Appropriate Technology for Treatment of Potable Water in Developing Countries: Coagulants Derived from Natural Materials

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Abstract

Coagulants derived from natural materials have an important role to play in the provision of potable water to rural communities in the developing world. Their use as primary coagulants and coagulant aids are reviewed with particular reference to seed preparations of the Moringa oleifera and Moringa stenopetala.

The use of model suspensions to prepare artificially turbid waters to evaluate coagulant performance is discussed. Problems of translating and extrapolating data obtained from studies on model suspensions to that of natural waters are identified.

It is emphasised that controlled laboratory experimentation must be planned and conducted with the ultimate rural application in view at all times. Differences between urban and specific rural infrastructures must be recognized as must socio-economic factors and cultural traditions.

Some areas for future research work and applications are presented.

Introduction

In the western world, aluminium sulphate is the most commonly used coagulant in water treatment to remove turbidity (the surrogate parameter for particles) and sometimes colour (the surrogate parameter for natural organic material). Also available in the western world are the well known iron salts, such as ferric sulphate, ferrous sulphate and ferric chloride. These chemicals are effective over a wider pH range and are therefore somewhat more useful in the removal of colour at low pH values, in the removal of manganese and in the softening process at higher pH ranges. A range of polyaluminium chlorides are now commercially available offering advantages for specific applications.

All these chemicals are generally readily available at a relatively low cost. Such attributes, however, cannot be translated to the rural areas of developing countries. Countries in West

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Africa, for example, pay seven times the price paid in Europe for imported aluminium sulphate /1,2/. Transportation and other infrastructures might also have to be established at a cost.

In situations such as this, the majority of people drink untreated and unchlorinated water. Where this water is derived from protected groundwater or surface water sources the bacteriological quality may be moderately good. In other situations e.g. a riparian population in the rainy season, surface water sources may be highly turbid and on occasions exhibit indicator bacterial concentrations similar to that of weak wastewater. As an illustrative example, the River Tigris in Iraq shows suspended solids in the range 100-200 mg/l with peaks of up to several thousand mg/l in the wet season. Bacteriological quality deteriorates markedly during such high flows and total coliform counts of more than 500,000 MPN/100ml have been recorded /3/.

Rapid, effective destabilisation of the colloidal material with its associated bacteria following by subsequent removal of the precipitated floc is of primary importance in the rural areas not served by piped treated water. Of concern also is that drawers of water may naturally dismiss a visibly poor source in favour of a more highly contaminated yet clearer water. This basic requirement to clarify water for drinking purposes has not escaped populations in the developing countries albeit principally for aesthetic reasons. Indeed, communities in Africa and Asia have been using coagulants derived from natural substances for centuries to remove suspended material in water prior to consumption. Sanskrit literature dating back to the first century A.D. suggests a number of vegetable substances, notably the seeds of Strychnos potatorum (nirmali) as a means of clarifying water. The practice may go back to several centuries B.C. /4/.

Given the complexity of the clarification process, repeatable laboratory experiments under controlled conditions, perhaps using artificially prepared raw waters, are necessary to establish the efficacy of treatment over a range of conditions with a view to optimisation. However at no time should the ultimate goal of the research be forgotten i.e. to be of use in the communities of the developing world, the technology must be appropriate and applicable. This means also that to be successfully adopted by a specific community it must be socially, economically and culturally acceptable. This theme is pursued in the companion paper.

Appropriate Technology

It has been suggested that only as a last resort should chemical coagulation be adopted in developing communities. If adopted, hydraulically based devices are preferable to mechanised equipment even if such equipment could be manufactured and maintained locally. Indigenous materials should be cultivated and used where feasible. If certain plant species have been demonstrated to be effective as coagulants and/or coagulant aids then treatment costs are reduced in parallel with boosting the local economy in associated industries. Use of a natural material with no regard to replenishment will of course weaken that community.

At this village level, any water treatment technology introduced should at least match the intellectual capacity of the inhabitants.

However it should not be forgotten that individual communities once suitably motivated, educated, trained and convinced of the benefits of basic water treatment practices will advance. This leads to future development of village life, perhaps centralising to a degree their individual efforts aimed at providing a safe and wholesome drinking water.

Coagulants Derived from Natural Materials

The Range of Natural Substances

A remarkable number and variety of natural substances have been examined for their coagulating properties systematically and spontaneously by village inhabitant and research work alike. They range from the more widely known seed and plant species to bone/shell extracts, bark resins, ashes, seaweed extracts to natural mineral soils. It is outwith the scope of this paper to review all such investigations. One aspect of this research area is the difficulty of making inter-study comparisons given the complexity and range of variable parameters involved. Generalisations beyond the scope of individual studies must be regarded as solely tentative. Attention is focussed primarily on seed preparations of the *Moringa oleifera*. *Moringa stenopetala* and to a lesser extent on the species *Hibiscus sabdariffa* and *Strychnos potatorum*.

Preliminary investigations at the University of Leicester have been conducted using seeds from the two *Moringa* species identified to clarify artifically prepared turbid raw waters. Initial collaboration with Dr. Jahn of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) yielded quantities of the seeds for testing.

The *Moringa oleifera* tree is a native of the sub-Himalayan region of India and is now under cultivation in the tropical regions of Africa, Asia and South America. Apart from its traditional yields of fuel, foodstuffs, vegetable oil and medicinal substances, seed preparations are recognised to be most effective in clarifying turbid waters /5-12/. The performance of *Moringa oleifera* under certain conditions is comparable to and at times has been shown to surpass that of aluminium sulphate in that the floc structure is strengthened.

Results of three chemical analyses of *Moringa oleifera* seeds appear in the literature. In one, the weight ratio of seed to skin is reported as 65:35 and that on a percentage of total weight basis the following apply: calcium 0.18, phosphorus 0.69, protein 36.0, fat 32.09 /8/. The second yields the following data: moisture 4%, crude protein 38.4%, oil 34.7%, N-free extract 16.4%, fibre 3.5% and ash 3.2% /11/. It is thought that the active ingredient is contained within the N-free fraction. In the third study the active fraction has been identified as amino acids with arginine present at a concentration of 14.8 Mol% /29/.

Seeds of Moringa stenopetala have proved particularly effective in clarifying waters over a wide range of turbidities. Their cultivation is particularly attractive as the seed produced has a significantly higher average yield than that of Moringa oleifera.

Laboratory Investigations

The Use of Model Suspensions

In the absence of a field laboratory it is necessary to use model suspensions to evaluate coagulation studies. One qualified advantage of this approach is that the variability of natural water sources is eliminated and treatment trends can be estabilished. Once a trend has been established, however, it is then necessary to plan further experiments reintroducing parameters likely to be experienced when evaluating specific raw waters.

Water drawn from surface sources in a developing country will in the first instance contain both true colloidal material in stable suspension in addition to coarser matter which will settle spontaneously with time. A specific example is Blue Nile water. Initial turbidities in the range 3000-4000 FTU will exhibit significant and rapid self clarification and after 24 hours residual turbidities of 130-135 FTU were measured /13/. The presence of the mineral montmorillonite in the river sediments enhancing this effect.

In the laboratory, it may be of interest to initially separate these two phenomenon and evaluate individual trends according to seasonal conditions. This could then be followed by investigations combining the two facets in the laboratory in conjunction with field sampling.

Kaolin is well established as a model suspension and it has been demonstrated that it exhibits treatment characteristics which are in many respects similar to raw waters derived from English rivers /14/. In one study, suspensions of seven different minerals viz. kaolin, sepiolite, halloysite, illite, quartz, coal and calcite were coagulated with aluminium sulphate /15,16/. Individual plots of coagulant dose required to reduce initial turbidity by 50% against pH were virtually coincident; the data points falling on a single curve having a minimum between pH 6.8 and 7.8. The one exception was the suspension of montmorillonite with an extended minimum pH range of 4 to 7.8.

Limitations on Use of Model Suspensions

Coagulant and coagulant aid doses required to achieve a given residual turbidity level in any situation are a complex function of numerous factors; the nature and applied concentration of the coagulant, the temperature and chemical characteristics of the water, the nature, size and characteristics of the suspended particles, the duration and intensity of rapid mixing and of the flocculation stage and the timing of the addition of the aid in relation to the primary coagulant dose.

The use of seed suspensions and model suspensions introduce further complexities. Returning to coagulant aid addition, some aids may directly assist in floc formation whereas others may strengthen or increase the size of the floc when formed. Moringa oleifera is thought to possess compounds capable of acting in both roles. There should be an optimum seed preparation procedure for any particular species. Moringa oleifera seed suspensions prepared from very finely pulverised seed have been shown to be particularly effective in comparison to other preparations /11/. This is not to infer that this procedure will necessarily be optimum for another species. Seeds and prepared extracts deteriorate in effectiveness with time. This theme is developed in the final section. In one study, the aging of stock clay suspensions has been shown to be worthy of note /17/.

Superimposed on all these factors must be the previously noted seasonal fluctuations in raw water quality and the problems of field/laboratory reproducibility of experiments.

Thus caution should be exercised when comparing or extrapolating jar test derived data to a particular raw water.

Natural Materials as Coagulants and Coagulant Aids

It is not possible to delineate between the more successful plant coagulants' role as sole coagulant and the role of an aid to say aluminium sulphate performance. As previously noted, Moringa seeds can perform effectively in both roles. When added prior to aluminium sulphate addition, turbidity removals were in excess of that possible by a seed or aluminium sulphate dose alone /12/.

Some general remarks on the use of coagulant aids are worthy of note. Their use in water treatment plants in the developed world is traditionally that of exercising control on floc formation and floc characteristics (increasing settling rates and improving floc strength) with a view to improving efficiency in the subsequent stage of the treatment sequence. A properly selected coagulant aid can materially assist in the treatment of difficult raw waters and can overcome specific problems such as low temperature or low alkalinity/hardness. Reduced consumption of the primary coagulant might perhaps be regarded as a bonus. The situation in developing countries would contrast with this in as much as materials, either imported or indigenous are held to be of higher value.

To produce water of uniformly good quality irrespective of rapid fluctuations in raw water quality would normally require careful and continuous laboratory control. It is well known that just as underdosing raw water fails to destabilize a colloidal suspension, overdosing the same raw water restabilizes the same colloids and the suspension remains as intact as if no coagulants were added.

In the developing world this problem is exacerbated with river water quality in a constant state of flux according to the seasons. Coagulants and aids may react differently according to the season. A balance must therefore be made between potential cost savings and the necessity for more expert control of the process. For certain village communities the use of aluminium sulphate in combination with a natural coagulant in some form of controlled dosage would be overly complex and thus not a viable proposition at present.

In India, seeds of the Hibiscus sabdariffa otherwise known as red sorrela /11,17-20/ and of the Strychnos potatorum known as nirmali /18,19,21-24/ have received particular attention due to their observed performance as natural coagulants. The former is widely cultivated in India and elsewhere. The plant is cultivated in the Sudan but not traditionally used in water treatment /11/.

Prepared powdered seeds of Hibiscus sabdariffa when mixed with sodium carbonate in the proportion 9:1 by weight can be stored without deterioration. In an artificially prepared raw water of initial turbidity 7600 units (natural minerals, predominantly montmorillonite in tap water) a 40 mg/l dose of the seed preparation reduced the residual turbidity to 170 units in 30 minutes /20/. An aluminium sulphate dose of 300 mg/l resulted in a residual turbidity of 400-500 units. As the raw water turbidity reduces, however, the percent removal rates fall significantly. A light floc was still apparent and a clear filtrate of turbidity <1 unit was obtained after passing through filter paper (Whatman No. 1).

Pilot plant studies using extracts of Strychnos potatorum as an aid concluded that when dosed at 1.5 mg/l, a 74-78% reduction in aluminium sulphate was possible /22/. Also, if a nominal amount of the extract is added at the pre-settlement stage of the treatment sequence then 90% of the suspended matter can be removed.

Chemical analysis of Strychnos potatorum seeds yielded the following constituents on a percent by weight basis /24/; carbohydrates 52.5, proteins 16.3, lipids 9.0 moisture and volatile fraction 11.5, ash 2.1, other material by subtraction 8.6. Evidence suggests that the material behaves as an anionic polyelectrolyte contributed by the protein fraction.

Seed extracts of Strychnos potatorum, maize starch and aluminium sulphate alone and in combination have been used in jar tests to coagulate coal washery wastes /25/. Particularly effective were tests with aluminium sulphate addition 3 minutes after the addition of the seed extract.

Three naturally derived polyelectrolytes identified by codes CA3, CA4 and CA5 are reported as effective coagulant aids and gave qualified performance as primary coagulants /21/. Their identification and chemical composition were withheld at publication as the products were under patent. CA3, CA4 and CA5 are subsequently identified as being Lens esculenta, Cajanus indicus and Phaseolus roxborghii respectively /4/. Studies were conducted both in the laboratory with a prepared turbid water (montmorillonite predominating) and at pilot plant scale level. The aids initially in dry powder form were made up as colloidal suspensions. Pre-boiling of the suspensions gave consistently improved turbidity removals and this procedure was adopted for all other tests. In one test on a raw water of turbidity >2000 mg/l, CA3 dosed at 3 mg/l as sole coagulant yielded similar percent removals to that of a sole of 150 mg/l aluminium sulphate. However, even at doses >10 mg/l, CA3 alone could not reduce the turbidity below 300 mg/l. A single dose of 450 mg/l aluminium sulphate could achieve a reduction to 50 mg/l. This was followed by successful tests on the conjunctive use of the two materials. In preliminary work, CA3 added prior to aluminium sulphate addition gave optimum results. Initial raw water turbidity of 3500 mg/l was reduced to 60 mg/l with 5 mg/l CA3 plus 100 mg/l aluminium sulphate. To achieve a similar 98% reduction required a sole aluminium sulphate dose of 450 mg/l. The aids compared favourably with some imported proprietary polyelectrolytes.

Health Aspects

Of prime importance in the use of any compound to chemically assist in the sedimentation process is that the compound be demonstrably non-toxic. This problem has been addressed with reference to Moringa oleifera seeds. In one study, laboratory mice, exposed to seeds at a level of 50 mg per 100 ml in distilled water, exhibited no side effects /8/. A more rigorous study had previously recognized that isolation of the compound 4(-L-rhamnosyloxy) benzyl isothiocyanate from the seed gave cause for concern /6/. Toxicity and mutagenicity tests in a series of biological assays on waters coagulated with seed suspensions indicated that there was no evidence that the application poses any acute or chronic health risk at the dose rate likely to be applied.

Future Research Work and Potential Applications

Some of the observations in this section are obviously beyond feasible 'household' treatment technologies, perhaps rather reflecting future developments as previously noted.

Investigate and attempt to quantify the reported loss of coagulant effectiveness with time and perhaps identify a suitable means of preservation. Any preservative identified should itself be non-toxic and ideally be indigenous. This would have implications at pilot plant/small treatment works level. This could also be an important consideration for laboratory based studies. Any particular batch of seeds may become less effective as the study proceeds and thus controls for all tests are essential. Attempts to quantify this deterioration effect in one study using natural coagulant aids gave erratic results; one material actually giving an enhanced performance as the prepared solution aged /21/.

There is good evidence that waters coagulated with the aid of natural materials initially show falling counts of indicator bacteria as one would expect. Remarkable improvements in bacteriological quality have been demonstrated over an initial 2 hour period /12/. The addition of *Moringa* seed at 25-30 mg/l to 'clear' Blue Nile river water of turbidity 3 FTU was unable to further reduce the turbidity but the total coliform count dropped from 225-250 per 100 ml to 35 per 100 ml after 2 hours. Another study enumerating indicator bacteria over 24 hours following coagulation exhibited this initial fall in bacterial counts but even decanted, stored samples yielded final counts in excess of untreated, stored, control samples /11/. Work on the assessment of the ability of *Strychnos potatorum* to coagulate E. Coli in both prepared and natural raw waters gave interesting results /24/. Bacterial removal rates in E. Coli suspensions alone were poor. Bacterial removal rates in mixed suspensions of E. Coli and kaolin reached 84% with turbidity removal measured at 93.6% from an initial turbidity of 500 FTU. Flocculation of bacteria is a complex process with cell excretions playing a role. Further work is necessary to examine the behaviour of pathogenic bacteria and perhaps viruses and other microbial organisms.

Investigate the conjunctive use of plant coagulants and so called 'solar disinfection'. Exposing water stored in transparent vessels to the sun's rays is another example of an ancient practice receiving some attention in recent years. Initial high turbidities will undoubtedly hinder the process. The concomitant rise in water temperature should aid the clarification process but will also render the water less palatable. However there are indications that coliform bacteria once inactivated by solar rays fail to become re-established even after 5 days. It was assumed that inactivated pathogenic bacteria would behave similarly /26/.

Attempt to establish the importance of particle number, particle size distribution (PSD) and settling velocities of the material in suspension in the raw water concerned. This might best be achieved by field sampling of waters and river sediments for subsequent analysis at a central laboratory. There is evidence to suggest that these parameters can best predict optimum treatment selection rather then relying solely on turbidity measurement which in itself is a gross quantity revealing nothing about the nature of the particles /27/. Turbidity measurement is most sensitive to particles that have diameters of similar magnitude to the wavelength of the dispersed light.

Work has been conducted to evaluate recycling of preformed alum sludge in the coagulation process, effectively returning the material as a coagulant aid. If viable, this technique offers two distinct advantages; reduction in the total volume of sludge produced and reduced chemical costs. Standard, batch jar test studies indicate that for optimum performance the sludge should be returned before rapid mixing and that there is an optimum value of the amount of sludge returned. When so conducted, fresh alum dosage was reduced by as much as 40% with no deterioration in the final turbidity as compared with a control using fresh alum alone without preformed sludge recycle /28/. Preliminary attempts at Leicester to return Moringa oleifera and Moringa stenopetala floc proved unsuccessful but further work is planned in conjunction with the Department of Bacteriology. Implicit in the return of preformed floc is the return of associated bacteria.

Temperature effects on coagulation using natural materials parallels that of traditional coagulants in that low temperature conditions give decreased turbidity removals. This may have implication when extrapolating laboratory derived data to communities that draw water from sources at times when the natural water temperature is low. Attempts at Leicester to establish this trend with seed preparations of Moringa oleifera and Moringa stenopetala can at best be described as erratic. If any trend was discernible from repeated experiments the opposite was the case. Further investigations are underway.

It may be possible to establish modified stability limit diagrams based on natural coagulants yielding distinct performance regions; the slow flocculation zone, central stability zone, rapid stability zone and the zero flocculation zone. Zone definitions may vary but such diagrams can prove useful treatment aids /27/.

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