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ORIGINAL PAPER

Comparing cactus (Opuntia spp.) and alum as coagulants for water treatment at Al-Mashroo Canal: a case study

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Abstract A comparative study was performed between cactus (Opuntia spp.) and alum as coagulants. Monthly samples of raw water, delivered from (Al-Mashroo Canal), were studied and analyzed for turbidity removal during the period from August 29, 2014, to July 23, 2015. The analysis was conducted to decide the optimum dose, optimum velocity gradient, and optimum flocculation time for both coagulants. The results of the study indicate the efficiency of alum over cactus and that the optimum dose of alum was larger than that of cactus. The pH level of raw water was in the range of 7.734–8.203, while the temperature of raw water was in the range of 13–35 °C during the period of the study. The reliable velocity gradient for both coagulants was 25 1/s, and the reliable flocculation time for both coagulants was 20 min. The residual turbidity for cactus was in the range of 0.0–296 NTU, while that of alum was in the range of 0.0–5.81 NTU.

Keywords Coagulation · Flocculation · Optimum dose · Optimum flocculation time · Optimum velocity gradient

Introduction

Recently, plant-based materials have gained a global interest for purifying drinking water. One of which is cactus (Opuntia spp.) which proved its competence in the coagulation process of drinking water and wastewater treatment including heavy metals removal (Vijayaraghavan et al. 2011; Kannadasan et al. 2013; Nougbode et al. 2013; Theodoro et al. 2013; Belbahloul et al. 2014; Mounir et al. 2014; Gomes et al. 2015; Vishali and Karthikeyan 2015; Taa et al. 2016).

Drinking water treatment typically includes coagulation, sedimentation, filtration, and disinfection. Coagulation is a critical step in water treatment processes, not only because it removes particles but because it also removes the microorganisms that are often attached to the particles (Miller et al. 2008; Zand et al. 2011). Under conditions normally encountered in settling basins, effluent removal of particles less than (50 μm) in diameter cannot be expected without coagulation (Peavy et al. 1986).

Aluminum sulfate (alum) which is a common coagulant globally used in water and wastewater treatment can achieve 90–99 % microbial removal under optimal conditions. However, alum produces large sludge volumes, reacts with natural alkalinity present in water leading to pH reduction, and demonstrates low coagulation efficiency in cold waters (Miller et al. 2008; Xiao et al. 2009; Shilpaa et al. 2012; Theodoro et al. 2013).

The high level of residual aluminum (resulting from alum coagulation) has been linked to several medical disorders including osteomalacia, dialysis encephalopathy syndrome, Alzheimer's disease, and renal failure (Shokralla 1995; Sieliechi et al. 2010). The use of natural environmentally benign agents in the treatment of drinking water is rapidly gaining interest due to their inherently renewable character and low toxicity (Young 2006; Buttice 2009; Mounir et al. 2014). Natural coagulants produce less sludge volume compared to alum, and they require no pH adjustment (Megersa et al. 2014).

Opuntia spp., commonly called *"nopal"* in Mexico, prickly pear or cactus leaf in USA, grows readily in

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Mexico, Texas, and other arid and semiarid regions. It is commonly eaten and is used for medicinal purposes (Mondragon-Jacobo et al. 2001; Nobel 2002; Miller et al. 2008; Torres et al. 2012; Pichler et al. 2012). It also grows abundantly in Iraq where this research has been conducted.

The high coagulation capability of Opuntia is most likely attributed to the presence of mucilage which is a viscous complex carbohydrate stored in cactus inner pads that has great water retention capacity (Yin 2010).

The results in (Miller et al. 2008) support the hypothesis that the predominant coagulation mechanism for Opuntia spp. is "adsorption and bridging" whereby clay particles do not directly contact one another but are bound to a polymer-like material from Opuntia spp. It was also concluded in the latter reference that the greatest coagulation activity of Opuntia spp. occurs in basic waters (optimum pH = 10). This result was in accordance with the results of (Crittenden et al. 2005; Zhang et al. 2006).

The most pronounced coagulation mechanism for alum, treating dilute suspensions of particulate matter with a negligible concentration of natural organic matter (NOM), is "sweep coagulation" which occurred at a pH range of 7–8.5 and an alum dose in the range of 10–100 mg/l, as described by alum coagulation diagram (Amirtharajah and Mills 1982). In the diagram, "Charge Neutralization" occurred at a pH range of 4–7 and an alum dose in the range of 1–10 mg/l.

It is important to note that the studies above were performed on synthetic turbidity (not natural river water turbidity) using kaolin clay. This study was performed on natural river water, and its objective was twofold:

1. To investigate the applicability of utilizing cactus (Opuntia spp.) as a natural coagulant and compare its ability during 1 year (monthly samples) with alum at the inlet chamber of the sedimentation tank delivering raw water at Al-Musayab Technical Institute Water Treatment Plant (WTP), Babylon, Iraq.
2. To investigate and decide the optimum dose, optimum velocity gradient, and optimum flocculation time for both coagulants.

Figure 1 shows an aerial view (Google Earth) showing the location of Al-Musayab Technical Institute Water Treatment Plant (WTP) that purifies raw water delivered from (Al-Mashroo Canal) which is a branch from the Euphrates River. The investigation was conducted during the period from August 29, 2014, to July 23, 2015.

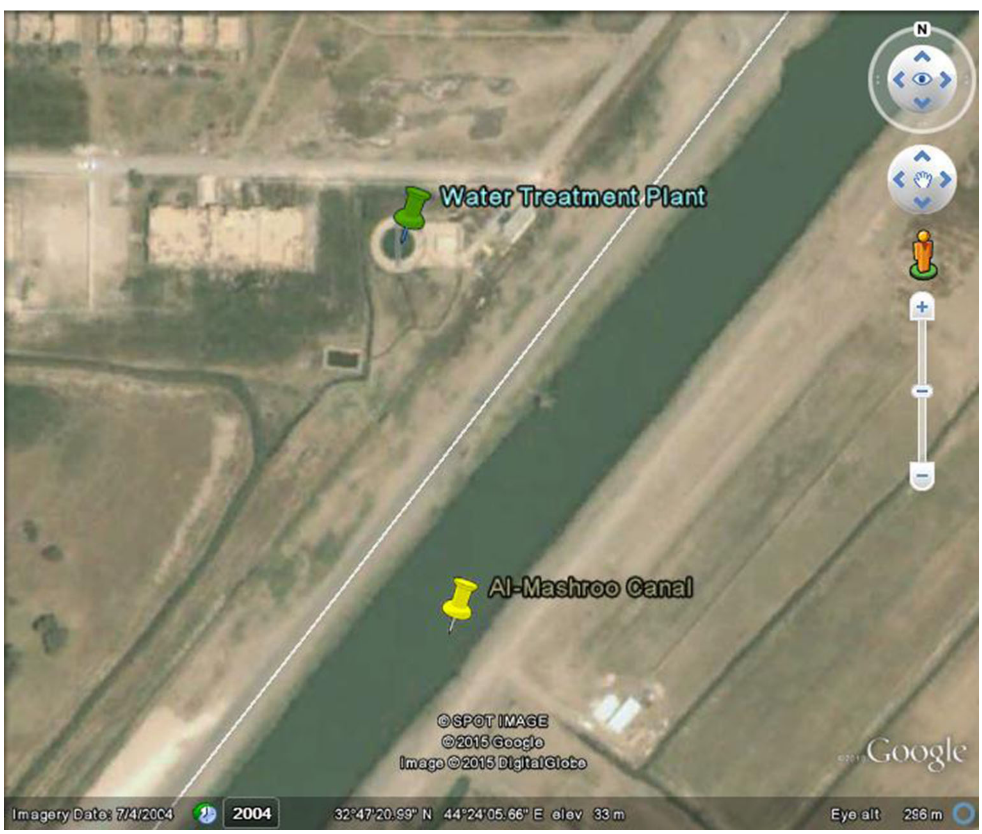

Fig. 1 Al-Musayab Technical Institute Water Treatment Plant

Materials and methods

Solution preparation

All solutions were prepared daily as follows:

Alum solution

Alum solution was prepared by dissolving 10 gm of powdered alum into 1 l of distilled water and stirred vigorously to produce a 1 % solution strength. Thus, 1 ml of this (stock solution) is equivalent to 10 mg of alum (or 10 mg/l dose when added to a 1-l raw water sample).

Cactus solution

Dry cactus powder was prepared by cutting fresh cactus species (pads) into strips of 1 cm width followed by drying at 60 °C for 24 h. Dry cactus species were ground in a coffee grinder and sieved to get particles of a size of ≤300 µm (Shilpaa et al. 2012). Then, 1 gm of powdered cactus was dissolved into (1 l) distilled water and stirred vigorously to produce a 0.1 % solution strength.

Theoretical background

Coagulation is defined as the destabilization of charge on colloids and suspended particles including bacteria and viruses by a coagulant. Flash mixing is an integral part of coagulation. Flocculation is the gentle mixing phase that follows the rapid dispersion of coagulants by the flash mixing. The seven important water quality aspects that control flocculation are turbidity, total organic compounds, pH level, alkalinity, color, algae counts, and temperature. The nature of the colloids, particularly the colloidal organic compounds [natural organic material (NOM)], and the particle size distribution of the turbidity are characteristics that are preferably known, since these factors affect the flocculation characteristics. The magnitude of the raw water turbidity alone is not likely to be a surrogate to coagulant dosage requirements (Kawamura 2000).

Humic substances are the major component of NOM in water supplies. Humic substances are anionic polyelectrolytes of low-to-moderate molecular weight; their charge is primarily caused by carboxyl and phenolic groups (Letterman et al. 1999).

The most important factors governing coagulation and flocculation are discussed herein briefly:

Rapid mixing

Rapid mixing, also called "Flash Mixing," occurs during coagulation to mix the coagulant with raw water efficiently. (Steel and McGhee 1979) define the optimum range of the product $G*T$ to be 30,000–60,000 where

G = velocity Gradient (1/s).

T = rapid mixing time (s).

Slow mixing

Slow mixing occurs during flocculation to enhance flocs agglomeration. (Steel and McGhee 1979) define the optimum range of G to be 25–65 1/s and that of T to be 20–30 min where

T = slow mixing time or flocculation time (min).

Floc disaggregation can apparently influence the flocculator performance (turbidity removal), especially when the mixing intensity is high ($G > 100$ 1/s) for which the floc suspension becomes destabilized (Letterman et al. 1999).

The governing equations for rapid and slow mixing for LOVIBOND floc-tester ET-750 (composed of 6 mixers) are given below. These equations physically define the relation between velocity gradient and mixer speed for different variables (Metcalf and Eddy 1979):

$$G = \sqrt{\frac{P}{\mu \forall}} \tag{1}$$

$$P = K \times \rho \times (n)^3 \times (D)^5 (\text{Turbulent}) \tag{2}$$

$$P = K \times \mu \times (n)^2 \times (D)^3 (\text{Laminar}) \tag{3}$$

where G = velocity gradient (1/s). P = power requirement (watt). ρ = mass density of water (998.2 kg/m^3 at 20 °C). μ = dynamic viscosity of water (0.001002 N S/m^2 at 20 °C). n = mixer speed (revolutions/s). D = diameter of impeller (0.075 m). K = constant (0.35).

$\forall$ = Water volume for 1 jar (1 l = 0.001 m^3)

The variables D and K are specified by the manufacturer (LOVIBOND). For the detailed specifications of the above instrument, the interested reader may refer to (http://www.lovibondwater.com/product/et-750.aspx).

Rearranging the above equations (for turbulent range), a new equation is obtained relating (n) to G for different values of μ and ρ, or for different temperatures:

$$n = (10.6384) * \left(\frac{\mu G^2}{\rho}\right)^{\frac{1}{3}} \tag{4}$$

Table 1 shows the effect of raw water temperature on mixer speed (n) in terms of a fixed value of velocity gradient (G) which is a solution of Eq. (4).

Jar testing

Jar testing was utilized in order to determine the following:

Table 1 Mixer speed (n) in terms of velocity gradient (G) for different raw water temperatures for LOVIBOND floc-tester ET-750

G (1/s)	*n* (rpm)					
	Raw water temperature (°C)					
	10	15	20	25	30	40
25	60	57	55	53	51	47
35	75	71	68	66	63	59
45	88	84	81	78	75	70
55	101	96	92	89	86	80
65	113	108	103	99	96	90
250	277	265	254	244	235	220

rpm revolution per minute

1. Optimum dose.
2. Optimum velocity gradient (G).
3. Optimum flocculation time (T).

Optimum dose

For both alum and cactus solutions, the following procedure has been applied (Shokralla 1995):

1. Preparing six beakers (1000 ml each) with raw water from the inlet chamber of the sedimentation tank which delivers raw water from Al-Mashroo Canal.
2. Measuring the initial turbidity, pH level, and temperature.
3. Adding six different doses of the coagulant.
4. Placing the six beakers in the floc-tester ET-750 (jar tester) and rapid mixing for $G = 250$ (1/s), $T = 120$ s, and according to Table 1, decide the speed of the mixers (n) according to the raw water temperature.
5. Slow mixing for $G = 25$ (1/s), $T = 20$ min, and according to Table-1, decide the speed of mixers (n) according to the raw water temperature.
6. Stopping the mixing and setting the beakers aside for settling for 15 min.
7. Taking samples from the top 30 ml of the beakers and measuring the residual turbidity. This is the clear water turbidity.
8. Drawing the curve between the coagulant dose and residual turbidity to decide the optimum dose which gives the minimum residual turbidity.
9. Calculating turbidity removal T.R. (%) according to Eq. 5:

$$\text{T.R.}\,(\%) = \left(\frac{N_0 - N_t}{N_0}\right) * 100 \quad (5)$$

where N_0 = initial turbidity (NTU). N_t = residual turbidity (NTU).

Optimum velocity gradient (G)

For the same raw water sample, the jar test was repeated using the optimum coagulant dose and the same G for rapid mixing while varying G for slow mixing to 35, 45, 55, and 65 1/s. Then, the residual turbidity is recorded. The curve between (G) and residual turbidity will decide the optimum (G) (Shokralla 1995).

Optimum flocculation time (T)

The jar test was repeated using the optimum coagulant dose and the same data for G for rapid mixing and slow mixing as specified in the optimum dose while varying the flocculation detention time (T) to 23, 26, and 30 min. Then, the residual turbidity was recorded. The curve between (T) and the residual turbidity determines the optimum (T) (Shokralla 1995).

Experimental work

Experiments were performed during the period from August 29, 2014, to July 23, 2015) based on 12-month points in order to have a reasonable decision about the studied case, taking into account different environmental variables, strictly speaking the effect of temperature and pH level. In this research, the real river turbidity (not synthetic turbidity prepared in the laboratory) was monitored.

Table 2 Raw water general characteristics

Date	Total dissolved solids (mg/l)	Alkalinity (mg/l)	TOC (mg/l)
27/3/2015	668	132	–
30/4/2015	680	180.5	–
28/5/2015	675	114	–
11/6/2015	700	152	8.0694
23/7/2015	750	84	1.88

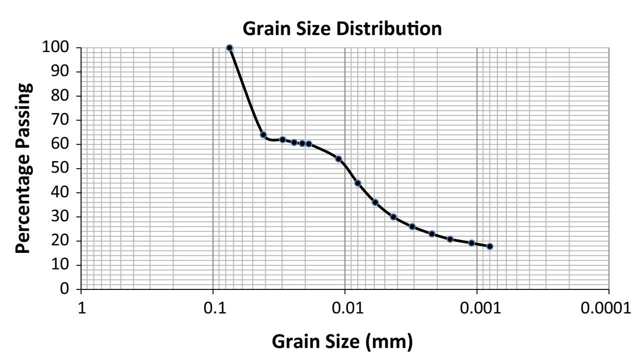

Fig. 2 Grain size distribution for the turbidity of raw water

Any experiment starts with a (60 l) raw water sample stored in a glass storage tank with 50 × 50 × 50 cm dimensions. Then, the experiment is continued by mixing the contents of the tank completely with a mixer (kitchen mixer) and finally drawing the samples to confirm a uniform initial turbidity, temperature, and pH values.

Results and discussion

General characteristics for the raw water under study are given in Table 2

Figure 2 shows the particle size distribution for the turbidity (as a soil) of raw water, using hydrometer analysis.

As shown in Fig. 2, it is clear that particles with a size of ≤50 µm or ≤0.05 mm represent 72 % of the raw water turbidity sample so that as described in Introduction, these particles required coagulation before passing to the settling basin (Peavy et al. 1986).

The experiments have been conducted every month during the course of the study. The minimum data points recorded for every run for initial turbidity and residual turbidity for both alum and cactus were as follows:

1. Optimum dose (6 points).
2. Optimum G (4 points).
3. Optimum T (3 points).

Table 3 Results of optimum dose

Date	Raw water properties			Alum			Cactus		
	pH	N_0 (NTU)	Temp. (°C)	O.D. (mg/l)	N_t (NTU)	T.R.* (%)	O.D. (mg/l)	N_t (NTU)	T.R. (%)
August 29, 2014	8.203	900	34	10	0.00	100	2.0	296	67.1
September 25, 2014	8.198	659	*29*	10	0.00	100	8.0	59	91.0
October 16, 2014	7.734	339	25	2	0.00	100	0.5	27.57	91.9
November 26, 2014	8.145	319	17	8	0.00	100	1.0	33.45	89.5
December 24, 2014	8.090	12.18	14	1	0.00	100	1.0	0.00	100
January 23, 2015	8.075	18.36	13	15	0.97	94.7	8.0	9.16	50.1
February 26, 2015	8.183	30.72	15	8	5.81	81.0	6.0	15.33	50.1
March 27, 2015	8.192	38.27	19	50	0.37	99.0	12.0	13.64	64.4
April 30, 2015	8.091	26.41	26	30	2.35	91.1	4.0	3.33	87.4
May 28, 2015	7.82	18.27	30	50	1.73	90.5	12.0	11.13	39.1
June 11, 2015	7.80	24.68	30	30	1.77	92.8	1.0	7.09	71.3
July 23, 2015	7.816	13.40	35	40	0.00	100	16.0	4.97	62.9

N_0 and N_t as specified by Eq. (5)

O.D. optimum dose

T.R. turbidity removal

Table 4 Results of optimum velocity gradient

Date	Raw water properties			Alum			Cactus		
	pH	N_0 (NTU)	Temp. (°C)	O.G. (1/s)	N_t (NTU)	T.R (%)	O.G. (1/s)	N_t (NTU)	T.R. (%)
August 29, 2014	8.203	900	34	25	0.00	100	45	158	82.4
September 25, 2014	8.198	659	*29*	25	0.00	100	25	59	91.0
October 16, 2014	7.734	339	25	25	0.00	100	25	27.57	91.9
November 26, 2014	8.145	319	17	25	0.00	100	65	26.73	91.6
December 24, 2014	8.090	12.18	14	25	0.00	100	25	0.00	100
January 23, 2015	8.075	18.36	13	65	0.63	96.6	25	9.16	50.1
February 26, 2015	8.183	30.72	15	25	5.81	81.0	25	15.33	50.1
March 27, 2015	8.192	38.27	19	25	0.37	99.0	25	13.64	64.4
April 30, 2015	8.091	26.41	26	45	0.00	100	35	2.29	91.3
May 28, 2015	7.82	18.27	30	65	1.15	93.7	55	7.20	60.6
June 11, 2015	7.80	24.68	30	45	1.36	94.5	35	4.98	79.8
July 23, 2015	7.816	13.40	35	25	0.00	100	35	3.02	77.5

Table 3 shows raw water properties during the 12 monthly points and the optimum dose for both coagulants. Table 4 shows the results of the optimum velocity gradient for both coagulants, and Table 5 shows the results of the optimum flocculation time for both coagulants.

Table 6 shows recorded data details for alum and cactus on March 27, 2015, for which

temperature = 19 °C (near the standard room temperature 20 °C), (pH = 8.192) and (initial turbidity = N_0 = 38.27 NTU)

Figures 3 and 4 depict the most important results withdrawn from Tables 3, 4, 5, and 6.

By analyzing Tables 3, 4, 5, and 6 and Figs. 3 and 4, it was apparent that:

1. Cactus has a lower turbidity removal efficiency than alum.
2. The optimum dose of cactus was in the range 0.5–16 mg/l, while that of alum is in the range 1–50 mg/l. This was also an indicative of the large sludge volume resulting from alum coagulation especially during the period from March 27 to July 23, 2015.

Table 5 Results of optimum flocculation time

CDate	Raw water properties			Alum			Cactus		
	pH	N_0 (NTU)	Temp. (°C)	O.T. (min)	N_t (NTU)	T.R. (%)	O.T. (min)	N_t (NTU)	T.R. (%)
August 29, 2014	8.203	900	34	20	0.00	100	23	253	71.9
September 25, 2014	8.198	659	29	20	0.00	100	20	59	91.0
October 16, 2014	7.734	339	25	20	0.00	100	20	27.57	91.9
November 26, 2014	8.145	319	17	20	0.00	100	30	28.18	91.2
December 24, 2014	8.090	12.18	14	20	0.00	100	20	0.00	100
January 23, 2015	8.075	18.36	13	30	0.93	94.9	20	9.16	50.1
February 26, 2015	8.183	30.72	15	20	5.81	81.0	26	13.68	55.5
March 27, 2015	8.192	38.27	19	20	0.37	99.0	20	13.64	64.4
April 30, 2015	8.091	26.41	26	26	0.42	98.4	20	3.33	87.4
May 28, 2015	7.82	18.27	30	30	1.51	91.7	30	8.94	51.1
June 11, 2015	7.80	24.68	30	26	1.03	95.8	30	4.26	82.7
July 23, 2015	7.816	13.40	35	20	0.00	100	26	3.87	71.1

O.T. optimum flocculation time

Table 6 Recorded data details for alum and cactus dated on March 27, 2015

Alum (N_0 = 38.27 NTU)					Cactus (N_0 = 38.27 NTU)				
N_t (NTU)	A (mg/l)	G (1/s)	T (min)	GT	N_t (NTU)	A (mg/l)	G (1/s)	T (min)	GT
16.19	2.0	25	20	30000	14.06	2.0	25	20	30000
10.88	4.0	25	20	30000	13.72	4.0	25	20	30000
9.39	8.0	25	20	30000	14.58	8.0	25	20	30000
7.75	12.0	25	20	30000	17.13	10.0	25	20	30000
6.00	20.0	25	20	30000	13.64	12.0	25	20	30000
3.41	30.0	25	20	30000	15.00	20.0	25	20	30000
1.08	40.0	25	20	30000	15.36	30.0	25	20	30000
0.37	50.0	25	20	30000	14.21	40.0	25	20	30000
1.22	60.0	25	20	30000	17.16	12.0	25	23	34500
2.21	50.0	25	23	34500	15.56	12.0	25	26	39000
2.24	50.0	25	26	39000	15.81	12.0	25	30	45000
1.15	50.0	25	30	45000	16.35	12.0	35	20	42000
2.06	50.0	35	20	42000	18.01	12.0	45	20	54000
1.50	50.0	45	20	54000	17.39	12.0	55	20	66000
1.37	50.0	55	20	66000	17.88	12.0	65	20	78000
2.08	50.0	65	20	78000	–	–	–	–	–

A coagulant dose

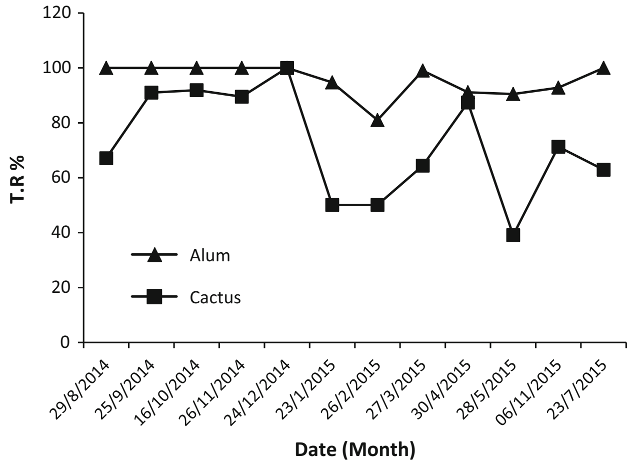

Fig. 3 Monthly variation of turbidity removal at optimum dose [$G = 25$ (1/s), $T = 20$ min] for both coagulants

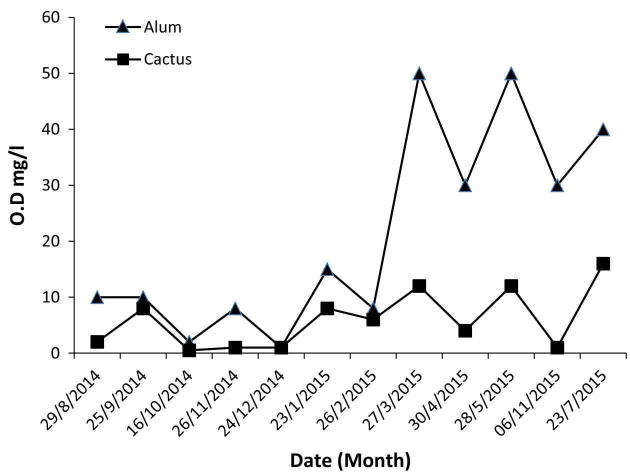

Fig. 4 Monthly variation of optimum dose for both coagulants

3. The residual turbidity for cactus was in the range of 0.0–296 NTU, while that of alum was in the range of 0.0–5.81 NTU.
4. $G = 25$ 1/s occurred most frequently for both cactus and alum.
5. $T = 20$ min occurred most frequently for both cactus and alum.
6. On August 29, 2014 (turbidity = 900 NTU), changing the velocity gradient from 25 (1/s) to 45 (1/s) enhanced the removal efficiency of cactus from 67.1 to 82.4 %.
7. Cactus could reach a removal efficiency of 100 % on December 24, 2014, when pH = 8.09, initial turbidity = 12.18 NTU, and temperature = 14 °C, and this was comparable to alum for the same raw water properties.
8. Cactus worked as a coagulant efficiently with a removal efficiency more than 90 % for the period September 25 to December 24, 2014.
9. pH was in the range 7.734–8.203 which was most suitable for "sweep coagulation" concerning alum and is not suitable for cactus as the optimum pH for cactus coagulation is pH = 10 as pointed out in Introduction.
10. Tables 3, 4, and 5 could be used as an operational guide for adding a coagulant in Al-Musayab Technical Institute WTP.
11. Table 6 clearly states that O.D. for alum is 50 mg/l and that for cactus is 12 mg/l, whereas O.G. for alum and cactus is 25 1/s, and O.T. is 20 min for both coagulants.

Conclusion

It is clear that there is no specified value of O.D. nor O.G. nor O.T. for the raw water under study concerning both coagulants (alum and cactus) as these controlling factors that result from the jar test change with time according to the change of environmental variables. This is an important factor to be taken into consideration by the operator of Al-Musayab Technical Institute WTP by referring to onsite long-term studies. Also it can be concluded that cactus (Opuntia spp.) can be used as a natural coagulant and the O.D. for alum is larger than that for cactus which implies an increase in the sludge volume resulting from alum coagulation compared to cactus. Furthermore, the reliable O.G. for both coagulants is $G = 25$ 1/s and the reliable O.T. is $T = 20$ min for both as well.

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