Studies on Natural Water Coagulants in the Sudan, with Special Reference to Moringa Oleifera Seeds

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Abstract

The coagulating properties of powdered seeds of *Moringa oleifera Lam.*, known as a traditional water coagulant in rural areas of the Sudan, were compared to those of alum, powdered root of *Maerua pseudopetalosa (Gilq & Bened.) De Wolf* and a mixture of *Hibiscus sabdariffa L.* seeds and soda.

Moringa seeds acted as a primary coagulant and compared favourably with alum with respect to rate of reaction and the decrease in turbidity of the treated water. Preliminary studies on the identification of the coagulating principles are also discussed.

The use of Moringa seeds in folk medicine and as a food, makes it unlikely that they contain any toxic substances. There is, however, evidence that *Maerua pseudopetalosa* is toxic and this needs further investigation.

The total bacterial count of the raw water was initially reduced after coagulation with Moringa seeds, but increased subsequently.

The results obtained with the seeds were also compared with those obtained when traditional water coagulants of soil origin were used.

Introduction

The rural population of the Sudan constitutes approximately 80% of the total inhabitants of the country and water is of vital importance in rural areas, both with respect to availability and wholesomeness. Many people have to use muddy water from rivers or intermittent streams (khours) during the rainy season or turbid water from natural rain ponds and from artificial rain water catchments (hafirs) during most of the year. Treatment of the water is traditionally done using natural coagulants of plant and soil origin (Jahn, 1976) and in some areas using alum and soda.

The crushed seeds of Moringa trees (*Moringa oleifera* Lam. and *Moringa peregrina* (Forssk.) Fiori) were found to be a promising coagulant. This paper deals with laboratory experiments with *Moringa oleifera* seeds in comparison with other experimentally tested natural coagulants of the Sudan, India and Peru.

Materials and Preparation

Raw water

The raw water for the experiments was obtained from two hafirs, *viz.* the Hafir of El Qerabin which is in a mountainous area of the Blue Nile Province, south of Sennar and west of the Blue Nile, and the Hafir of Wad Hassuna in the Butana, Khartoum Province, east of the River Nile.

The colour of El Qerabin water was grey to chalky, possibly due to clays. A chemical analysis by the Laboratory of the Ministry of Agriculture and Natural Resources, April 1976, did not provide further information on this point.

Wad Hassuna water was reddish brown in colour. Iron (as Fe) was found in concentrations of 40 – 50 mg/l in the unfiltered water. After filtration no iron could be detected (Chemical Laboratories of the Ministry of Health, December 1975 and March 1976). The pH was 8,5 in El Qerabin and 7,2 – 7,5 in Wad Hassuna water.

The total solids in unfiltered El Qerabin water amounted to 7290 – 8640 mg/l and in Wad Hassuna water to 6480 – 8100 mg/l.

Moringa seeds

Moringa oleifera Lam. is a cultivated tree in the Sudan, belonging to the family of *Moringaceae*. It is called "shagara al rauwāq" (clarifier tree) in Sudanese Arabic, a name which already indicates its importance for water purification. Seeds were collected in the Gezira and Blue Nile Province. The average weight of the seeds is 0,27 g.

The native custom is to crush the seeds in mortars and the powder is then added to a small amount of water in a deep plate or a calabash and sometimes stirred for 10 – 30 min. The suspension is then poured on the turbid water in the water jar of burnt clay or other material.

In laboratory experiments the seeds were crushed in a mortar when fine powder was required and ground by means of a small electrical blender when an extra fine powder was required.

Root of Maerua pseudopetalosa

Maerua pseudopetalosa (Gilg & Bened.) De Wolf is a woody herb or subshrub belonging to the family *Capparidaceae*. It is found in parts of the Blue Nile Province, the Western Sudan and the Southern Provinces and is known as "kordala" in Sudanese Arabic.

According to traditional water treatment methods a piece of the root is put in turbid water and turned around (by nomads and semi-nomads in the El Qerabin and Jebel Dali area) or crushed root is added to the water (in areas between Burām and Bahr el Arab in Southern Dafur).

In laboratory experiments a powder was prepared from the root.

Seeds of Red Sorrela

Red Sorrela (*Hibiscus sabdariffa* L.), a subshrub, belonging to the family of *Malvaceae*, is cultivated in the Sudan, but not used for water purification. (In Sudanese Arabic the plant is called "kerkadē".)

The laboratory experiments with Red Sorrela seeds were carried out according to a method recently recommended for Indian villages (Bulusu and Pathak, 1974.)

Alum

Alum is used as the essential water coagulant in public water works in the Sudan. The experiments were carried out with "filter alum".

Methods and Results

Turbidity tests

The coagulating effects of the plant materials and alum were studied by a simplified "jar test". The coagulant was added in a concentration of 200 mg/l to cylinders containing 500 ml of muddy water. Stirring was carried out for exactly 5 min using a glass rod. The degree of clarification was measured in terms of

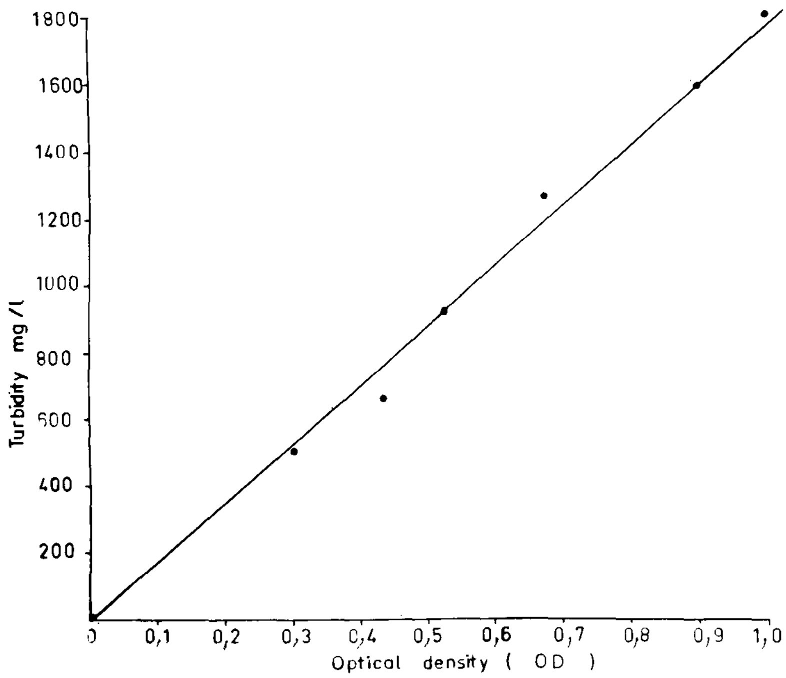

Figure 1
Optical density readings plotted against total solids in unfiltered raw water

optical density (OD) with a Hilger colorimeter using a blue filter (4 300 nm) with distilled water as a blank. The optical density of the raw water was measured immediately before the start of the experiment. After addition of the coagulant further readings were taken at 15 min intervals over a period of one hour. In order to allow comparison of the results obtained with those of work carried out at other laboratories, the total solids of the water was determined and a conversion curve prepared (Fig. 1). Turbidity of untreated hafir water was unchanged after 50 to 60 min or was reduced by a maximum of 7%.

Samples for OD determinations were taken with a pipette from the geometrical centre of the water column. Special care was taken to ensure that neither cleaner water from the top of the cylinder nor any of the floc was drawn up by the pipette.

Moringa seeds in comparison with other water coagulants

In a first series of experiments the properties of powdered Moringa seeds were compared with alum as a water coagulant. When both were added to water from the El Qerabin hafir in a concentration of 200 mg/l, their reaction rates and turbidity reduction were very similar; alum giving only a further 1% reduction on initial turbidity (Fig. 2).

The clarifying effect of *Maerua pseudopetalosa* when added at the same concentration, was almost completed after 30 mins as was the case with Moringa and with alum, but the reduction in turbidity was 4,4% less than with Moringa (Fig. 2). Maerua root can therefore be regarded as an effective water coagulant, but there were disadvantages such as the formation of foam when the powdered root was stirred in the raw water and a brownish discoloration of the clarified water as well as some plant odour. It would appear that the root contains a gum-like substance which causes the foaming and also stickiness of the root powder as soon as it becomes wet.

Red Sorella (*Hibiscus sabdariffa*) seeds do not act as a primary coagulant but as a 'coagulant aid' and were therefore mixed with soda in the proportion of 9:1 by mass. This mixture was added at a dose of 40 mg/l to water from the El Qerabin hafir and according to the dosage indicated for high turbidity (7 600 ± 300 turbidity units). After 40 min the residual turbidity was

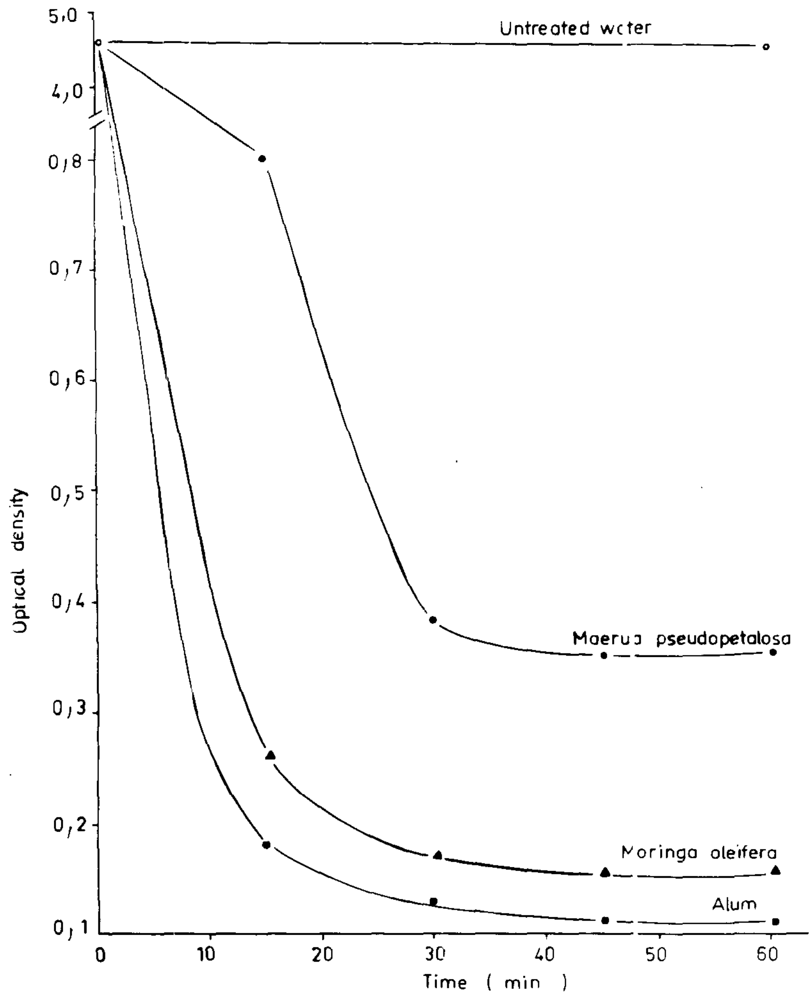

Figure 2
Coagulating properties of Moringa oleifera *seeds in comparison with alum and the root of* Maerua pseudopetalosa *for raw water of the Hafir of El Qerabin (concentration of coagulants: 200 mg/l)*

55,2% and after one hour 46%. Even after 9 h it had only dropped to 10,6% which is slightly higher than the maximum residual turbidity measured in El Qerabin water 60 min after treatment with Moringa seeds.

The coagulating properties of Moringa seeds

Comparison between whole seeds and seed pulp

People in rural areas usually claim that the "wings" of the seeds should be removed before crushing them in the mortar, but that the seed coat should be left or only partially removed. In the case where the seeds are used in folk medicine, for example among Fellata minorities in Khuwei in Northern Kordofan, the seed coat is carefully removed in order to crush only the pulp material. Some women in the area of Roseires (Blue Nile Province) place the crushed seeds in a small bag of thin cloth to which a thread is attached and stir the bag in the turbid water in the jars and by so doing effectively clarify the water with a filtered extract of the seeds.

In order to judge the efficiency of different traditional modifications, laboratory experiments were performed with extra fine powder of seed pulp and fine as well as extra fine powder prepared from whole seeds. The three different powders were added in concentrations of 200 mg/l to water from the El Qerabin hafir. Seventy-five minutes after the onset of the experiment extra fine seed powder had reduced the turbidity by 98%, fine seed powder by 97% and extra fine powder of the pulp by 96%.

Pure seed cover material dosed at a rate of 200 mg/l reduced the initial turbidity of hafir water by only 9,5% after 60 min, whereas simultaneous sedimentation of the untreated water resulted in turbidity reduction of 5,3%.

Determination of the optimum concentration

Extra fine powder from whole seeds which had been the most efficient in previous experiments was tested in concentrations of 100, 200, 400 and 800 mg/l. The best effect on water from the El Qerabin hafir was obtained with a concentration of 200 mg/l. Lower and higher concentrations were less effective (Table 1).

Effect of a "standard concentration" on raw waters with different chemical composition

Daily fine adjustments in the concentration of the natural coagulant to compensate for the fluctuations in turbidity occurring in natural waters, are not feasible in rural surroundings. The proper dose of the coagulant, therefore, depends mainly on observation and for this reason the results of water purification in a particular village may show great variation (Jahn, 1977a).

As mentioned previously, suspended matter of El Qerabin and Wad Hassuna water was not identical. Moringa seed powder at a concentration of 200 mg/l was added to the two types of hafir water when total solids concentrations were the same (8 100 mg/l.) One hour after commencing with coagulation the residual turbidity dropped to 5,8% (470 mg/l) in El Qerabin water, but was twice as high, 11,1% (900 mg/l), in Wad Hassuna water. (In both cases a higher concentration of the plant coagulant might have given better results.)

The results of these experiments are summarized in Table 2.

TABLE 1
EFFECT OF DIFFERENT CONCENTRATIONS OF EXTRA FINE MORINGA SEED POWDER ON THE RESIDUAL TURBIDITY (TOTAL SOLIDS OF RAW WATER FROM EL QERABIN HAFIR : 7 300 mg/l)

Coagulant concentration (mg/l)	Residual turbidity in percent after (a) 40 min	(b) 80 min
100	5,1	4,0
200	2,4	2,0
400	3,9	2,9
800	5,9	5,9

TABLE 2
COMPARISON OF THE COAGULATING EFFICIENCY OF 200 mg/l MORINGA SEED POWDER ON TWO DIFFERENT TYPES OF RAW WATER

Original Optical Density	Optical Density, 60 min after adding the coagulant	Residual turbidity (%)
Water from El Qerabin hafir		
4,05	0,08	1,98
4,20	0,13	3,10
4,50	0,26	5,78
4,60	0,15	3,26
4,65	0,17	3,66
4,80	0,35	7,29
Water from Wad Hassuna hafir		
3,60	0,40	11,11
3,75	0,52	13,87
3,95	0,48	12,15
4,10	0,32	7,80
4,50	0,50	11,11

Experiments on the nature of the coagulating principle in Moringa seeds

In order to obtain more information on the nature of the coagulating constituent(s), the following experiments were done:

Suspension of seed powder in distilled water

In an experiment similar to that depicted in Fig. 2, extra fine dry seed powder was added in a concentration of 200 mg/l to El Qerabin water. After 60 min the residual turbidity was 2,3%. When the same amount of powder was suspended in a small quantity of distilled water before it was poured into the raw water, the coagulating effect was less. With a suspension prepared 1 min before onset of the experiment the residual turbidity after 60 min was 8,7% and with a suspension prepared 30 min before onset of the experiment it was 9,7%.

Boiling the seed powder suspension

The coagulating properties of Moringa seed powder were even more reduced if the suspension was boiled before it was added to the hafir water. With a suspension boiled for 30 min the residual turbidity was 18,8% after 1 h. However, it is important to note that most of the coagulating ingredient of the seeds was not destroyed by boiling.

Dialysis

When 200 mg/l Moringa seed powder suspension was dialysed for 24 h against distilled water at 4°C most of the coagulating activity was lost. The dialysed sample was only capable of lowering the initial turbidity to 71,4%.

Oil extraction

The seeds of *Moringa oleifera Lam.* contain Ben or Behen oil. After extraction of this oil by petroleum spirit the cake, tested in a concentration of 200 mg/l remained an effective coagulant, reducing the initial turbidity of El Qerabin water by 93,3%. The oil fraction had no effect.

Incineration

Ash from Moringa seeds, tested in concentrations of 200, 400 and 800 mg/l had no coagulating effect.

Effect of Moringa seeds on the bacteriological quality of water

Samples for microbial counts were taken in the same way as those for OD determination. Total bacterial counts were carried out by the pour plate method using Difco plate count agar. Plates were incubated at 37°C for 48 h.

The total bacterial count of Wad Hassuna water amounted to 1 x 10^5/ml. Thirty minutes after adding 200 mg/l Moringa

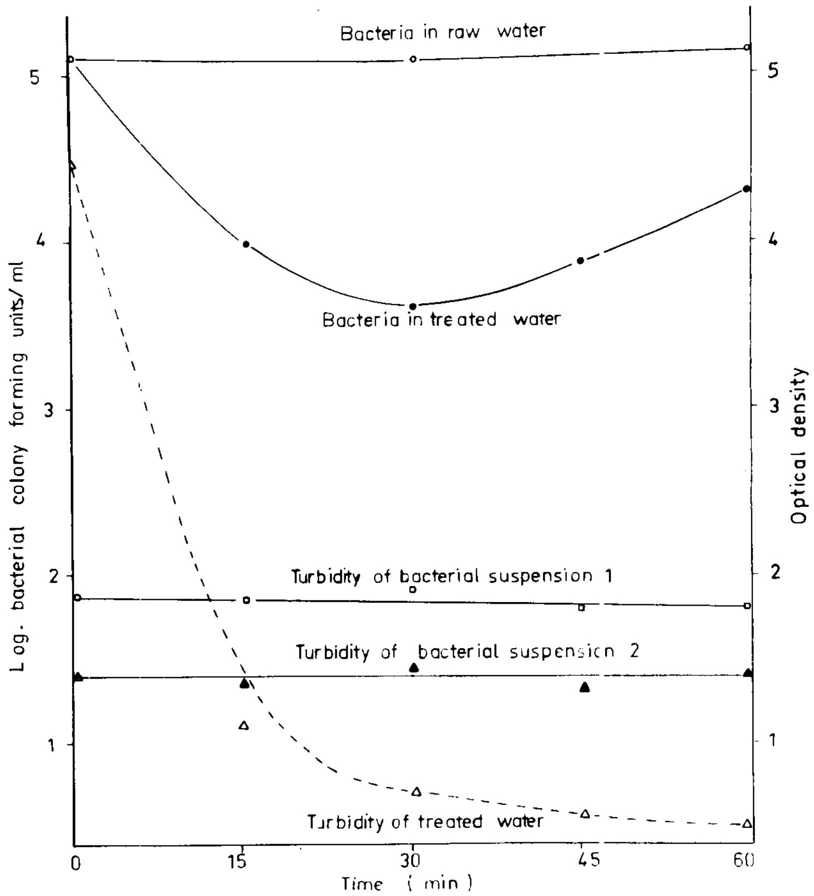

Figure 3
The effect of Moringa seeds on the total bacterial count during coagulation and on the turbidity of bacterial suspensions for raw water of the Hafir of Wad Hassuna (concentrations of the coagulant. 200 mg/l = hafir water, bact. suspension 2 and 400 mg/l = bact. suspension 1)

seed powder it dropped to 0,4 – 1,0 x 10^4/ml. After one hour the turbidity continued to decrease, but the bacterial count started to rise (Fig. 3).

Even with alum the initial reduction of the bacterial count was followed after 13 h by a secondary rise, reaching a 2,5 fold increase. After treatment with Moringa seed powder the secondary rise was observed in both the supernatant left in contact with the floc and in the water decanted one hour after coagulation. The stationary phase was reached after about 24 h with a 300 fold increase (Fig. 4). Effects on pathogenic bacteria have not yet been studied.

Discussion

Effectiveness as coagulant

Water purification with natural coagulants of plant origin is not only a traditional method in the Sudan and other African countries, but was also reported from other parts of the world (Bulusu and Sharma (1965); Kirchmer, *et al.* (1975); Bulusu (1976, 1977).

Nirmali seeds (*Strychnos potatorum L.*) have been used in India for centuries to clarify muddy waters (Technical Digest, 1976). The mud in Indian rivers increases during the monsoon and turbidity ranges from a few hundred to 15 000 mg/l. In the villages Nirmali seeds are grinded on rough stone and mixed with water to a paste which is added to the raw water. Used as primary coagulant Nirmali seeds can only reduce the turbidity to a level of about 300 mg/l. In the laboratory they were used as a coagulant aid in combination with ferric alum. In a pilot plant, water from the Yamuna River with an influent turbidity of 1 200 to 1 530 mg/l was treated with 10 mg/l ferric alum and 1,5 mg/l Nirmali seeds. The resulting effluent turbidity was 84–114 mg/l in the first stage and 22–29 mg/l in the second stage. At the same time the alum consumption was reduced by 74–78% which made the cost of operation much cheaper (Bulusu and Sharma, 1965).

In Peru water is traditionally clarified with "tuna" (*Opuntia ficus indica Mill.* (Barbary Fig, Prickly Pear), *O. monocantha, O. tuna, O. vulgaris, O. inerme,* etc.) which was once brought by the Spanish invaders from Mexico. In the villages the cactus leaves are broken, the sap is allowed to drop down and stirred with the turbid water. The effect is rather poor if tuna leaves are used as primary coagulant. Two promising coagulant aids were isolated from *O. ficus indica,* viz. "Tunafloc A" and "Tunafloc B". These two, in concentrations of 0,4 mg/l, reduced the initial turbidity of water from the Rimac River from 500 mg/l to 70–75 mg/l. By using these coagulant aids it was possible to lower alum consumption from 32 to 5 mg/l. Tunafloc did not prove to be an effective primary coagulant except at extremely high dosages. The lowest residual turbidity obtained by treatment of Tunafloc B plus alum was in the range of 30 mg/l (Kirchmer, *et. al.*, 1975).

Nirmali seeds and Tunafloc A and B are therefore ineffective as primary coagulants but must be regarded as coagulant aids. The low dosages in which they are used as coagulant aids will probably be much higher for the treatment of natural

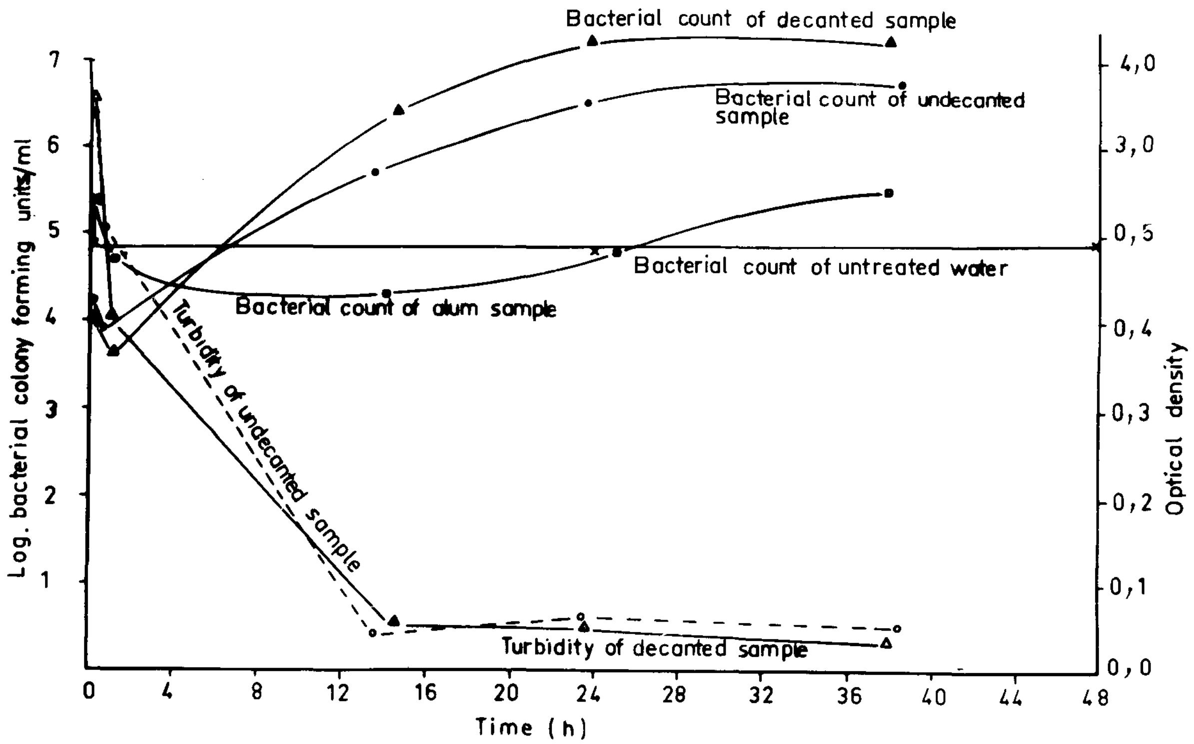

Figure 4
Long-term observations on bacterial counts after water treatment with alum and Moringa seeds and comparison between decanted and undecanted samples for raw water of the Hafir of Wad Hassuna (concentration of the coagulants: 200 mg/l)

waters with higher turbidities. In contrast with these, Moringa seed powder — although used in a concentration of 200 mg/l — was able to reduce an initial turbidity of hafir water from 7 290 mg/l to 144 mg/l within 1 h. After 24 h the turbidity dropped to 0,5% of its original value, *viz.* 36 mg/l. This figure compares well with the lowest values of residual turbidity achieved by combined treatment of low-turbidity waters with alum and Nirmali seeds or Tunafloc. The result is also very good in terms of Sudanese standards as indicated by the fact that the "clear water" from the Blue Nile during the dry season still contains 20—50 mg/l suspended matters (Omar el Badri, 1972). Should the suspended solids of hafir water have certain elements in a concentration far beyond the maximum desirable or even the maximum permissible level for international drinking water standards (WHO, 1971) like the Fe in Wad Hassuna water, the use of an effective natural coagulant like Moringa seed powder would be of great value.

Another natural water coagulant used traditionally in Northern Chad and villages around Maiduguri (Northern Nigeria), is plant ash of any origin. According to laboratory studies carried out by Egbuniwa (1978) waters from a laterite runoff used as water source by villagers living around Nsukka (Eastern Nigeria) could be clarified faster by adding wood ash (wood charcoal and ash dust). The initial turbidity of 420—580 JTU was reduced by 5 g ash per litre to less than 19 JTU and Fe from 18—21 mg/l to less than 1 mg/l. Readings were taken after a sedimentation period of one day.

The main objective of the Indian and Peruvian studies was not to improve traditional methods but to find cheaper methods for water clarification in urban water supply. The use of a natural coagulant in combination with alum would be far too complicated for rural households in a country like the Sudan. Apart from this, it is known from experience that overdosage of alum may cause gastro-intestinal disturbances and are therefore inclined to restrict its use to the purification of washing water. Furthermore, the women in Eastern Kordofan are afraid to drink water treated with alum during pregnancy because they believe this will result in abortions.

The Indian suggestion to use seeds of *Hibiscus sabdariffa L.* with soda would also be too complicated as a routine method for the rural Sudan. The poor result of clarification of hafir water by this method may be ascribed to the suspended matters in El Qerabin water which are chemically quite different from those of the artificially prepared turbid water in the Indian experiments, containing mainly caoline. The efficiency of Moringa seeds was also less in the treatment of Wad Hassuna water (Table 2).

Finally, the efficiency of Moringa seed powder should be compared with *Rauwāq* (which means "clarifying matter") which is a Sudanese natural coagulant of soil origin with bentonite as regular component in the clay fraction (Jahn, 1976; Rösch and Jahn, to be published). A handful of this soil is added to water in a small bowl, stirred for 10 to 30 min as in the case of the plant material and then poured on the turbid water in the jar. For Nile water with turbidities between 2 000 and 7 800 mg/l (the solids determined as total solids) the optimum concentration for outstanding Rauwāq varieties from the Gezira Province (Wad el Said, Eseyba) and the Northern Province (Uqda, Basa) was 1 100—2 900 mg/l. After 2 h the residual turbidity was still 200—400 mg/l (Mohamed Osman el Obeid and Jahn, to be published). The optimum concentration of Rauwāq is therefore 6—14 times higher than for Moringa seeds, the rate of reaction is slower and the residual turbidity higher.

Health risk considerations

Natural coagulants used regularly for water purification could be a potential health risk if they contain any toxic substances. There might not be any danger from acute intoxication if a method became traditional but there could be chronic effects due to accumulation.

Toxicological studies have not yet been done on *Moringa oleifera* seeds. According to literature and to field work experience in the Sudan, the seeds are used as food and in folk medicine. In Tanzania they are added to curries (Watkins, 1960) and in India they are fried, tasting like peanuts (Council of Scientific and Industrial Research, 1962). In folk medicine *Moringa oleifera* seeds are mainly used as a hot tea for gastro-intestinal troubles in the Sudan and Northern Nigeria. In Egypt they are replaced for the same purpose by seeds from *Moringa peregrina* (Täckholm, 1976). In India and Pakistan *Moringa oleifera* seeds are used in addition as an antipyretic, purgative and against enlargement of liver and spleen (Dastur, 1962). It is reported that Moringa seeds contain an alkaloid called "nuclein" but nothing was mentioned about its toxicity (Watt and Breyer-Brandwijk, 1962).

More or less the same applies to water coagulants from *Opuntia sp.* After removal of the prickles, "tuna" leaves are used as fodder for animals and in rural areas of Peru, people eat them as cooked vegetable. Apart from this the mucilage is used to treat sunburn and to relieve toothache. The chemical analysis did not reveal toxic substances (Kirchmer, *et al.*, 1975).

In the Indian papers the question of toxicity of natural coagulants is not directly discussed. The seeds of *Strychnos potatorum* contain strychnine, which was supposed to be responsible for the coagulating properties by Subbaramaiah and Sanjiv Rao (Tripathi, Chaudhuri and Bokil, 1976).

The question of whether there is a serious health risk in the traditional use of the root of *M. pseudopetalosa* for water coagulation needs further investigation. The plant was previously known as *Courbonia virgata Brongn.* A fatal accident in Bahr el Ghazal Province, where it is called "amyok" or "mayook" by the Dinka, led to the discovery of a Curare-type toxic principle, tetramine iodide, in leaves, stem and mainly the root (Henry, 1947; Henry and Grindley, 1949). People used to chew pieces of the root, which initially gives a somewhat bitter taste sensation, but after drinking water it becomes very sweet and pleasant, encouraging the consumption of water. As a preliminary action an urgent circular to all health authorities of the Sudan was sent to prevent the use of *Maerua pseudopetalosa* roots for water coagulation and as a sweetener (Jahn, 1977b).

The chemical nature of the coagulating agents

The chemical nature of the coagulating principle in *Moringa oleifera* seeds is not yet known. According to chemical analysis of specimens from India (Council of Scientific and Industrial Research, 1962), they contain: moisture 4%; crude protein 38,4%; oil 34,7%; N-free extr. 16,4%; fibre 3,5% and ash 3,2%. The mineral matter consists mainly of lime, phosphoric acid and potash. The amount of CaO (0,4% in the cake after oil extraction) seems to be too small to play any important role in the process of water coagulation with Moringa seeds.

Preliminary laboratory experiments by the authors have indicated that the active principle is found in the cake, is an organic compound and is present in the N-free fraction. This view was also supported by the finding that the dialysed sample lost most of its coagulating activity.

It can, however, not be ruled out that *Moringa oleifera* seeds probably contain both a primary coagulant and a substance acting as coagulant aid. Meanwhile further chemical fractionation and tests on the ability to coagulate turbid water are continuing.

The different effects of Moringa seed powder on the waters from the El Qerabin and Wad Hassuna hafir (Table 2) might be mainly due to differences in chemical composition of the suspended matter and probably also to the pH. Ions known to affect the coagulation process, like calcium (Black, Birkner and Morgan, 1965) or sulphate (American Water Works Association, 1971) are present in almost the same concentrations in both raw waters, which makes their interference unlikely.

Studies with infrared spectroscopy provided evidence that the coagulating agent in *Strychnos potatorum* seeds is a protein and an anionic polyelectrolyte with carboxylic and hydroxylic groups as major groups (Tripathi, *et al.*, 1976).

The gum-like nature of the sap from the leaves of *Opuntia sp.*, from which Tunafloc A and B were extracted, suggested the presence of polysaccharides, triterpenes, poly-glucosides, arabinose and galactose (Kirchmer *et al.*, 1975).

Effect on the bacteriological quality of water

Efficient flocculation and sedimentation are known to remove bacteria from raw water (Cox, 1964). The initial decrease of the bacterial count in hafir water treated with alum or *Moringa oleifera* seeds was of the same order. The secondary increase of the bacterial count after water coagulation could be due to bacterial growth on impurities, whereby the organic material present in Moringa seed powder offers additional substrate. The practical consequences on the health of consumers can not be properly assessed as long as there is no experimental data on growth patterns of pathogenic microorganisms.

Similar observations were made in India with alum and seeds of *Strychnos potatorum* (Tripathi *et al.*, 1976). The coagulants initially removed bacteria, but after several hours the bacterial count rose. Nirmali seed extracts (0,5 – 10 mg/l) reduced the initial count in canal water (390/ml) after 30 min to 50 – 60% of its original value, but in samples studied after 24 h the bacterial count was 2 – 5% higher than in untreated raw water. The same effect was observed after coagulation with 25 mg/l alum but the final increase after 24 h was still 35% below the initial count. In addition it was also found that Nirmali seed extract had no flocculating effect on *E. coli* suspensions which is in agreement with the authors' observations on Moringa seeds (Fig. 3).

In most Sudanese villages fresh supplies of drinking water are brought twice daily; in the morning and before sunset. Most of the water is therefore consumed after about 8 h, which is within the period when the secondary increase of the total bacterial count after treatment with Moringa seeds, is just beginning.

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nisms; it is still the cheapest means of disinfection in general water treatment practices (Budde, Nehrn and Boyle, 1977) and it has the important advantage of a residual effect. The latter refers to the fact that chloramines also inactivate micro-organisms. Although chloramines are about 25 to 100 times less active disinfectants and require much longer contact periods than hypochlorous acid (Budde *et al.*, 1977), they serve an excellent purpose in controlling the numbers of micro-organisms in reservoirs and distribution systems. For this reason it is desirable that water chlorinated for drinking purposes should contain trace amounts of ammonia since this will ensure the presence of protective chloramines. As a result of these properties, as well as technical advantages of automatic dosing and control facilities, chlorination is excellent for the final polishing of properly pretreated water.

Disadvantages of chlorination

Application of chlorine for the decontamination of water which contains excessive amounts of chlorine-reactive materials such as partially treated wastewater, violates the basic concepts and advantages of chlorine disinfection. Among the many reasons are the reduced disinfection efficiency of chloramines. A wide variety of micro-organisms are not inactivated by the chlorine concentrations and contact periods prevailing in most wastewater chlorination systems (Selleck and Collins, 1975). Viruses are of particular concern in this regard (Shuval, 1977; Nupen and Morgan, 1978). Many bacteria are merely injured and under favourable conditions at reduced levels of chloramines they regrow and their numbers may eventually reach levels similar to those prior to chlorination. Such regrowth has been recorded for both total and faecal coliform bacteria (Comptroller General, 1977; Shuval, 1977). It is, furthermore, technically difficult to obtain proper mixing in wastewater chlorination systems which implies that many micro-organisms are not exposed to the desired concentration of chlorine (Selleck and Collins, 1975). Micro-organisms may also be embedded in organic matter which shelters them from the action of chlorine. Complete inactivation of micro-organisms in wastewater requires breakpoint chlorination and a prolonged contact period. The establishment of these conditions are expensive and technically difficult to control (Selleck and Collins, 1975). An important implication of incomplete decontamination is that it creates ideal conditions for the selection of resistant organisms. Mutants of *Escherichia coli* (Farkas-Himsley, 1964) and poliovirus (Bates, Shaffer and Sutherland, 1977) with increased resistance to chlorine have been described. Such mutants may reach sources of drinking-water and survive conventional treatment processes. Another serious implication of inefficient disinfection is that it may create a false sense of security which may have far-reaching implications (Nupen and Morgan, 1978).

In view of the mechanisms by which chlorine, chloramines and other chlorinated compounds inactivate micro-organisms, it is not surprising that in sufficiently high concentrations they also have deleterious effects on higher forms of life. One can hardly imagine a better way of creating the widest possible spectrum of chlorinated compounds than by sewage chlorination (Hoadley and Gould, 1976). The effects which discharges of chlorinated sewage have on aquatic life in streams, rivers, dams, lakes, estuaries and even the sea have been described in detail elsewhere (Brungs, 1973; Capuzzo, 1977; Comptroller General, 1977; Johnson, Williams and Arnold, 1977; Larson, Hutchins and Schlesinger, 1977; Oliver and Carey, 1977; Utzinger and Schlatter, 1977; Blakemore and Carey, 1978; Nupen and Morgan, 1978; Smith, 1978; Ward and DeGraeve, 1978). Some of the chlorinated compounds have toxic effects. This implies that in relatively small amounts they exert by virtue of chemical action damage to structure or disturbance of function which directly results in irritation, malfunction, inhibition of growth or multiplication, or death. The potential toxicity of chlorinated wastewater is illustrated by an incident in 1973 in Virginia, USA, when such discharges killed an estimated 5 to 10 million fish in the lower James River (Comptroller General, 1977).

Chlorinated compounds may also have mutagenic effects. This means that they induce chemical changes in the nucleic acid (chromosomes) of living cells which may result in mutated genes. Such genes may no longer be able to exert their normal functions and the effect of mutagens is only detectable in the expression, or lack of expression, of mutated genes. In the case of bacteria which have a very short generation period of 30 min or less and which multiply by binary fission, the expression of genes involved in biochemical activities such as substrate utilization are easily detectable within a day or two. In the case of higher animals such as man the earliest detectable mutations are those which give rise to cancers, in which case the mutagens are known as carcinogens. In man cancers may only be detectable many years after the original mutation had taken place and even in experimental animals such as mice and rats this may take a year or more. Some mutations are only detectable in the progeny, in which case the causative agents are known as teratogenic substances. Since the basic effect of mutagens is identical in all living cells, bacteria and other micro-organisms are excellent tools for the rapid detection of mutagenic substances (Ames, McCann and Yamasaki, 1975).

Mutagenic substances in water is currently a matter of concern since it has for instance been found that products of chlorination, notably chloroform, cause cancers in rats and mice (Comptroller General, 1977; Stockinger, 1977; Tardiff, 1977). Recently reported epidemiological data also indicate that consumers of surface waters subject to pollution tend to have higher cancer rates than consumers of groundwater supplies (Kuzma, Kuzma and Buncher, 1977). Hyperchlorinated water has furthermore been found to suppress macrophages in mice, and macrophages play a major role in host defense mechanisms against microbial pathogens and the development of cancers (Fidler, 1977). Mutagenic substances in water may of course not only originate from chlorination but also from a wide range of other sources (DeRouen and Diem, 1975; Harrison, Perry and Wellings, 1975). However, the practical implications of mutagenic substances in water are difficult to assess and at present the situation is uncertain and a highly debated controversy (DeRouen and Diem, 1975; Genetelli, Lubetkin and Cirello, 1975; Comptroller General, 1977; Ibrahim and Christman, 1977; Stokinger, 1977; Tardiff, 1977). An important issue which contributes to the confusion is that the validity of extrapolating data on cancer induction by high concentrations of mutagens in rats to cancer induction by low concentrations of these agents in man, is questionable. Furthermore, the efficiency of man's natural defense mechanisms against hazardous substances may be underestimated (Ibrahim and Christman, 1977; Stokinger, 1977; Tardiff, 1977). Some investigators maintain that the present situation constitutes no health risk at all since extrapolation of results obtained in rat experiments indicates that induction of cancer in humans would require a daily intake of 57 000 to 114 000 dm^3 of the worst drinking-water supplies tested so far (Stokinger, 1977).

Although many questions regarding the adverse health implications of wastewater chlorination remain unanswered, there is ample evidence that this practice may seriously harm the natural fauna and flora of water environments which, among other things, play a vital role in the self-purification abilities of these waters. Furthermore, there is good reason to believe that, generally, inactivation of pathogenic micro-organisms is unsatisfactory. Inefficient chlorination of wastewater may also result in taste and odour problems (White, 1972). One aspect about which there is no doubt is that wastewater chlorination is expensive and that production of the chlorine involved consumes a great deal of energy. These disadvantages have to be considered carefully when evaluating the advisability of wastewater chlorination (Comptroller General, 1977).

Ways to Overcome the Adverse Implications of Wastewater Chlorination

Selected application of wastewater chlorination

Although chlorine may be used to control tastes and odours in water (White, 1972), the primary objective of wastewater chlorination is to limit the discharge of pathogenic micro-organisms into waters which may be used for recreational, agricultural or drinking purposes. In order to attain this goal, high standards have been set for the microbiological quality of wastewater discharges. In 1973 the United States Environmental Protection Agency (EPA) specified that discharges should contain less than 200 faecal coliforms per 100 cm^3 (Genetelli *et al.*, 1975) and in South Africa the Water Act requires the complete absence of faecal coliforms from 100 cm^3 (Department of Water Affairs, 1962; Grabow, 1979). These standards have limited scientific or epidemiological support (Comptroller General, 1977; Genetelli *et al.*, 1975) and apparently the only motivation for their promulgation is the well intended objective to ensure a wide safety margin. In practice these standards imply that they cannot be met by conventional wastewater purification techniques and decontamination by chlorination or equivalent treatment is required. Gradually, however, a better understanding of the disadvantages of wastewater chlorination emerged which resulted in a soft-pedalling of the restrictions. In 1976 the EPA repealed its coliform restriction for all discharges except those affecting waters used for purposes such as swimming (Comptroller General, 1977). In South Africa, application may be made for permits to exceed the coliform limit and as far as is known no such request has yet been rejected. Another illustration of the current state of confusion and uncertainty is that, after the discovery of chloroform-induced cancer in rats, the United States Food and Drug Administration in 1976 banned chloroform from foods and medicinal and cosmetic products. The EPA, however, has no restrictions regarding the production of chloroform and other mutagenic and toxic substances during wastewater chlorination or their discharge into environmental waters (Comptroller General, 1977).

Easing limits for the microbiological quality of wastewater effluents appears to be justified by epidemiological data. In the United States the chlorination of wastewater has become common practice only recently and even today not all discharges are decontaminated. In 1958 about 30 per cent of treatment facilities were equipped for chlorination, in 1968 41 per cent and in 1976 74 per cent. Epidemiological data do not indicate any difference in the incidence of water-borne diseases before and after wastewater chlorination, or between areas with and without chlorination. In addition, the incidence of water-borne diseases in the United States does not differ significantly from that in countries which seldom, if ever, chlorinate wastewater effluents, such as Great Britain, Norway, Sweden, West Germany, France, the Netherlands (Comptroller General, 1977) and South Africa.

In view of the available information on the pros and cons of wastewater chlorination, it would seem advisable to judge each individual case on its merits (Genetelli *et al.*, 1975). Discharges into waters which are unlikely to transmit pathogenic micro-organisms or which provide for a large dilution factor, need not be chlorinated. Discharges into waters which are used for swimming and other recreational purposes may not require chlorination during winter periods when these activities are limited to a minimum (Comptroller General, 1977). If indeed chlorination proves necessary, it should be done efficiently. Research on the toxic effects of chlorine and chlorinated compounds has indicated that aquatic life can tolerate between 0,002 and 0,2 mg/dm^3 total residual chlorine in discharges depending on the volumes concerned and whether discharge is intermittent or continuous (Brungs, 1973; Comptroller General, 1977; Nupen and Morgan, 1978; Ward and DeGraeve, 1978). Discharge of effluents containing total chlorine residuals of the order of 10 mg/dm^3, as has been recorded in the United States (Comptroller General, 1977), should therefore be avoided. Wastewater chlorination facilities should be constructed and operated to ensure proper mixing, adequate contact periods and reliable chlorine control (Kruse, Kawata, Olivieri and Longley, 1973; Comptroller General, 1977).

Dechlorination of treated effluents

The toxic effects of chlorinated effluents may be eliminated by treatment with agents such as sulphur dioxide, sodium bisulphite or sodium thiosulphate (Ward and DeGraeve, 1978). Although no adverse effects of dechlorination have yet been reported, the potential implications of long-term exposure are uncertain (Brungs, 1973). Dechlorination by means of sulphur dioxide, the most commonly used agent, increases the cost of wastewater chlorination by about 20 to 30 per cent (Comptroller General, 1977). Chlorine residuals may also be reduced considerably by storage in ponds.

Alternative methods of disinfection

Intensive research on a wide range of alternative methods for the disinfection of drinking-water supplies and wastewater is in progress. Although various agents are equally or even more efficient disinfectants than chlorine, their application is generally still more expensive and in some cases technical aspects of treatment require further improvement. However, excellent progress is being made in this field of research and cost-competitive alternatives may be available in the near future. The following are among the most promising alternative methods of disinfection:

Ozonation. Ozone is the most powerful oxidizing agent used for water disinfection and it inactivates micro-organisms, particularly viruses, more efficiently than chlorine (White, 1972; Richards and Shaw, 1976; Lawrence and Cappelli, 1977). The earliest effect on bacteria is denaturation of the cell membrane by oxidation of tyrosine and tryptophan, and in viruses oxidation of the same amino acids leads to denaturation of the capsid (Hoadley and Gould, 1976; Richards and Shaw, 1976). Ozone has been used for the disinfection of drinking-water in France since 1906, and today it is being used for this purpose in more than 1 000 plants all over the world (Bollyky, 1976). Ozone is generated on site from air or oxygen which eliminates transport, storage and handling of toxic chemicals such as chlorine. As a result of its powerful oxidation properties, ozone disintegrates organic molecules to a much greater extent than chlorine which reduces taste, odour and colour problems. The available information indicates that ozonation produces less toxic and mutagenic substances than chlorine (Cotruvo, Simmon and Spanggord, 1977; Kuo, Chian and Chang, 1977; Elia, Clark, McGinnis, Cody and Kinman, 1978). The efficiency of ozonation may be improved by application in combination with ultraviolet irradiation (Farooq, Engelbrecht and Chian, 1977). Disadvantages of ozonation include relatively high cost and the absence of a residual effect (Budde *et al.*, 1977). The latter implies that final chlorination is advisable since the breakdown products of ozonation support multiplication of certain micro-organisms which results in aftergrowth (Van der Kooij, 1977; Guirguis, Cooper, Harris and Ungar, 1978).

Chlorine dioxide. This is a more efficient disinfectant than chlorine and apparently does not produce harmful byproducts (Hoehn, 1976). In the United States it is the most commonly used water disinfectant after chlorine. Chlorine dioxide treatment may prove particularly useful when applied in combination with chlorination (Tifft, Moffa, Richardson and Field, 1977). An important disadvantage of chlorine dioxide is that it has to be generated at a high cost on the site of application (White, 1972).

Bromine and iodine. These two halogens share various properties with chlorine but their application is more expensive (Budde *et al.*, 1977; Hoehn, 1976; White, 1972). Iodine is suitable for use in swimming pools and it does not readily react with ammonia or organic compounds which implies that in water it remains in its active molecular form for longer periods than either bromine or chlorine. An important disadvantage of iodine is its physiological thyroid activity and brominated compounds exhibited higher carcinogenic activity than their chlorinated analogues (EPA Statement, 1977).

Bromine chloride. Application of this agent for the treatment of wastewater has been described by Hoehn (1976). It is a more active disinfectant than either chlorine or bromine. It is also safer and easier to handle and is less corrosive than bromine. The application of bromine chloride is primarily restricted by its high cost.

Ultraviolet radiation. Ultraviolet light at a wavelength of about 254 nm inactivates micro-organisms by photochemical destruction of nucleic acids (Richards and Shaw, 1976). Disinfection is efficient and no harmful byproducts are formed. The equipment requires little attention other than cleaning, and the handling of toxic chemicals such as chlorine is eliminated (Hoehn, 1976). Ultraviolet disinfection proved successful for application in certain industries and treatment of small water supplies (White, 1972; Hoehn, 1976). Unfortunately, ultraviolet light has a limited penetration efficiency which implies that treatment is restricted to waters with low turbidities and even then the water has to be exposed in a thin film (White, 1972; Oliver and Carey, 1976). Another disadvantage is the absence of a residual effect. At present ultraviolet disinfection is still more expensive than chlorination but improvements in equipment may render it more cost competitive in future. Ultrasonic pretreatment improves the efficiency of ultraviolet disinfection (Oliver and Carey, 1976).

Silver. The antimicrobial effect of silver has been known for centuries and a variety of methods has been developed for treating small supplies (Richards and Shaw, 1976). The oligodynamic action by which the metal ions inactivate micro-organisms is not well understood (White, 1972). Treatment is based on the release of silver into water at a concentration of 0,01 to 0,04 mg/dm^3. Disinfection by this method is rarely applied since silver is expensive, a long contact period is required and substances such as phosphates and sulfides reduce the disinfection efficiency. In addition, silver is toxic to humans to the extent that drinking-water standards limit its presence to 0,05 mg/dm^3 (White, 1972; Richards and Shaw, 1976). The development of catadyn candles and electro-catadyn processes have facilitated technical aspects of application (White, 1972).

Ionizing radiation. This is an effective means of inactivating micro-organisms (Feates and George, 1975; Ballantine, 1978). In addition it has the advantage of modifying and destructing organic matter which reduces the chemical and biochemical oxygen demands of wastewater and increases its biodegradability. Irradiation is either by gamma rays from cobalt-60 or caesium-137, or by intense beams of high energy electrons produced by electron accelerators. Gamma rays have a higher penetration power than electron beams and application of gamma radiation is more convenient than high energy electrons which have to be produced on site. Limiting factors in ionizing radiation are restricted penetration efficiencies, high cost and safety aspects of handling radio-active materials. However, this is a relatively new field of research and rapid progress is being made towards the development of competitive disinfection technology (Feates and George, 1975; Ballantine, 1978).

Photodynamic oxidation. In this method of disinfection a suitable dye such as methylene blue is added to water in a concentration of 1 to 10 mg/dm^3. This is followed by exposure of the water to monochromatic light with a wavelength of about 670 nm or to ordinary sunlight. The dye penetrates micro-organisms, attaches itself to substrates such as enzymes or nucleic acids and exposure to suitable light induces an oxidation reaction which disrupts the substrate (Acher and Juven, 1977; Gerba, Wallis and Melnick, 1977). Efficiency is optimal at high pH levels and not extensively affected by turbidity or the presence of organic material. The treatment is not known to result in the production of toxic or mutagenic substances and the dye itself is also non-toxic. The application of this method in practice has not yet been reported but laboratory experiments yielded promising results. Limiting factors may include the ultimate removal of dyes and high cost (Acher and Juven, 1977; Gerba, Wallis and Melnick, 1977).

Advanced tertiary treatment and wastewater reclamation

The ideal solution to the problems of wastewater disposal is suitable purification for re-use. This does not only limit the spread of pathogenic micro-organisms, damage to aquatic fauna and flora, eutrophication and pollution of natural water resources with organic and inorganic wastes, but also has the advantage of a well-controlled additional source of water. Technology has been developed which makes the re-use of water for agricultural, industrial, recreational and even drinking purposes an economically feasible proposition under many circumstances (Sebastian, 1974; Stander and Clayton, 1977). The conditions favouring water re-use increase rapidly in the face of the growing demand for potable water, progress in technical and economical aspects of wastewater purification (Cillié, 1975) and accumulating evidence on the health aspects of reclaimed water (Grabow and Isaäcson, 1978; Van Rensburg, Hattingh, Siebert and Kriek, 1978; Van Rensburg, Van Rossum and Hattingh, 1978).

The Detection of Shortcomings in Disinfection Processes

Methods for evaluating the efficiency of disinfection processes with regard to the inactivation of micro-organisms have been available for many years and their accuracy and reliability is being increased continually (Grabow, Bateman and Burger, 1978; Grabow, 1979). The detection of harmful byproducts of disinfection processes is a more recent field of interest. Analysis of water for the presence of these substances by means of physical and chemical techniques is an almost impossible task, the reason being that the variety of organic and inorganic substances in water is too great for isolation and identification by presently available technology. The thousands of chemical compounds which have so far been isolated and identified, represent only a minor fraction of the total variety present in wastewater (EPA Report, 1975; Kuzma *et al.*, 1977; Shuval, 1977; Winklehaus, 1977). Furthermore, only a few of these have so far been tested for deleterious effects on living organisms. In view of this situation intensive research is in progress on biological screening procedures. Excellent results have been obtained with fish assay systems which give early warning of low concentrations of toxic substances in water on an in-line continuous monitoring basis (Morgan, 1978). Since the sensitivity of different organisms to different toxicants varies, a wide spectrum of additional tests has been developed. The sensors employed in these tests include bacteria, protozoa, algae, phytoplankton, invertebrates and tissue cultures of human and other cells (Axt, 1973; Bringmann and Kühn, 1973, 1975; Jacobs and Schweisfurth, 1975; WHO Report, 1975; Wennberg, 1976; Dutka and Switzer-Howse, 1978; Little, 1978; Trotter, Hendricks and Cairns, 1978). Bioassays have also been developed for the detection of mutagenic and carcinogenic substances in water. Sensors employed in these tests include bacteria, protozoa, tissue cultures of human and other cells, rats, mice, dogs and in a way man himself (Ames *et al.*, 1975; Bridges, 1976; Ember, 1976; Green, Muriel and Bridges, 1976; Cotruvo, Simmon and Spanggord, 1977; Kuzma *et al.*, 1977; Mager *et al.*, 1977; Pelon, Whitman and Beasley, 1977; Tardiff, 1977; Van Rensburg *et al.*, 1978).

Bioassay and physical-chemical procedures are closely integrated in studies on harmful substances in water. The sensitivity of bioassays is greatly increased by physical-chemical concentration of potentially harmful substances. Bioassays are primarily used for screening purposes and they offer little if any assistance in the identification of the substances to which they respond. The isolation and identification of these substances have to be done by physical-chemical techniques. Although methods for the detection of hazardous chemicals in water have been developed to high levels of efficiency, this field of research receives high priority all over the world since it concerns one of the most important safety aspects of water.

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