

Characterisation and Performance of three Kenaf coagulation products under different operating conditions

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1 **Title:**

2 Characterisation and Performance of three Kenaf coagulation products under different
3 operating conditions

4

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22 **Abstract**

23 The Sustainable Development Goal (SDG) 6.1, established by the United Nations General
24 Assembly in 2015, targets universal and equitable access to safe and affordable drinking water
25 for all by 2030. An essential factor in achieving this goal is the harnessing of “green”
26 coagulants – naturally occurring, environmentally friendly materials which are effective
27 coagulants for use in water treatment, with good availability in developing countries, inherent
28 renewable properties and ease of biodegradation. In order to gain from these benefits, it is
29 essential to fully understand how such coagulants may best be utilised, particularly concerning
30 their practical application in developing countries. In this study, three different plant-based
31 coagulation products (PCPs), namely Hexane (HxKP), saline (StKP) and crude (CrKP) extracts
32 of Kenaf plant seed (*Hibiscus cannabinus*, a species of the Hibiscus plant), were applied to high
33 (HTW), medium (MTW) and low (LTW) turbidity water in order to determine their
34 performance and coagulation ability. The ability of the three Kenaf coagulant products (KCPs)
35 to remove hydrophobic fractions of natural organic matter (NOM) was measured. The impact
36 of KCPs on the treated water organic matter content (a known disinfection by-product (DBP)
37 precursor) was examined using known surrogates of natural organic matter (NOM) i.e. the
38 dissolved organic carbon (DOC), ultraviolet absorbance at 254 (UV₂₅₄) and specific ultraviolet
39 absorbance (SUVA₂₅₄). Results obtained quantify the implications of using these coagulants
40 during the water disinfection process. A parametric study, measuring the effect of different
41 operating parameters, such as untreated water turbidity, pH, dosages, retention time, and KCP
42 storage time, was completed. Turbidity removal performance for HxKP and StKP was very
43 good with > 90% removal recorded for HTW and MTW, respectively, at pH seven within 2
44 hours retention time. Images obtained from scanning electron microscopy (SEM) analysis

45 revealed a high likelihood of the coagulation mechanism of KCPs to be adsorption-interparticle
46 bridging brought about by their flake-like structures and surfaces charges. Varying pH had no
47 measurable influence on the coagulation performance of the KCPs. Comparing their efficiency
48 with *Moringa Oleifera* (MO, a previously researched PCP) and alum showed that HxKP had a
49 negligibly different particle removal as MO. StKP turbidity removal performance was below
50 HxKP by 1% for HTW and LTW and 2% for MTW but performed higher than the CrKP by
51 5% and 7% in HTW and MTW, respectively. The optimum dosage of HxKP and StKP reduced
52 DBP surrogate values, indicating that its precursor is also minimized, although a slight shift
53 from this optimum dosage showed a significant rise in their concentration thus signifying a
54 potential increase in DBPs during disinfection.

55 **Keywords:** Turbidity; Coagulation-flocculation; Molecular interaction; Plant-based
56 coagulants; Water treatment

57 **List of Abbreviations:** Chemical coagulation products (CCPs); Chromatographically purified
58 Kenaf protein (ChrKP); Crude extracted products (CrKP); Disinfectant by-product products
59 (DBP); Dissolved organic carbon (DOC); Electric double layer (EDL); Electrophoretic
60 mobility (EM); Energy dispersive analysis of X-rays (EDAX); Fourier Transform Infra-Red
61 analysis (FT-IR); Fruit seed extract (FSE); Hexane extracted products (HxKP); Hexane leaf
62 extract (HLE); High turbidity water (HTW); Humic acid (HA); Isoelectric point (IEP); Kaolin
63 model water (KMW); Kenaf coagulation products (KCPs); Low turbidity water (LTW);
64 Medium turbidity water (MTW); *Moringa oleifera* (MO); Natural organic matter (NOM); Plant
65 coagulation products (PCPs); Salt extracted products (StKP); Scanning Electron Microscopy
66 (SEM); Specific ultraviolet absorbance at 254nm (SUVA₂₅₄); Sustainable development goal
67 (SDG); Trihalomethanes (THMs); Ultraviolet light (UV) absorbance at 254 nm (UV₂₅₄);
68 United Nations International Children's Emergency Fund (UNICEF); Water Kenaf product
69 (WKP); World health organisation (WHO); Zeta potential (ZP);

70

71 **1. Introduction**

72 Unimproved water sources, especially in sub-Saharan Africa and Oceania, remain a threat to
73 the realisation of the United Nations Sustainable Development Goal (SDG) 6.1 of safe and
74 affordable water for all by 2030 (WHO and UNICEF, 2019). Eight out of ten people in rural
75 neighbourhoods in the sub-Saharan Africa region lack even essential water services, with the
76 majority depending on surface water or unimproved water sources (WHO and UNICEF, 2017;
77 WHO and UNICEF, 2019). Most surface water sources like rivers, streams and ponds are
78 polluted and unfit for drinking due to natural and anthropogenic influences such as unregulated
79 industrial discharges (Ezeabasili *et al.*, 2014), climate change and the drought-induced
80 migration of livestock to water sources servicing rural populations (Bello, 2013). Most of the
81 polluted rivers, streams and ponds contain high concentrations of natural organic matter
82 (NOM) including humic acid (HA), adding taste, odour and colour to them (Ezeabasili *et al.*,
83 2014). The presence of NOM in drinking water makes water unpotable due to several hygiene
84 and health reasons, with one of the most important being the formation of toxic chemical
85 species during the disinfection process. During disinfection of NOM enriched waters,
86 disinfection by-products (DBPs), e.g. trihalomethanes (THMs) and haloacetic acids, are
87 formed, which are reported to be harmful to health owing to their lethal, carcinogenic and
88 mutagenic potentials (Brown *et al.*, 2015; Niu *et al.*, 2015; Gough *et al.*, 2014; Bongiovani *et*
89 *al.*, 2015). Removing NOM in water should be to strict standards in order for this undesirable
90 consequence of disinfection to be avoided. However, water quality compliance in most
91 developing countries is severely lacking due to the lack of infrastructure and government
92 commitment to water supply, thus diminishing access to primary and improved service delivery
93 with a resultant negative impact on the population's health.

94 Chemical coagulation is a well-established technique used at the start of a water treatment
95 process. Most of the commercially available coagulation products are chemical-based (hence
96 chemical coagulation products, CCPs) such as iron (FeCl_3) and aluminium salts (Al_2SO_4)
97 (Sharp et al., 2006; Guo et al., 2015). Studies have associated the use of CCPs such as alum
98 with Alzheimer's disease (Flaten, 2001; Exley, 2017) and neurological syndromes (Zatta *et al.*,
99 2003), casting doubt on their safe and sustainable use as a coagulant. Several chemical-based
100 household water treatment products currently in the market are not affordable, especially to
101 those in rural communities, due to the high costs of procurement (WHO, 2019), while other
102 CCPs are only effective for the treatment of low turbidity water, limiting their application.
103 Further; these CCPs produce high sludge volume, have a reduced sludge recyclability rate and
104 a high carbon footprint during their production (Villanueva *et al.*, 2004). Consequently, an
105 alternative, for use in combination with or as a replacement for CCPs, is desirable in order to
106 overcome or reduce these limitations.

107 The use of plant coagulation products (PCPs) in place of CCPs is not only efficient in terms of
108 cost but also means access for all since these plants are widely grown and have a good
109 adaptation to different soils. Several studies have investigated the potential of using PCPs in
110 the treatment of water in developing countries, with research examining the use of *Moringa*
111 *Oleifera* (MO) (Ndabigengesere and Subba Narasiah, 1998; Camacho *et al.*, 2017; WHO and
112 UNICEF, 2019) and extracts from members of the Hibiscus (Jones and Bridgeman, 2019) and
113 Cactaceae (Oladoja *et al.*, 2017) families. These PCPs have been shown to have antibacterial
114 abilities (Jones and Bridgeman, 2017), and the active coagulation components, e.g. the
115 carbohydrates and protein, are rich in nutrients and have no known health impact in humans.
116 Sludge generated by these PCPs are biodegradable and also of reduced volume
117 (Ndabigengesere and Narasiah, 2010). Chemical coagulants such as alum perform better at
118 lower pH values thereby making the water acidic and requiring adjustment to make it potable,

119 whereas pH change seldom occurs when using PCPs, enhancing their suitability as water
120 treatment materials. When used as an aid to coagulation with alum, PCPs have the advantage
121 of improving the effectiveness of alum by forming larger and denser flocs and thereby reducing
122 the quantity of alum needed. For example, the use of Hibiscus leaf extract (HLE) as a coagulant
123 aid is reported to improve turbidity removal from 45 to 72% (Awang and Aziz, 2012).

124 Kenaf is from the Malvaceae family, which is known for its tall, woody nature, and is grown
125 widely in the tropical and subtropical regions of many countries. Kenaf varieties obtained from
126 different parts of the world are also rich in oil, fatty acid (palmitic, linoleic and oleic acid
127 (Mohamed *et al.*, 1995)), and other important bioactive chemical components. The seed also
128 contains phospholipids, sterols, and other nutritional components (Mohamed *et al.*, 1995;
129 Nyam *et al.*, 2009). Just like most plant seeds, Kenaf predominantly contains proteins
130 (Ndabigengesere and Narasiah, 1996; Ghebremichael *et al.*, 2005) although other compounds
131 such as phenolic acids (Nyam *et al.*, 2009) and carbohydrates (Nyam *et al.*, 2009; Mariod *et*
132 *al.*, 2010) have been found and may also contribute to their coagulative behaviour (Oladoja,
133 2015). The active agents in Kenaf crude seed were reported to be anionic proteins with a
134 molecular weight between 10 – 100 kDa (Mariod *et al.*, 2010; Jones, 2016). Jones (2016) also
135 reported that a thermo-resistant protein exists with a molecular weight of 6 kDa, and that it
136 possesses good coagulation potential.

137 These compounds can be extracted using different techniques to produce Kenaf coagulation
138 products (KCPs) with different concentrations of these coagulation compounds. (Jones, 2016)
139 study is the only known work that used different KCPs, i.e. water extracted (WKP) and
140 chromatographically purified Kenaf protein (ChrKP) as a coagulant-flocculant, and tested for
141 their coagulation/flocculation potentials. Jones' tests used Kaolin model water (KMW) seeded
142 with chemical compounds present in organic materials. Jones' report showed that ChrKP gave
143 the best turbidity removal of 92% in 100NTU KMW, while the WKP gave 90%, 79% and 73%

144 for 200NTU, 100NTU and 50NTU KMW, respectively. Despite attaining high turbidity
145 removal, ChrKP and WKP could not attain the WHO minimum turbidity standard of 4NTU,
146 thereby, making the water unsuitable for use. KCPs derived from the salting-in process (StKP)
147 (Ndabigengesere and Narasiah, 1996; Okuda *et al.*, 1999), solvent purification (HxKP) (Dos
148 Santos *et al.*, 2016) and the protein fractionation process (Mariod *et al.*, 2010; Dos Santos *et*
149 *al.*, 2016) have not previously been examined for their potential use in water treatment. Some
150 KCPs such as ChrKP involve expensive extraction processes which may be costly to acquire
151 by poor households. However, simpler extracts like the WKP, involve very little or no cost of
152 preparation and can easily be used by villagers and commoners. Determining the best of these
153 KCPs is arguably a balance between having the highest performance and the lowest processing
154 cost and time.

155 Limited information is available on the morphology of these KCPs, their coagulation
156 mechanism, and their performance, despite the increasing interest in this crop in academia and
157 industry (Yang *et al.*, 2019). To produce potable water, disinfection (usually using chlorine) is
158 required after coagulation/flocculation, yet there is currently no study on DBP formation using
159 KCPs. Therefore, a comprehensive study would be beneficial to understand the effect the
160 different KCPs on the DBP formation in the treated water.



161 (a)

(b)

162 Fig. 1. Kenaf (*Hibiscus cannabinus*) plant showing (a) plant flower (b) raw, grinded and
163 delipidated kenaf seed derived from Kenaf plant

164 Inspired by recent results on the use of PCPs in water treatment, this study evaluates the
165 performance of three KCPs (Fig. 1), i.e. Crude Kenaf (CrKP), Salted Kenaf (StKP) and Hexane
166 (solvent) extracted Kenaf (HxKP) in turbidity removal from low (LTW, 30NTU), medium
167 (MTW, 150NTU) and high turbidity water (HTW, 500NTU). It provides a better understanding
168 of the three KCPs' performance and examines the coagulation mechanism involved under a
169 range of pHs, contact times and dosages, which is lacking in published literature. This
170 introduction is followed by a description of the methodology applied (Section 2), a detailed
171 discussion of the key results (Section 3) and finally the important conclusions which have been
172 drawn from this work.

173 **2. Materials and methods**

174 Coagulation/flocculation experiments were performed using three water samples to examine
175 the performance of three KCPs extracted from Kenaf seeds. Water quality indicators including
176 pH, turbidity, dissolved organic carbon (DOC), 254nm light absorbing compounds (UV₂₅₄),
177 and specific absorbance (SUVA₂₅₄) were studied to understand the KCPs influence during the
178 water treatment process. Zeta potential, Fourier Transform Infra-Red analysis (FT-IR) and
179 Scanning Electron Microscopy (SEM) were used to determine the morphology and
180 characteristics of the KCPs studied.

181 **2.1 Materials**

182 Analytical grade chemicals and reagents used included sodium chloride (NaCl-Fisher product
183 #: 10428420) for improving protein solubility and hexane (Fisher product #: 10735141) as the
184 delipidating solvent. Milli-Q water (18 MΩ·cm) was used for the preparation of all solutions.
185 The dried *Hibiscus cannabinus* (Kenaf) seeds were obtained from Yola Market located in Yola,

186 Adamawa State, Nigeria, located between the geographic coordinates 9°13'48" North latitude
187 and 12°27'36" East longitude. The Kenaf seeds from this source are typical of Kenaf
188 worldwide. 2% w/v of Aluminium sulphate $Al_2(SO_4)_3$ (Fisher product #: 10233850) was
189 prepared and used as a comparative coagulant.

190 **2.2 Natural and composite water samples**

191 Samples were collected from the Bournbrook river, Birmingham, UK, between November
192 2018 and April 2019. The river traverses both rural and urban catchments and is recharged by
193 runoff from surrounding areas and combined sewer overflows (Carstea *et al.*, 2009). Turbidity
194 values studied in this work reflected the range of turbidity experienced in developing countries
195 like sub-Saharan Africa and are consistent with previous research (Pritchard *et al.*, 2010). Low
196 turbidity water (LTW) and medium turbidity water (MTW) were collected from two points
197 along the river course, with high turbidity water (HTW) being derived by adding river-bottom
198 sediment to MTW. Only samples with turbidity within 10% of the target values of 30NTU,
199 150NTU and 500NTU were used. Turbidity values were measured by a calibrated Hach 2100N
200 Turbidimeter. Water samples were collected in a set of 10-litre plastic containers and were
201 stored at 4°C after collection until use to minimise sample perturbation; water was removed
202 from storage no more than 8h before sample analyses in order to preserve water quality and
203 prevent ingrowth of organic materials. Bottom sediments were collected using a metal scoop,
204 carefully transferred to a clean container and then washed through a 65µm sieve to eliminate
205 debris.

206 **2.3 Preparation of Kenaf Coagulant Products (KCPs)**

207 The samples were processed based on the modified procedure reported by Jones and
208 Bridgeman (2016). Seeds were stored in a dry environment at room temperature. Milli-Q water
209 was used to rinse the seeds to remove all impurities, after which the seeds were dried for 24-

210 hours, ground for 3 minutes and passed through a 300 μ m sieve. The powder obtained was
211 termed Crude Kenaf, CrKP, and was stored for further use. To obtain a 5% weight to volume
212 (w/v) suspension of sodium chloride (NaCl), 58.44g of 1.0M (NaCl) in 1000 ml of Milli-Q
213 water was added to the CrKP, followed by thorough mixing for 30 minutes using a magnetic
214 stirrer (Stuart Scientific, UK). The obtained solution was filtered through a Whatman No. 3
215 filter paper to eliminate residue, and then the filtrate was dried. The residue obtained was
216 referred to as Salted Kenaf product, StKP.

217 The unwanted compounds that might reduce the coagulation performance, such as the fatty
218 acid present in the seeds, were removed using an electro-thermal Soxhlet apparatus.
219 Approximately 20g of seed powder was placed in the apparatus' thimble before heating hexane
220 up to 80°C for 8 hours with each intermediate cycle taking approximately 2-3 minutes (Muyibi
221 and Alfugara, 2010). The residue collected from the thimble was dried at room temperature,
222 and then 1g was mixed with 100 mL of saline solution (NaCl: 1 mol/L) which was stirred for
223 30 min, filtered and dried and stored for further use. Hexane delipidated flour was called
224 Hexane Product (HxKP).

225 **2.4 Coagulation/ Flocculation Experiments**

226 Coagulation/flocculation tests were conducted using each of the KCPs. For each jar test, 1 litre
227 of untreated water was used in the simulated coagulation/flocculation process using a variable
228 speed, 2-blade impeller with square section (Phipps and Bird Jar tester), in a 1L capacity
229 un baffled beaker. The beakers had no stators to suppress vortices and maximize energy transfer
230 to the fluid (Hocking *et al.*, 1999). Most containers used by rural and poor households are
231 expected to be un baffled so the absence of stators in jar test beakers is arguably more
232 representative of real-world application. Similar to the procedure of Antov *et al.* (2010), the
233 samples in the beakers were stirred at 200 rpm for 1.5 min. After rapid mixing, the mixing

234 speed was then reduced to 30 rpm for 15min and, at this stage, zeta potential measurements
235 were taken. After the slow mix stage, water samples were drawn from 3cm below water surface
236 using a syringe into a 30mL cuvette and turbidity values were taken 10 mins, 20 mins, 50 mins,
237 70 mins, 120 mins and 24hrs (1440mins) after the sample was taken. The different settling
238 times used gave an insight into the settling behaviour of the suspended particles. Samples were
239 also collected at 48 hours (2880 mins) to monitor the organic matter content in treated water.
240 A control assay using only untreated water was also used to evaluate the effect of unaided
241 sedimentation on particle removal and the overall treatment process. The turbidity removal
242 percentage was calculated using:

$$243 \quad \% \text{ turbidity removal} = \frac{T_{\text{initial}} - T_{\text{residual}}}{T_{\text{initial}}} \times 100 \quad \text{Eq. (1)}$$

244 where T_{initial} is the turbidity of the untreated water and T_{residual} denotes the turbidity of the
245 treated water at the end of the settling period. Total suspended solid (TSS) concentration was
246 approximately 2.3 times of turbidity value of the untreated water (Tchobanoglous, 2014).
247 Dosage optimisation tests were conducted to examine the performance of HxKP, StKP and
248 CrKP in treating high, mid and low turbidity river water. Different protein dosages for the
249 KCPs were chosen to investigate the impact of coagulant dosage on the water types and these
250 results are provided in Section 3.3.1.

251 **2.5 KCP and Water Characterization**

252 The surface morphologies of KCPs give an understanding of their role in the
253 coagulation/flocculation process by providing insight into their adsorption-bridging behaviour
254 and the nature of their surface. The functional groups and chemical fingerprint on the surface
255 of the KCPs were determined using a Perkin Elmer Fourier Transform Infrared spectrometer
256 (FT-IR) (Yu and Irudayaraj, 2005). Also, the surface morphology and elemental analysis of the

257 KCPs were examined using a Hitachi TM3030 Plus scanning electron microscope (SEM),
258 equipped with energy dispersive analysis of X-rays (EDAX).

259 Water quality variables examined included turbidity, UV₂₅₄ absorbing compounds and DOC.
260 The method of Lowry *et al.* (1951) was used for soluble protein determination by taking
261 absorbance at 660nm, and all experiments were replicated thrice to rule out random or
262 experimental error. Turbidity measurements conformed with the Standard Method for
263 Examination of Water and Wastewater (Rice *et al.*, 2012), and were made using a 2100N Hach
264 turbidity meter by placing a 30 ml unfiltered (untreated or treated) sample in a pre-rinsed vial.
265 Instrument calibration was done using the StablCal Calibration Set for the 2100N turbidity
266 meter, obtainable from Hach. pH readings were obtained using Therm-Scientific Orion 3 Star
267 according to the Standard Method procedures (Rice *et al.*, 2012). Also, the zeta potential was
268 measured using a Zetasizer Nano ZSP (Malvern instrument, UK) with a disposable
269 polycarbonate folded capillary cell with gold plated electrodes (DTS 1070). The zeta potential
270 test uses the electrostatic forces of repulsion between particles to determine the surface charge
271 of the particles. UV₂₅₄ absorbing compounds were measured using a Varian Cary 50 Probe.
272 The SUVA₂₅₄ value indicating the composition of natural organic matter in water is given by
273 the ratio of UV₂₅₄ to DOC:

$$274 \quad \text{SUVA}_{254} = \frac{\text{UV}_{254}}{\text{DOC}} \times 100 \quad \text{Eq. (2)}$$

275 **3. Results and discussions**

276 **3.1 Properties of river water**

277 Characteristics of the untreated water samples are shown in

278 Table 1. Medium and high turbidity samples had high values of UV₂₅₄ and SUVA₂₅₄, which
279 reflect organic material compounds present in water. SUVA₂₅₄ values greater than 4 indicate

280 compounds that are hydrophobic and aromatic, while SUVA₂₅₄ values less than 3 show that
 281 the organic materials are mostly hydrophilic (Matilainen *et al.*, 2011). Organic materials with
 282 high SUVA₂₅₄ values have higher molecular weights (mW). They may require more advance
 283 treatment procedures and also have a high chlorine demand and total disinfectant byproduct
 284 formation potential. Untreated low turbidity water gave the lowest SUVA₂₅₄ and DOC values
 285 signifying a reduced concentration of hydrophobic NOM. Also, the zeta potential values
 286 obtained from all waters showed that suspended particles in water are negatively charged,
 287 which agrees with previous reports (Jarvis *et al.*, 2005). These similar charges on particles
 288 make them disperse and agglomeration resistant.

289 Table 1. Characteristics of untreated water.

Quality Variable	Water A - HTW	Water B - MTW	Water C - LTW
Turbidity (NTU)	500 ± 2	150 ± 7	32 ± 3
UV _{254nm} (cm ⁻¹)	1.8 ± 0.12	0.7 ± 0.01	0.13 ± 0.02
SUVA ₂₅₄ (L/mg m)	14.1	10.2	2.5
DOC (mg/L)	12.8 ± 0.6	7.0 ± 0.4	5.2 ± 0.2
pH	7.6 ± 0.3	7.3 ± 0.0	7.2 ± 0.2
Zeta potential (mV)	-16.3 ± 0.6	-16.6 ± 1.2	-16.9 ± 1.2

*Result shown are in mean concentration ± standard deviation (SD)

290 3.2 KCP characterisation

291 The protein content of the StKP and HxKP products were found to be higher than the CrKP
 292 (Table 2; zeta potential shown in the table is discussed in Section 3.3.3). The low solubility of
 293 the protein in the crude extract could be due to shielding of the coagulating proteins by the fatty
 294 layer and other compounds present. Camacho *et al.* (2017) made similar observations using
 295 *Moringa Oleifera* (MO) in treating cyanobacteria rich water. Research conducted by Jones

296 (2016) revealed protein concentration in *Hibiscus esculentus* (Okra) salt extract to be 1018
 297 mg/L and 264 mg/L for Okra water extract. This variation in protein concentration is due to
 298 the nature of the solvent used in the extraction process. During extraction, water was observed
 299 to be a weak and mild solvent for protein extraction due to its low ionic strength, whereas NaCl
 300 solution was very effective in this regard due to the salting-in process (Ndabigengesere and
 301 Subba Narasiah, 1998). This salting-in process helps stabilise the protein molecules by causing
 302 a reduction of the electrostatic energy between the protein molecules, thus, improving their
 303 solubility.

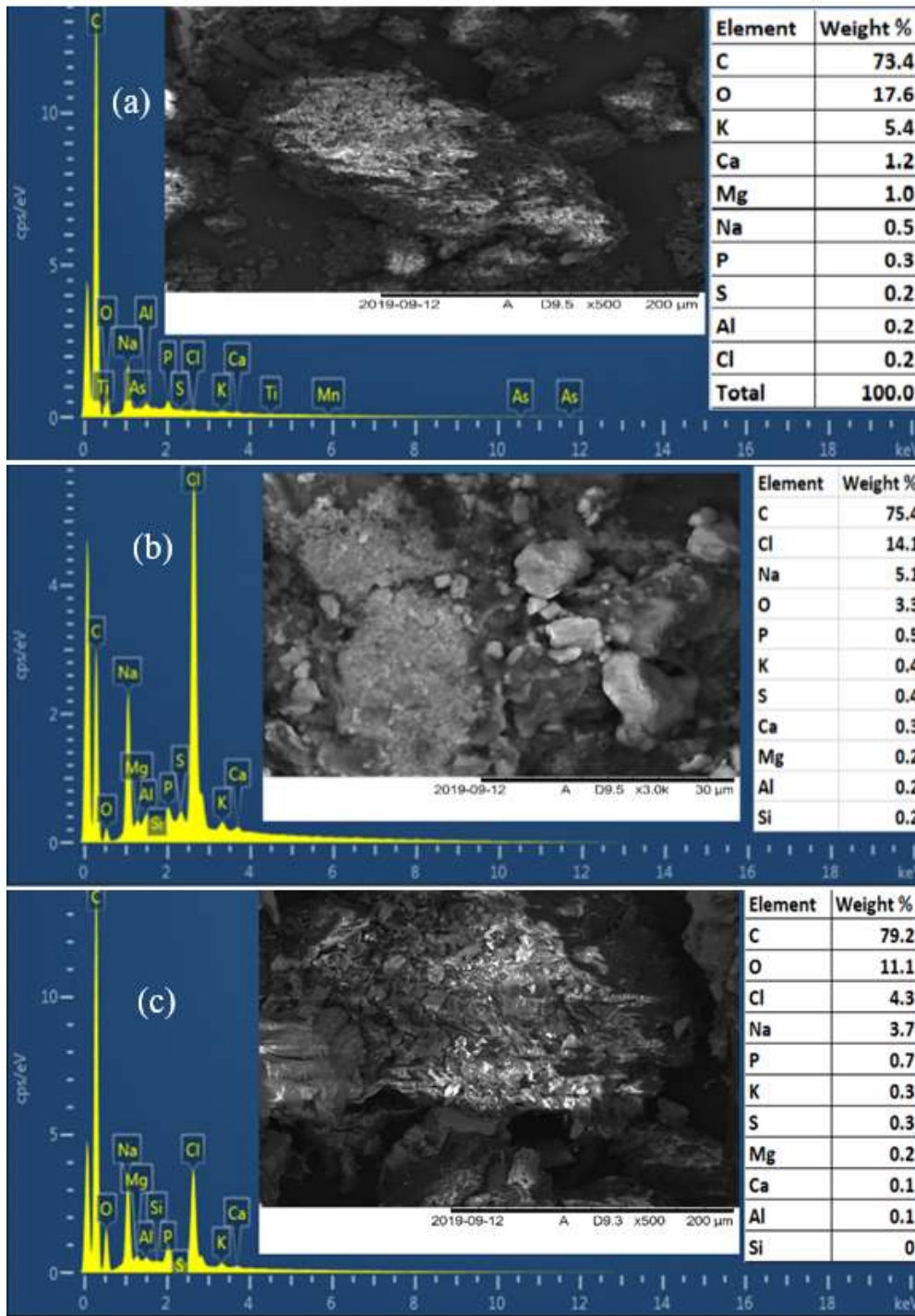
304 Table 2. Protein Characterization of KCPs.

KCP	Protein content (mg/L)	Zeta potential (mV)	pH
CrKP	667 ± 0.1	-21 ± 0.1	7.1 ± 0.0
StKP	1307 ± 0.2	-15 ± 1.0	6.3 ± 0.1
HxKP	1030 ± 0.1	-17 ± 0.3	6.8 ± 0.2

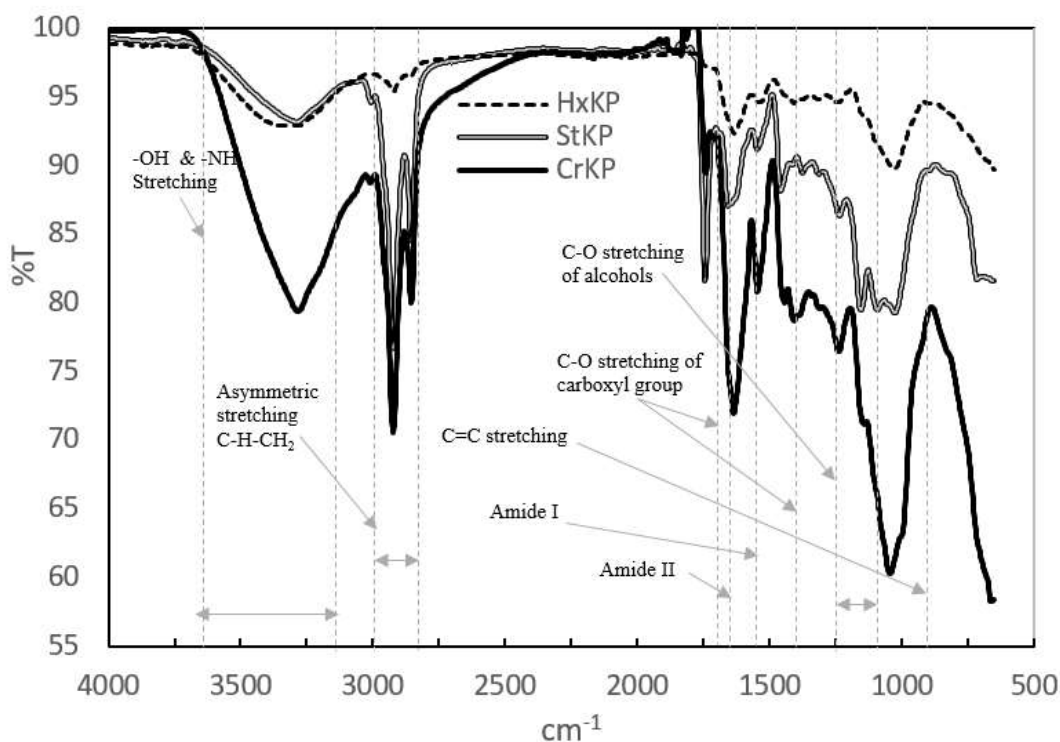
Result shown in mean concentration ± standard deviation (SD)

305 The SEM images of the CrKP, StKP and HxKP (Fig. 2a-c) reveal a heterogeneous flake-like
 306 structure. At a magnification of x500, it was observed that the CrKP had interconnected
 307 channels with narrow pores and flake-like structures, suspected to be the active binding sites.
 308 Results show a highly carbonaceous and fibrous structure of seed. Elemental composition of
 309 KCPs obtained by EDAX revealed an irregular shaped structure and highly carbonaceous
 310 material. Chemical analysis showed the presence of inorganic elements in trace amounts. From
 311 the mapping image and cross-sectional layout of the elemental profile, it was observed that
 312 Carbon (C) appears to be evenly distributed in the sample with a few dense spots noted (not
 313 shown) which confirms the high carbon content (73%) of the KCP. Inorganic elements detected

314 in trace amounts were K, Ca, Mg, Na, P, S, Al and Cl. Higher performance of the StKP and
 315 HxKP can be confirmed by the presence of a higher concentration of NaCl in both products.



316
 317 Fig. 2. SEM imagery and EDAX elemental analysis of the (a) Crude Kenaf, CrKP (b) Salted
 318 Kenaf, StKP and (c) Hexane Kenaf product, HxKP



319

320 Fig. 3 FT-IR spectra of crude, salt and hexane KCPs.

321 The FT-IR analytical spectrum depicted in Fig. 3 shows various functional groups present in
 322 the investigated KCPs. The bands between 3150cm^{-1} and 3500cm^{-1} correspond to hydroxyl (-
 323 OH stretching vibration mode) and amine group (-NH stretching) which are present in fatty
 324 acids, proteins and carbohydrates (Nidheesh *et al.*, 2017). Bands corresponding to peaks
 325 2925cm^{-1} and 2851cm^{-1} are attributed to asymmetric and symmetric stretching of C-H-CH₂ –
 326 an aliphatic compound, present in organic compounds such as fatty acids (Araújo *et al.*, 2010).
 327 Significant differences exist between the FT-IR spectra of the three KCPs, especially in C-H-
 328 CH₂ stretching vibration group, which show a higher peak in CrKP and StKP compared to
 329 HxKP. The difference could be due to the delipidating process, which resulted in the
 330 elimination of most of the fatty compounds present. Bands at $1721\text{-}1580\text{cm}^{-1}$ reflect the
 331 presence of carboxylic acid C=O and amides groups, respectively. Bands $1420\text{-}1460$, and the
 332 peak at approximately 1510 , correspond to C=C aromatic group. These groups are present in
 333 lignin, cellulose and hemicellulose (Meneghel *et al.*, 2013). The peak at approximately 1329

334 cm^{-1} indicates the presence of a C=O bond and N-H vibrational mode, which extends to
335 primary and secondary amides (Reddy *et al.*, 2011), therefore, confirming the presence of
336 protein in KCPs. Presence of phenols C-O is indicated by the band at 1237-1243 cm^{-1}
337 (Meneghel *et al.*, 2013). Spectra show a strong C-O band in 1055-1063 cm^{-1} which confirms
338 the presence of alcohols, ethers and carbohydrate (Musikavong and Wattanachira, 2013).
339 Different functional groups like C-O-C stretching illustrate the presence of polysaccharides
340 and -OH bending bonds in the spectral region between 1015 and 800 cm^{-1} (Kwaambwa and
341 Maikokera, 2008). These bands confirm the presence of coagulating compounds in KCPs.

342 **3.3 Evaluation of the coagulation/flocculation process**

343 **3.3.1 Effect of water turbidity and coagulant dosage**

344 The optimum dosage for the turbidity experiment was derived by using different protein
345 concentration shown in Table 3. The protein concentration was analysed using the Lowry
346 method of protein estimation (Lowry *et al.*, 1951) for the LTW and MTW ranging between 13
347 mg/L-100 mg/L, 26mg/L-196mg/L and 21 mg/L-154 mg/L for CrKP, StKP and HxKP,
348 respectively. After the jar test experiment, the minimum residual turbidity (RT) values for all
349 the water types were noted, and the dosages corresponding to these RTs were selected as the
350 optimum dosages which were used for subsequent experiment. The optimum CrKP, StKP and
351 HxKP dosages used in the HTW were selected from their estimated protein concentrations
352 ranging between 33-534 mg/L, 65-1046 mg/L and 51-824 mg/L respectively. The optimum
353 dosages derived for the high turbidity water (500 NTU) experiments were 824 mg/L for HxKP,
354 915 mg/L for StKP and 67 mg/L for CrKP. For medium turbidity (150NTU) water tested, the
355 optimum dosages were 82 mg/L, 196 mg/L and 67 mg/L for HxKP, StKP and CrKP while for
356 low turbidity water, optimum dosages obtained were 21 mg/L, 26 mg/L and 13 mg/L for HxKP,

357 StKP and CrKP, respectively. Derivation of the optimum KCPs dosages are not discussed in
 358 detail, only a summary of their performance is provided

359 Table 3. Protein dosage used for optimisation experiment tests in LTW, MTW and HTW.

Water type	KCPs	mg polymer/g of TSS (*)					
LTW	CrKP	0.18 (13)	0.36 (27)	0.54 (40)	0.73 (52)	0.91 (67)	1.36 (100)
	StKP	0.36 (26)	0.71 (52)	1.07 (78)	1.42 (105)	1.78 (131)	2.67 (196)
	HxKP	0.28 (21)	0.56 (41)	0.84 (62)	1.12 (82)	1.40 (103)	2.10 (154)
MTW	CrKP	0.04 (13)	0.08 (27)	0.12 (40)	0.15 (52)	0.19 (67)	0.29 (100)
	StKP	0.08 (26)	0.15 (52)	0.23 (78)	0.30 (105)	0.38 (131)	0.57 (196)
	HxKP	0.06 (21)	0.12 (41)	0.18 (62)	0.24 (82)	0.30 (103)	0.45 (154)
	Equivalent weight measured in the Jar test experiment (mg/L)	20	40	60	80	100	150
HTW	CrKP	0.03 (33)	0.06 (67)	0.12 (133)	0.23 (267)	0.41 (467)	0.46 (534)
	StKP	0.06 (65)	0.11 (131)	0.23 (262)	0.45 (523)	0.80 (915)	0.91 (1046)
	HxKP	0.04 (51)	0.09 (103)	0.18 (206)	0.36 (412)	0.63 (721)	0.72 (824)
	Equivalent weight measured in the Jar test experiment (mg/L)	50	100	200	400	700	800

360 * Values enclosed in brackets are protein concentration (mg/L) estimated using Lowry method.

361 Table 4 shows the optimum polymer concentration/ g of suspended solid, obtained for the
 362 coagulation/flocculation experiments. The optimum dosages for KCPs varied from 0.04 to 0.8
 363 mg polymer/ g TSS, with the CrKP having the least dosage. It is interesting to note that using
 364 dosages above the optimum CrKP dosage of 0.18 polymer/g TSS, diminished the particle
 365 destabilising ability, and this is attributed to high dissolved organic carbon content caused by
 366 its insoluble non-coagulating molecules. Conversely, the HxKP and StKP had a higher dosage

367 range owing to their additional treatment such as delipidation and salting-in, which improved
 368 the polymer-particle interaction.

369

370 Table 4. Optimum dosage of KCPs for treating High, Medium and Low turbidity water at pH
 371 7.

KCP	LTW	MTW	HTW
	mg polymer/g of TSS (*)		
CrKP	0.18 (13)	0.04 (13)	0.06 (67)
StKP	0.36 (26)	0.57 (196)	0.80 (915)
HxKP	0.28 (21)	0.24 (82)	0.72 (824)

372 * Values enclosed in bracket are protein concentration (mg/L) estimated using Lowry method.

373 Table 5 Residual turbidity (RT) NTU at different settling times for HxKP, StKP and CrKP in
 374 (a) LTW (b) MTW and (c) HTW. Experiment pH = 7

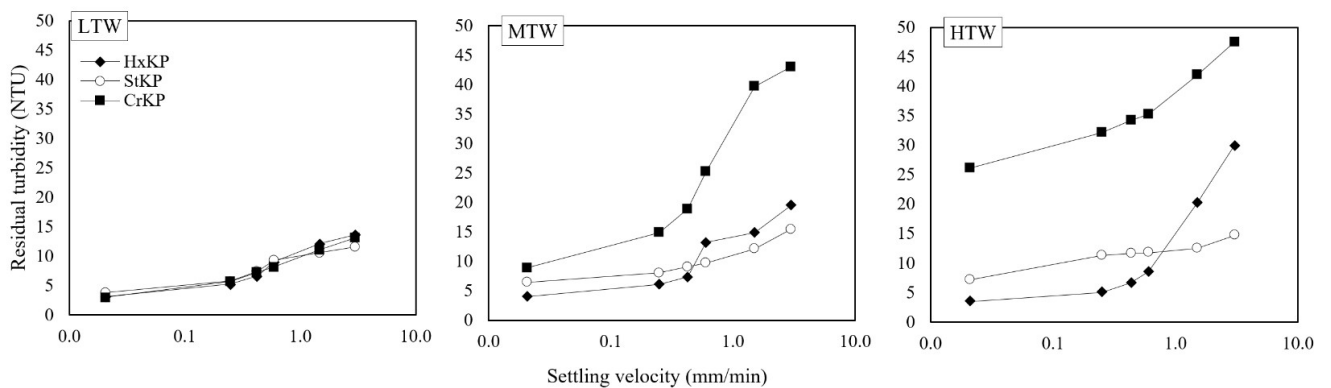
KCPs	LTW	MTW	HTW	LTW	MTW	HTW	LTW	MTW	HTW
	10mins			20mins			50mins		
CrKP	13 ± 0.15	43 ± 1	48 ± 0.78	11 ± 0.15	40 ± 0.56	42 ± 0.15	8 ± 0.05	25 ± 0.21	35 ± 0.15
StKP	12 ± 0.31	16 ± 0.3	15 ± 0.42	11 ± 0.23	12 ± 0.17	13 ± 0.25	9 ± 0.14	10 ± 0.16	12 ± 0.11
HxKP	14 ± 0.15	20 ± 0.31	30 ± 2.8	12 ± 0.1	15 ± 0.13	20 ± 0.12	9 ± 0.1	13 ± 0.24	9 ± 0.11
KCPs	70mins			120mins			1440mins		
	CrKP	7 ± 0.08	19 ± 0.1	34 ± 0.27	6 ± 0.18	15 ± 0.21	32 ± 0.13	3 ± 0.06	9 ± 0.06
StKP	8 ± 0.15	9 ± 0.04	12 ± 0.1	6 ± 0.17	8 ± 0.01	11 ± 0.03	4 ± 0.09	6 ± 0.16	7 ± 0.14
HxKP	7 ± 0.31	7 ± 0.05	7 ± 0.01	5 ± 0.15	6 ± 0.04	5 ± 0.01	3 ± 0.08	4 ± 0.03	3 ± 0.03

375 Result shown in mean concentration ± standard deviation (SD)

376 The values displayed in Table 5 shows that the minimum turbidity removal recorded for low
 377 and medium turbidity waters after about 70 mins settling period were 77%, i.e. attained 7 NTU

378 residual turbidity (RT) and 87% (RT of 7 NTU), respectively. The turbidity removal using the
 379 KCPs optimum values are shown in sedimentation curves given in Fig. 5. Comparing Fig. 4 a-
 380 c revealed that at 70min settling time, the HTW had the highest floc sedimentation rate,
 381 followed by medium and low turbidity waters. The floc settling velocity thresholds at 10min
 382 was 3 mm/min. Subsequent retention times of 20, 50, 70 120 and 1440mins gave average
 383 settling velocity of 1.5, 0.6, 0.43, 0.25 and 0.02 mm/min respectively. Settling velocity explains
 384 the average sedimentation rate of colloidal particles in the polymer-particle suspension. The
 385 settling velocity for all KCPs in the LTW was similar and varied little, compared to the MTW
 386 and HTW, and this was due to particle concentration in suspension.

387 From the figures, particle destabilisation was lowest at the highest settling velocity of 3
 388 mm/min. The influence of mixing after the flocculation process is seen in the high settling
 389 velocity at the start of residence (settling) time (10 min). As the residence time increases, the
 390 settling velocity reduces from 3 mm/min to 0.02 mm/min due to the reduction in the interaction
 391 of the flocculated particle. The CrKP gave the least residual turbidity for all the settling
 392 velocities at optimum dosages. The low performance of CrKP implies that it had a lower
 393 destabilisation power than the HxKP and StKP, especially in the MTW and HTW.



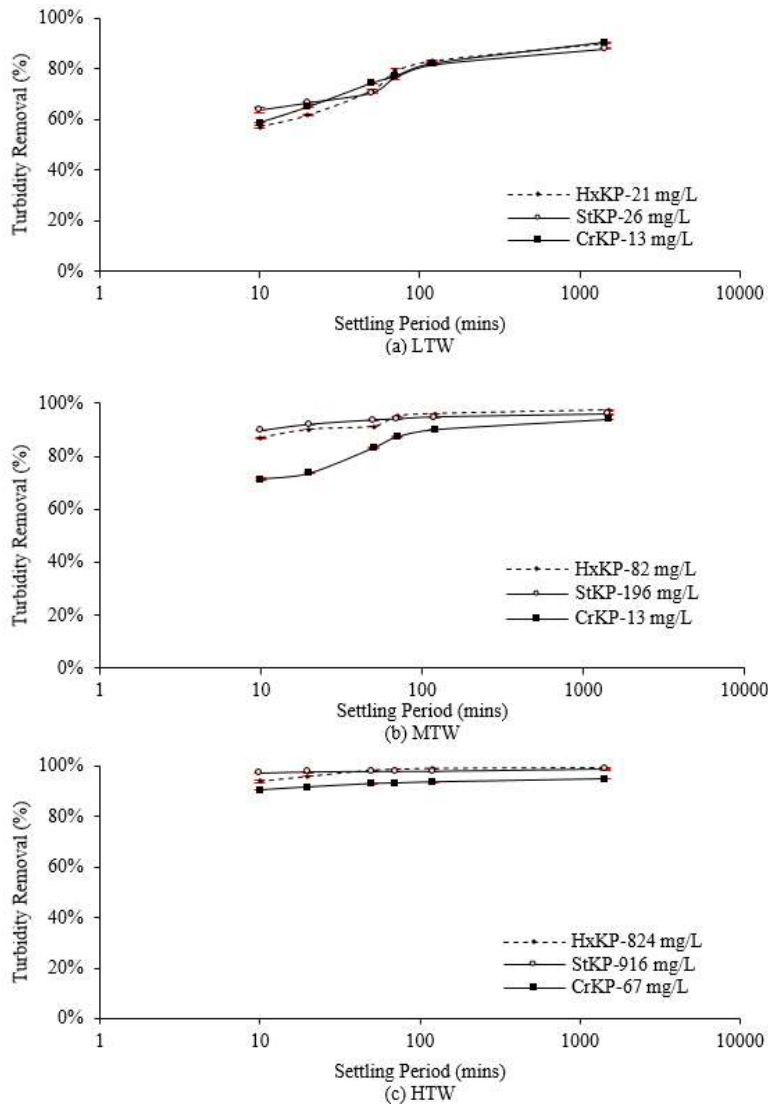
394

395 Fig. 4 Settling velocity distribution curve for optimum dosage of KCPs in (a) LTW (b) MTW
 396 and (c) HTW. Experimental pH = 7

397 From Table 5, the least turbidity removal recorded for optimum dosages of HxKP in LTW,
398 MTW and HTW were 57% (RT of 14 NTU), 87% (RT of 20 NTU) and 94% (RT of 30 NTU)
399 respectively after 10min of settling time. This is expected as most of the flocs formed only
400 began settling 10min post-flocculation period. Turbidity removal recorded for all the samples
401 exceeded 60% with the majority attaining 90% removal after settling for 10 mins. The high
402 sedimentation rate recorded was due to the rapid flocs settlement after the coagulation-
403 flocculation process using KCPs. Also, the high concentration of particles in the HTW might
404 have led to increased particle interaction and collision as they settle. Comparing the results
405 obtained after 70min settling time with that of WHO (2012) revealed that the treated water
406 exceeded the maximum allowable limit (MAL) of 4NTU.

407 Further evaluation of turbidity removal revealed that using optimum CrKP dosage of 66 mg/L
408 in HTW gave a removal of 93% (RT of 34 NTU) after 70 mins settling period. Both the
409 optimum value of the HxKP and StKP exceeded the turbidity removal of CrKP, by 6% and 5%
410 respectively. This reduced performance of the CrKP is likely caused by fatty substances and
411 the low concentration of coagulation agents in the KCP. The delipidating process of the HxKP
412 involved oil extraction from the seeds with hexane, an organic solvent which aided the removal
413 of most of the fat and oil present (Camacho *et al.*, 2017). The seed oil is said to form a barrier
414 around the PCPs, thus preventing contact between them and the particles in solution (Camacho
415 *et al.*, 2017). Improved performance of the salt extraction process is similar to reports of Okuda
416 *et al.* (1999) showing higher protein dissociation and increased solubility, thus demonstrating
417 that HxKP and StKP can significantly reduce the suspended particles in water.

418



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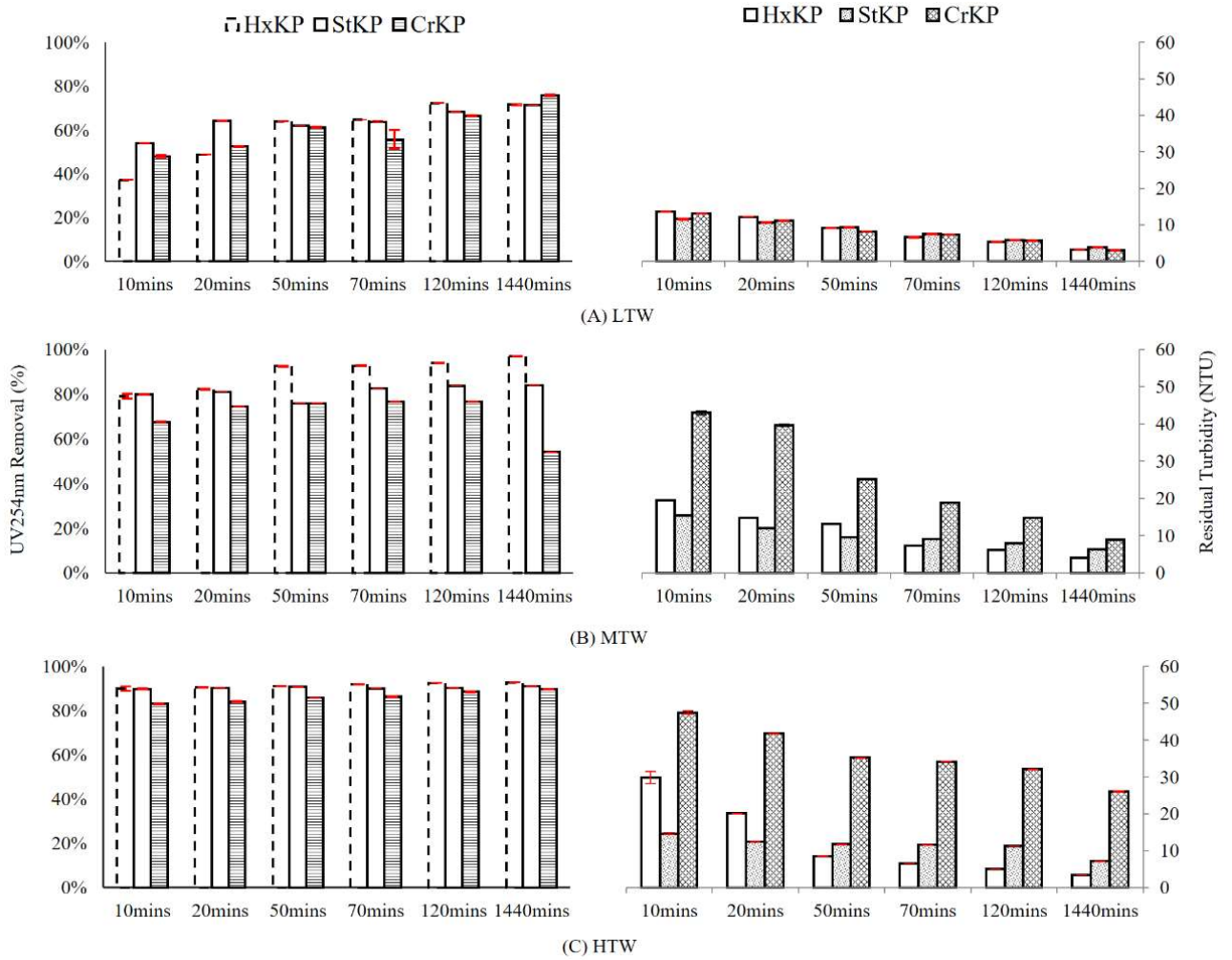
420 Fig. 5. Coagulation/flocculation assay showing turbidity removal percentage at different
 421 settling times for HxKP, StKP and CrKP in (a) LTW (b) MTW and (c) HTW. Experiment pH
 422 = 7

423 Prolonged settling time significantly influenced the final turbidity of the coagulated water. In
 424 the turbidity tests with prolonged settling periods (greater than 720 mins), turbidity was
 425 successfully reduced to 3 NTU for StKP. Similarly, for MTW, the turbidity value for HxKP
 426 and StKP at 720mins settling time were both 3 NTU, while 4 NTU was obtained when StKP
 427 was used in LTW. The best performance recorded at the 24-hour settling period revealed
 428 turbidity reduction of 99% (26 NTU), 97% (9 NTU) and 90% (3 NTU) for the HTW, MTW

429 and LTW samples, respectively. From the shape of the curve in Fig. 5a and Fig. 5b, it is
430 believed that clumping of particles and subsequent sedimentation continued after the slow stir
431 period. This continuous but gradual particle settlement could be attributed to the continuous
432 solubilisation of protein as experienced in another research using MO (Baptista *et al.*, 2015).

433 **3.3.2 Contribution of KCP dosage to organic load of treated water**

434 To complement the turbidity results and provide insight on the effects of KCPs on coagulated
435 water, NOM surrogates such as the DOC, SUVA₂₅₄ and UV₂₅₄ were analysed to determine the
436 concentration of dissolved organic matter, which is a known precursor to DBP. The analysis
437 for UV₂₅₄ absorbing compounds provided information on the aromatic (double-bonded ring
438 structures) organic matter present (Matilainen *et al.*, 2011). The optimum KCP dosages found
439 for turbidity also apply for the NOM surrogates, and were used for these tests. The UV₂₅₄ results
440 revealed significant removal across the various sample waters. As shown in Fig. 6a-c, the use
441 of hexane and salted KCPs gave higher removal than their crude form-CrKP. It can also be
442 seen that the HxKP gave the best UV₂₅₄ removal (93%) compared to the StKP (91%) and CrKP
443 (90%). The optimum protein concentration in the StKP coagulant was higher than the HxKP
444 and CrKP (Table 4), but despite this high protein content, removal of 254nm light absorbing
445 compounds was below that for HxKP, indicating a higher concentration of suspended and
446 dissolved compounds in the StKP itself. A similar trend exists for the optimum CrKP used,
447 which gave a higher UV₂₅₄ absorbance value than the HxKP and StKP. This is expected since
448 CrKP contains the highest concentration of suspended solids.



449

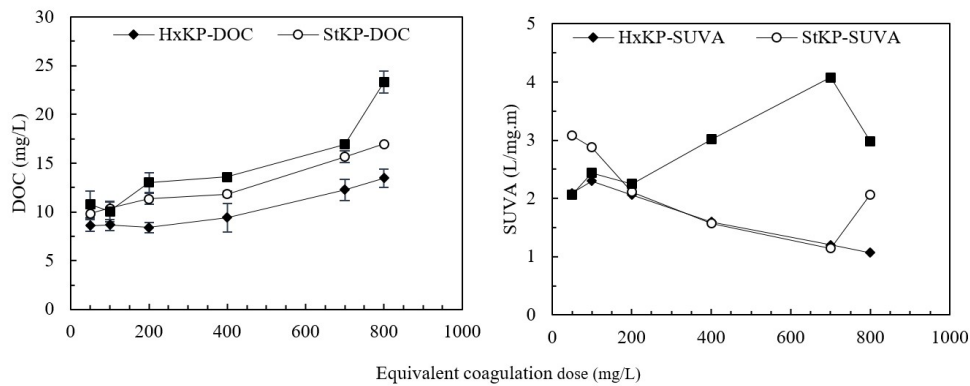
450 Fig. 6. Coagulation/ flocculation assay showing UV₂₅₄ removal efficiency at different settling
 451 times for HxKP, StKP and CrKP in (a) LTW (b) MTW and (c) HTW. Experiment pH = 7.
 452 Error bars signify standard deviation of triplicate measurements.

453 SUVA₂₅₄ values obtained in river water revealed high concentrations of organic matter content,
 454 predominantly of hydrophobic origin. Fig. 7 shows the DOC and SUVA₂₅₄ values over a range
 455 of KCP dosages. Based on the DOC analysis, the increase in KCP dosage resulted in a linear
 456 increase in DOC value specifically for the dose range 400 mg/L to 800mg/L, whereas the
 457 SUVA₂₅₄ analysis showed that KCP dosages above the optimum level led to an increase in
 458 values for the specific light-absorbing compounds at 254nm. For HTW, using optimum
 459 dosages of HxKP, StKP and CrKP slightly reduced the DOC after a 70min settling time, while

460 a value above the optimum range caused an increase in DOC concentration. The lowest DOC
461 concentration of 23mg/ L was recorded for CrKP dosage of 534 mg/L while similar dosages
462 for HxKP and StKP gave DOC values of 14 mg/L and 17 mg/L respectively, indicating that
463 the crude extract performed poorly relative to the other KCPs. Treated water TOC
464 concentration above the USEPA guideline value of 2mg/L is presumed to favour chlorinated
465 by-products formation (USEPA, 2010), the KCPs DOC were above this range, indicating that
466 an additional treatment process would be required to make water potable. Also, KCPs
467 contribution to the DOC of treated water confirms that the chemical components in the seed
468 can decrease water quality. This is probably due to the high dosages required for KCPs when
469 applied as primary coagulant, and could be potentially resolved using KCPs as coagulant aids
470 (lower dosages) instead. Similar reports exist confirming PCPs contribution to DOC of treated
471 water (Feihrmanna *et al.*, 2017) and this is worrisome as the continued presence of these
472 compounds in treated water could encourage DBP formation on disinfection.

473 The $SUVA_{254}$ values derived when optimum dosages of HxKP, StKP and CrKP were used in
474 HTW were 1.1 L/mg.m, 1.1 L/mg.m and 2.2 L/mg.m. Comparing these results with the
475 $SUVA_{254}$ value of untreated water (14 L/mg.m) in Table 1 shows a $SUVA_{254}$ reduction of 92%
476 for both HxKP and StKP and 84% for CrKP. All $SUVA_{254}$ values obtained were below 4,
477 except for a CrKP dosage of 467 mg/L. $SUVA_{254}$ values below 4 reflect acceptable extent of
478 hydrophobic and non-humic hydrophilic compounds in the water while a value above 4 implies
479 that the system may require additional treatment processes to dispose of the organic load
480 (Matilainen *et al.*, 2011). The reduction of $SUVA_{254}$ by the HxKP and StKP was because of
481 the delipidating and salting-in process, which do not occur for the CrKP. The delipidating
482 process possibly reduced the lipids content which is responsible for forming an oil or emulsion
483 coat around the coagulating agents, leading to a reduction of reactive surfaces for the
484 coagulation/flocculation processes. Examination of the FT-IR spectra of CrKP, StKP and

485 HxKP in Fig. 3, shows reduction (especially for the HxKP) in bands between 3150cm^{-1} and
 486 3500cm^{-1} . These bands correspond to the hydroxyl group (-OH stretching vibration mode),
 487 which are present in fatty acids (Nidheesh *et al.*, 2017). The delipidating process possibly
 488 removed the lipophilic compounds from the seeds responsible for sheathing protein in solution.

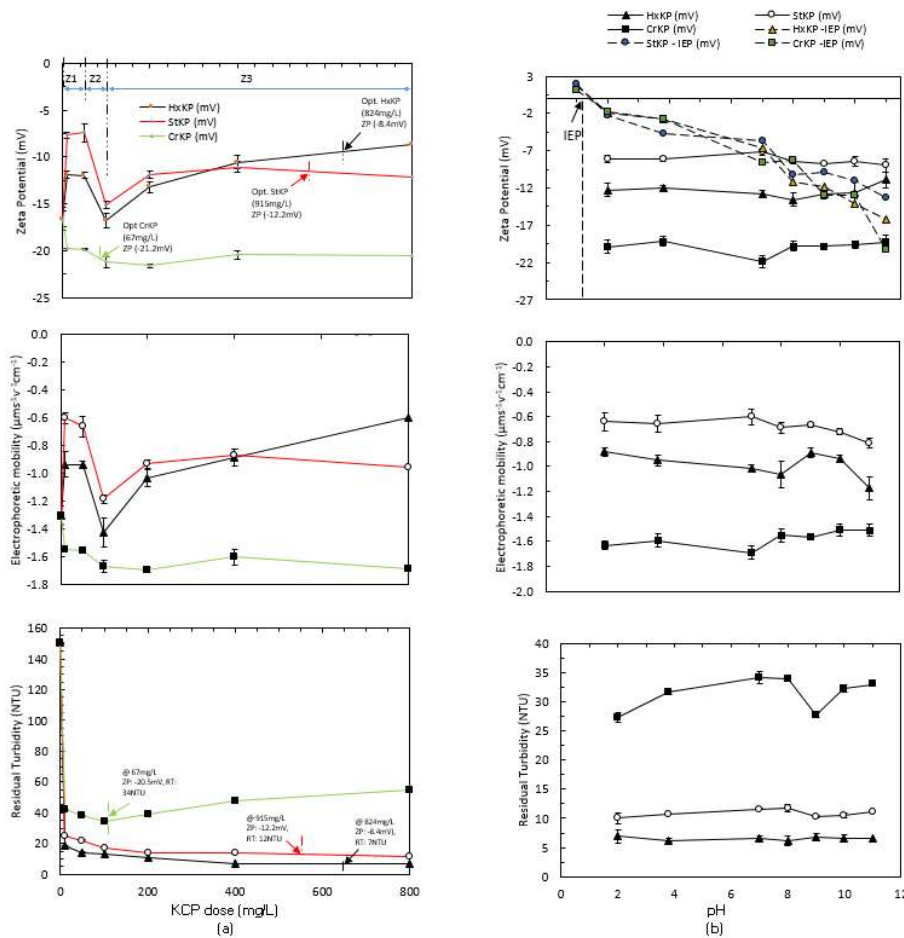


489
 490 Fig. 7. DOC and SUVA_{254} values for different KCP Dosage in HTW using HxKP, StKP and
 491 CrKP. Conditions: settling period = 70 mins, pH = 7. Error bars signify standard deviation of
 492 triplicate measurements

493 Allowing the treated water stand for 24-hours (1440 mins) and 48-hours (2880 mins) showed
 494 a significant difference in DOC and turbidity level. In order to avoid odour issues, previous
 495 studies recommended a 24 h storage duration for PCPs (Jahn *et al.*, 1986; Jones and Bridgeman,
 496 2016). In this study, it was observed that the optimum dosage of HxKP and StKP produced no
 497 odour at 48 h storage period. In many practical cases, the 48h residence time is likely to be
 498 used by households in rural areas, especially communities located several kilometres from
 499 untreated water sources. This long storage time may require chlorine disinfection to make water
 500 safe and free from objectionable odours caused by microbial decomposition of organic
 501 materials.

502 3.3.3 KCPs Coagulation Mechanism

503 The particle-polymer interaction shown in Fig. 8a, is grouped into three regions. The first
504 region (zone 1) illustrates the behaviour of KCPs below their optimum dosage and gradual
505 destabilisation of suspended particles. Particle destabilisation is indicated by a decrease in the
506 particle electrophoretic mobility (EM) for StKP and HxKP respectively. For the CrKP, an
507 initial increase in the EM signifies poor floc formation as illustrated by lowest residual
508 turbidity. In zone 2, the negative mobility of the suspended particles in all water increased to
509 the prominent point of inflection. This increase, which is similar to the previous zone, reflects
510 low turbidity removal. Following the inflection, the negative mobility of the particles decreased
511 (zone 3) up to the optimum dosage of the HxKP, slightly increased for the StKP, while the
512 CrKP remained unchanged. A change is seen in the residual turbidity for StKP and HxKP,
513 respectively. However, CrKP dosages caused the resuspension of particles. Fig. 8a gives the
514 zeta potential of the KCPs across a range of dosages. The use of different KCPs dosages gave
515 significantly different zeta potential values. Two-way analysis of variance showed that there
516 was a significant difference ($p < 0.05$) between the zeta potential of HxKP, StKP and CrKP (F
517 = 44.91, $p = 0.00$). This change in zeta potential value provides evidence of particles
518 destabilisation and restabilisation for the range of dosages used. Different particle stability
519 reported may be because of a range of reasons including molecules in KCPs (polymer), the
520 influence of their polymer preparation technique such as salting-in, and the untreated water
521 chemistry such as the valency of ions present.



522

523 Fig. 8. (a) Zeta potential, electrophoretic mobility and residual turbidity – dosages profile of
 524 KCPs in HTW; pH = 7 (b) Zeta potential, electrophoretic mobility and residual turbidity – pH
 525 profile of KCPs in HTW using optimum dosages Conditions: settling period = 70 mins; error
 526 bars signify standard deviation of triplicate measurements. IEP curve for medium ionic strength
 527 water solution (0.5M) is shown by the dotted lines; solid lines depicts HTW. Z1, Z2, Z3 depicts
 528 zone1, 2 and 3.

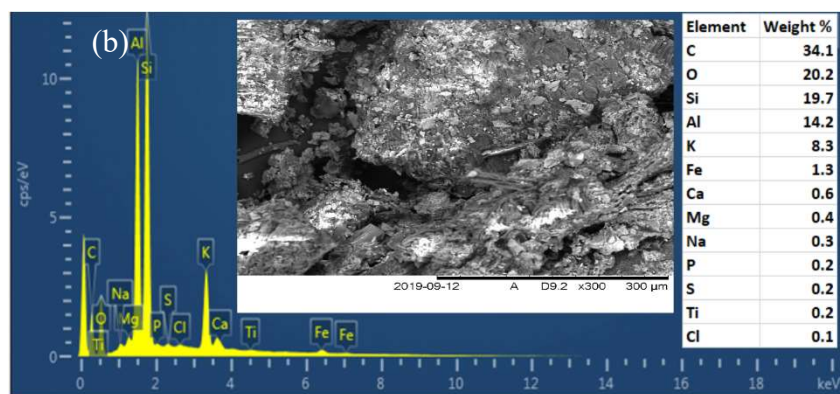
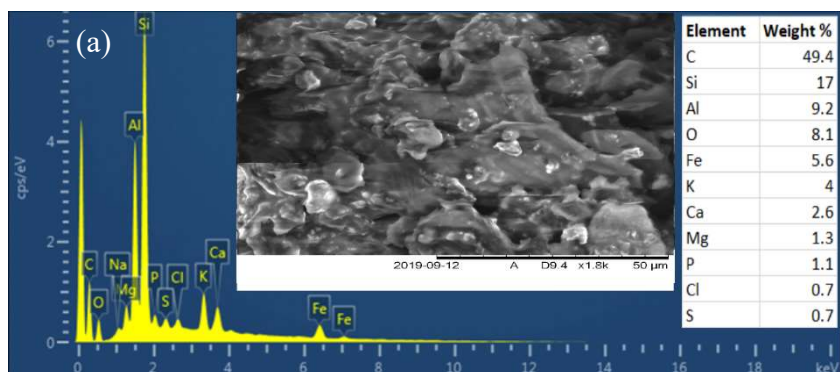
529 Acidic and basic pH influences the magnitude of the zeta potential (ZP) by making it more
 530 positive or negative (Bhattacharjee, 2016). The ZP magnitude gave useful information on the
 531 surface electrical properties of the polymer-particle suspension. Fig. 8b shows the isoelectric
 532 point (IEP) of KCPs at their optimum dosage. IEP was approximately at 1.5, confirming that
 533 KCPs are anionic and that negative charges predominate on their surface. Around the IEP, the

534 suspension is unstable, and the chances of particles clumping together is high. Acidity causes
535 the KCPs to be hydrolysed into a cationic polymer, favouring reaction with negatively charged
536 NOM. Consequently, the energy barrier between the two surfaces is overcome, resulting in floc
537 formation. Based on residual turbidity of the KCPs, it is hard to rule out adsorption of anionic
538 polyelectrolytes to the surfaces of negatively charged particles. Adsorption was facilitated by
539 increase in ionic strength of the suspension by the salting-in process during KCPs preparation,
540 which increases the sodium chloride concentration of the suspension, leading to increased ionic
541 strength. This rise in ionic strength has previously been reported to improve particle
542 destabilisation (Oladoja *et al.*, 2017).

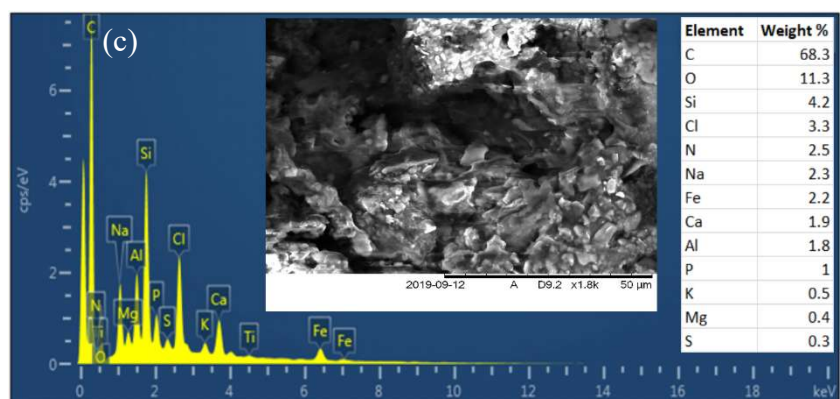
543 It is also worth noting that cations such as calcium, magnesium, potassium and sodium are
544 present in natural water samples. The EDAX analysis indicated in Fig. 9, provides evidence of
545 divalent (Ca^{2+} , Mg^{2+}) and possibly trivalent cations (Fe^{3+} , Al^{3+}) in the water. At a low pH, Ca^{2+}
546 preferential binds with the carboxylic groups while Zn^{2+} prefers the amine group (Adusei-
547 Gyamfi *et al.*, 2019). It is assumed that other cations in the suspension bounded to various
548 functional groups present such as the hydroxyl, carboxyl, amine and methoxy groups as
549 previously observed in the FT-IR spectra (Fig. 3), which have undergone the hydrolysis
550 process. Their dissociation minimised the negative charge density on the KCPs, causing
551 attraction of negatively charged particles and later production of several attractive and
552 repulsive interactions such as polymer-polymer and polymer-particle interaction. Similar
553 reaction involving low calcium concentration assisted in flocculating negatively charged
554 particles by linking anionic sites on polymer and particles by a 'calcium bridging' process
555 (Gregory, 2013). Based on this observation, the turbidity removal by the HxKP and StKP was
556 thought to be because of complexation of functional groups on their surface with ligands
557 possessing opposite charges. It is assumed that an increase in ionic strength caused
558 compression of the electric double layer (EDL) and led to a decrease of the zeta potential of

559 the water. Conversely, the water treated using CrKP, had a lower ionic strength which slightly
 560 decreased the particle's zeta potential causing only a partial destabilisation of particles.

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 564



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 566

567 Fig. 9. SEM imagery and EDAX elemental analysis of sludge of (a) CrKP treated water (b)
 568 StKP treated water (c) HxKP treated water

569 Furthermore, the proximity of KCPs active sites to colloid particles can also result in stronger
 570 bridge assembly, causing friction due to their proximity, and this must have led to the bridging-
 571 out coagulation recorded especially for HxKP and StKP. Obstruction of some active binding
 572 sites by non-coagulating molecules and poor protein solubility is likely to have reduced the

573 effectiveness of the CrKP. Besides, the optimum dosages used in water increased with the
574 particle concentration, which supports the adsorption phenomenon. KCPs have low to medium
575 weight ranging from 10 – 100 kDa (Mariod *et al.*, 2010; Jones, 2016), which further confirms
576 their ability to promote particle-polymer interactions. However, considering the performance
577 recorded for the KCPs, it was evident that electrostatic repulsion, which is associated with the
578 charge neutralisation process, was not the dominant coagulation mechanism. Although there
579 was a slight decrease in EM and the zeta potential value, these values remained negative
580 indicating that the polycations were insufficient in removing the negative charge. It is also
581 unlikely that sweep flocculation took place since EM remained negative. So, based on the
582 strength of above observation, the KCPs coagulation mechanism is a combination of particle
583 electric double layer compression by polymeric compounds facilitated by ligand complexation
584 or particle adsorption on one or more sites through charge-charge interaction, hydrogen
585 bonding and van der Waals forces of dispersion.

586 **4. Conclusions**

587 This study examined the use of Kenaf Coagulation Products (KCPs, an extract of Kenaf plant
588 seeds) produced using three methods: crude extract (CrKP), salted extract (StKP) and hexane
589 (delipidated) extract (HxKP). The structural characteristics of CrKP, StKP and HxKP and their
590 performance in terms of turbidity removal, dissolved organic carbon (DOC) concentration,
591 specific absorbance (SUVA₂₅₄) value in high (HTW), medium (MTW) and low (LTW)
592 turbidity water have been measured. Results obtained from the SUVA₂₅₄, DOC, FT-IR, SEM–
593 EDAX analysis, IEP and pH values can be summarised as follows:

- 594 • Soluble protein concentration of KCPs, determined by Lowry's method, varied and was
595 of the order HxKP > StKP > CrKP. Variation in concentration was due to salting-in

596 effect which aided in the dissolution of active coagulation components, and delipidating
597 effect on seed which removed the poorly coagulating compounds.

598 • StKP and HxKP were found to be effective for turbidity treatment of both MTW and
599 HTW (>90%) whereas performance in LTW was below 80%. For all waters tested,
600 HxKP gave the highest turbidity followed by StKP then CrKP. HTW and MTW
601 required higher KCPs dosages than the LTW.

602 • SUVA₂₅₄ values showed that pre-treatment of water with HxKP and StKP significantly
603 removes the hydrophobic fraction of NOM in water, thus, reducing the potential for
604 THMs formation during disinfection. A linear relationship existed between the KCPs
605 dosage and DOC, implying that the addition of organic matter from the KCPs occurs
606 as dosage increases. The study shows the benefit of optimum dosage selection in
607 controlling DBPs precursor concentration in water.

608 • Particle bridging facilitated by the adsorption process was the destabilisation
609 mechanism of KCPs, and their performance was only slightly affected by the pH of
610 water. Also, the IEP of KCPs was found to be approximately 1.5, signifying that
611 surfaces are predominantly negatively charged.

612 • The FT-IR and SEM – EDAX studies indicated the bonding mechanism of the KCPs.
613 The bonding between suspended particles and KCPs was mainly by the shielding and
614 attachment using their flake-like structures of the KCPs.

615 By comparing both the qualitative and quantitative analysis, the KCPs studied can be used only
616 as a pre-treatment coagulant where there is no suitable alternative coagulant for effective
617 treatment of LTW, MTW and HTW. Irrespective of the untreated water turbidity, using
618 dosages outside of the optimum dosage range can affect treatment performance. Further
619 research effort should focus on getting high-performing low-cost purified KCP to provide users
620 and scientific community with information on their treatment efficiency and their range of

621 application. KCPs contributes differently to the organic matter load of the treated water and
622 their performance also depends on the untreated water turbidity and settling duration. High
623 organic load recorded for the KCPs treated water especially for CrKP, makes them potential
624 precursors for DBPs formation on disinfection. Since, no studies currently exist profiling KCPs
625 ability to form DBP under typical exposure conditions, new studies would help to address and
626 overcome this knowledge gap and also identify the safest conditions needed for their use.

627 **CRedit authorship contribution statement**

628 Benjamin U Okoro: Methodology, Software, Formal analysis, Investigation, Data curation,
629 Writing - original draft.

630 Soroosh Sharifi and Mike Jesson: Conceptualization, supervision, writing - review and editing

631 John Bridgeman and Rodrigo Moruzzi: Conceptualization, writing – review and editing.

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636 **References**

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