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(*SO₄*)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(*SO₄*)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

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
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.

**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 1984; 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, Al₂(SO₄)₃·18H₂O (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, \(\text{Al}_2(\text{SO}_4)_3\)) 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 floccs immediately began to form and settle. The height of the visible solid/liquid interface was then recorded with time until the floccs 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 50 min 50 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 Al₂(SO₄)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.

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 (Al₂(SO₄)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 Al₂(SO₄)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...
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.

**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

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**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 flocculant because it requires much less material to obtain the same settling rates. GE was dosed at 0.01 mg L\(^{-1}\). \(\text{Al}_2(\text{SO}_4)_3\) was dosed at 300 times that concentration (3 mg L\(^{-1}\)). Reprinted with permission (Young et al. 2006).

**Figure 5** | Residual turbidity of GE, and CE and alum (\(\text{Al}_2(\text{SO}_4)_3\)) in the low dose region, where GE and CE are still better flocculants than alum. Reprinted with permission (Young et al. 2006).

**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 bonding as small bands are observed in the absorptions at 890, 960 and 1,100 cm\(^{-1}\) \((\nu_{C-O-C})\) in the spectrum for GE. The broad band in all the spectra at 1,414 cm\(^{-1}\) (with two maxima at 1,402 and 1,450 cm\(^{-1}\)) is due to \(\delta_{\text{CH}_2}\) 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 \(\delta_{\text{H}_2\text{O}-\text{H}_2}\), \(\delta_{\text{C}-\text{C}}\) and \(\delta_{\text{C}-\text{O}}\) vibrations, respectively (Haxaire \textit{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 \(\alpha_{\text{CH}_3}\) and \(\alpha_{\text{CH}_2}\) 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 \textit{et al}. 2006). Often it is the fear of the unknown or unfamiliar which causes the failure (Ahmed \textit{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 \textit{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
Anazalone 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.

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