indica* mucilage in lime mortar performance in the protection of historical buildings. *Journal of the Professional Association for Cactus Development* **3**, 64–71.

Cardenas, M. L., Serna, S. & Velasco de la, J. 1998 Effect of raw and cooked nopal (*Opuntia ficus-indica*) ingestion on growth and total cholesterol lipoproteins and blood glucose in rats. *Archivos Latinoamericanos de Nutricion* **48** (4), 316–323.

Cardenas, A., Goycoolea, F. M. & Rinaudo, M. 2008 On the gelling behaviour of 'nopal' (*Opuntia ficus indica*) low methoxyl pectin. *Carbohydrate Polymers* **73** (2), 212–222.

Deng, S. B., Bai, R. B., Hu, X. M. & Luo, Q. 2003 Characteristics of a bioflocculant produced by *Bacillus mucilaginosus* and its use in starch wastewater treatment. *Applied Microbiology and Biotechnology* **60**, 588–593.

El Kossori, R. L., Sachez, C., El Boustani, E. S., Maucourt, N., Sauvaire, Y., Mejean, L. K. & Villaume, C. 2000 Comparison of the effects of prickly pear (*Opuntia ficus-indica* sp.) fruit, arabic gum, carrageenan, alginic acid, locust bean gum and citrus pectin on viscosity and in vitro digestibility of casein. *Journal of the Science of Food and Agriculture* **80**, 359–364.

Eyring, A. M., Weinberg, H. S. & Singer, P. C. 2002 Measurement and effect of trace element contaminants in alum. *Journal of American Water Works Association* **94** (5), 135–146.

Fernandez, M. L., Lin, E. C. K. & Trejo, A. 1994 Prickly pear (*Opuntia* sp.) pectin alters hepatic cholesterol metabolism without affecting cholesterol absorption in guinea pigs fed a hypercholesterolemic diet. *Journal of Nutrition* **124**, 817–824.

Galati, E. M., Pergolizzi, N., Monforte, M. T. & Tripodo, M. N. 2002 Study on the increment of the production of gastric mucus in rats treated with *Opuntia ficus indica* (L.) Mill. cladodes. *Journal of Ethnopharmacology* **83**, 229–233.

Garti, N. 1999. Hydrocolloids as emulsifying agents for oil-water emulsions. *Journal of Dispersion Science and Technology* **20** (1&2), 327–355.

Goycoolea, F. M. & Cárdenas, A. 2003 Pectins from *Opuntia spp*: a short review. *Journal of the Professional Association for Cactus Development* **5**, 17–29.

Haxaire, K. M., Milas, M. & Rinaudo, I. 2003 Hydration of polysaccharide hyaluronan observed by IR spectrometry. *Biopolymers* **72** (1), 10–20.

Howard, G., Bartram, J., Schaub, S., Deere, D. & Waite, M. 2001 Regulation of microbiological quality in the water cycle. In: *Water Quality: Guidelines Standards and Health. WHO Water Series* (L. Fewtrell & J. Bartram, eds.). IWA Publishing, London, pp. 377–393.

Jakubowski, W., Boutros, S., Faber, W., Fayer, R., Ghiorse, W., Le Chevallier, M., Rose, J., Schaub, S., Singh, A. & Stewart, M. 1996 Environmental methods for *Cryptosporidium*. *American Water Works Association Journal* **88** (9), 107–121.

Kan, C., Huang, C. & Pan, J. R. 2002 Time requirement for rapid-mixing in coagulation. *Colloids and Surfaces A: Physiochemical and Engineering Aspects* **203** (1–3), 1–9.

Madjoub, H., Roudesli, S., Piction, L., Le Cerf, D., Muller, G. & Grissel, M. 2001 Prickly pear nopals pectins from *Opuntia ficus indica* physico-chemical study in dilute and semi-dilute solutions. *Carbohydrate Polymers* **46**, 69–79.

McGarvie, D. & Parolis, P. H. 1979 The mucilage of *Opuntia ficus indica*. *Carbohydrate Research* **69**, 171–179.

Medina-Torres, L., Brito- De, E., Torrestiana-Sanchez, B. & Katthain, R. 2000 Rheological properties of the mucilage gum (*Opuntia ficus indica*). *Food Hydrocolloids* **14** (5), 417–424.

Mishra, A., Agarwal, M. & Yadav, A. 2003 Fenugreek mucilage as a flocculating agent for sewage treatment. *Colloid and Polymer Science* **281** (2), 164–167.

Munk, P. & Aminabhavi, T. M. 2002 *Introduction to Macromolecular Science*. Wiley-Interscience, New York, pp. 609.

Nyquist, R. A. & Kagel, R. O. 1977 Organic materials. In: *Infrared and Raman Spectroscopy* (E. G. Brame & J. G. Grasselli, eds.). Marcel Dekker, Inc., New York, pp. 442–565.

Radia, L., El- Kossori, C. V., El Boustani, E., Sauvaire, Y. & Mejean, L. 1988 Composition of pulp, skin and seeds of prickly pears fruit (*Opuntia ficus indica* sp.). *Plant Foods for Human Nutrition* **52**, 263–270.

Rath, S. K. & Singh, R. P. 1997 Flocculation characteristics of grafted and ungrafted starch, amylose, and amylopectin. *Journal of Applied Polymer Science* **66** (9), 1721–1729.

Sáenz, C., Sepúlveda, E. & Matsuhiro, B. 2004 Opuntia spp mucilage's: a functional component with industrial perspectives. *Journal of Arid Environment* **57**, 275–290.

Sáenz, C. H. 1997 Cladodes: a source of dietary fiber. *Journal of the Professional Association for Cactus Development* **2**, 117–123.

Schwartz, J., Ronnie Levin, R. & Goldstein, R. 2000 Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia. *Journal of Epidemiology and Community Health* **54**, 45–51.

Singh, R. P., Nayak, B. R., Biswal, D. R., Tripathy, T. & Banik, K. 2003 Biobased polymeric flocculants for industrial effluent treatment. *Materials Research Innovations* **7** (5), 331–340.

Sobsey, M. D. 2006 *Managing water in the home: accelerated health gains from improved water supply*. WHO/SDE/WSH/02.07 (WHO) World Health Organization, Chapel Hill, CA.

Techtenberc, S. & Mayer, A. M. 1981 Composition and properties of *opuntia ficus-indica* mucilage. *Phytochemistry* **20** (12), 2665–2668.

Trinh, T. K. & Kang, L. S. 2011 Response surface methodological approach to optimize the coagulation-flocculation process in drinking water treatment. *Chemical Engineering Research and Design* **89** (7A), 1126–1135.

Tu, A. T. 1982 *Raman Spectroscopy in Biology* John Wiley, New York, pp. 234–255.

WHO 2008 *Guidelines for Drinking-Water Quality. Volume 1: Recommendations*, World Health Organization, Geneva.

Young, K. A., Anzalone, A., Pichler, T., Picquart, T. & Alcantar, N. A. 2006 The mexican cactus as a new environmentally benign material for the removal of contaminants in drinking water. In: *Materials Science of Water Purification* (M. A. Shannon, D. Ginley & A. M. Weiss, eds.). Materials Research Society, Warrendale, PA 930, 0930-JJ01-01.

First received 18 August 2011; accepted in revised form 18 November 2011