Natural zeolites

Some potential agricultural applications for developing countries

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Zeolites, a suite of porous, fine-grained minerals commonly found in certain near-surface, sedimentary rocks, have special physical and chemical properties that could make them valuable to farmers in developing countries. Zeolites have been used to improve soil fertility; develop slow-release fertilizers; improve animal waste disposal; and improve animal health. To date most research on zeolite deposits and their various applications has been undertaken by the industrialized nations. Some zeolite deposits, however, also exist in developing countries and the likelihood of the existence of additional deposits in those countries is high. However, thorough assessment of the mineralogy, geology, and various agricultural uses is still needed. Strengthening developing countries' geological surveys in non-metallic mineral exploration and assessment will improve the likelihood that the use of zeolites will reach their full potential in developing country agriculture.

Some 50 species of a certain group of natural minerals called zeolites have their atoms arranged so that they form hollow cages with tiny openings through which other ions or molecules of the right size can pass. Larger ions or molecules are screened out from the cages and channels of the zeolites. Because of these unique properties and behaviour, zeolites are referred to as 'molecular sieves'.

'Rarely in our technological society does the discovery of a new class of inorganic materials result in such a wide scientific interest and kaleidoscopic development of applications as has happened with the zeolite molecular sieves' (Breck [6]). Such was the optimism as much as 15 years ago when the properties of natural and synthetic molecular sieves gained considerable scientific attention. With steadily increasing knowledge of zeolites and their applications (Pond and Mumpton [31]), today it seems evident that those minerals can play an increasingly important role in agriculture.

Much of the 'zeo-agricultural' research conducted in developed countries seems relatively successful, indicating that similar successes could be achieved in developing countries as well. Those successes will probably occur in such areas as improving soil fertility and animal waste disposal, developing slow-release fertilizers and in improving animal health. Certainly additional possibilities exist but those few potential uses will illustrate the general principles of how the many species of zeolites function and why they behave as they do. The important role of zeolites in aquaculture is not addressed in this paper; however, Pond and Mumpton [31] have given considerable attention to the topic.

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What role could zeolites play in solving the special and difficult agriculturally related problems of developing countries? This paper's intent is to provide a short review of the literature and suggest possible applications of natural zeolites to common agricultural needs and problems of developing countries. Adequate research into known zeolite deposits and their agricultural uses today is insufficient to assure developing country agriculturalists that such uses will in fact yield successful results. Therefore, what follows is a short guide for cooperative research between geologists and agricultural scientists of developing countries to help them identify opportunities for using zeolite minerals to improve the agricultural productivity of their countries' farmers.

Zeolites – origin and structure

Zeolites form through natural geologic processes, but may also be synthesized in the laboratory. The importance of synthetic zeolites has grown rapidly due to their use as catalysts in petroleum refining and in the synthesis of certain organic compounds (Newsam [26]). They are synthesized commercially to match a desired chemical purity and inherent pore size making them ideal for narrowly defined industrial uses. Today, active research on synthetic zeolites continues to uncover new uses for molecular sieves. Their synthesis increases their cost over that of extensive, naturally occurring zeolite deposits but synthesis assures industry of a uniform product. The cost of producing synthetic zeolites largely precludes their extensive use in developing country agriculture. For example, the cost per ton of a particular synthetic zeolite in the USA can be about four times that of the natural zeolite (Clifton [13]). The difference in cost between the two kinds of zeolites is probably considerably greater in developing countries where natural zeolites would be less expensive to mine than in the USA.

Although synthetic zeolites are relatively new on the scientific scene, the Swedish mineralogist Cronstedt recognized natural zeolites as early as 1756 (Mumpton [23]). Natural deposits commonly contain several kinds of zeolites in addition to significant amounts of other common minerals. Commercial separation of natural deposits into their constituent zeolite minerals and non-zeolite minerals would be a costly operation. Thus, using zeolites in agriculture probably would require large deposits of natural zeolites located near the region of agricultural application. This would be true particularly for agricultural applications of zeolites in developing countries. Therefore, should developing country geologists seek zeolites for agricultural uses they might prudently search for deposits containing large amounts of the desired zeolite mineral and small amounts of non-zeolite minerals.

Zeolites deposits occur in a variety of geological settings, but most of them form:

- from volcanic materials in hydrologically 'closed' saline-alkaline lakes;
- from volcanic materials in alkaline soils;
- in hydrologically 'open' fresh-water lakes or groundwater;
- in marine environments;
- in low-grade, metamorphosed sediments;
- in hydrothermally altered deposits; and
- in burial diagenetic systems (Mumpton [24]).

They can form as alteration products of volcanic glass or they can precipitate directly from fluids moving through certain rocks or sediments. The diameters of many zeolite crystals are very small, 1/1000–5/1000 millimetre (Mumpton [24]), and individual crystals can only be seen clearly with an electron microscope. Each crystal contains tiny channels and somewhat larger cavities in its structure, thus giving zeolites their porous nature. Even though the size of the openings and cavities depends on the zeolite's specific chemical composition the openings commonly range in size from 3–8 Angstrom units (1 Angstrom unit = 1×10^{-8} cm). The name 'molecular sieve' refers to the mineral's ability to allow certain size molecules to enter its structure and its ability to reject others. Table 1 shows some chemical and physical properties of representative zeolites.

Silicon, oxygen and aluminium make up the framework of the cage-like zeolite structure. The arrangement of the chemical components leaves up to about 50% void space within the crystal. It is on those internal surfaces where adsorption of ions and foreign molecules occurs. Aluminium occurs as a substitute for silicon in the mineral's structure which results in the crystal's overall negative electrical charge. To achieve electrical neutrality, various hydrated ions (eg potassium, sodium and calcium) enter the zeolite's structure and are retained in the crystal's cavities. The surface area provided by the cavities and channels in zeolites can reach as much as several hundred square metres per gram of zeolite making zeolites highly effective ion exchangers (Mumpton [24]). Because the ions are bound loosely to the crystal, they can be replaced by certain other ions that enter the structure. This ion exchange property of zeolites coupled with the unique properties of their porous structure, accounts for the interesting and potentially important usefulness of zeolites in agriculture.

Table 1. Representative formulae and selected physical properties of important zeolites.

Zeolite	Representative unit-cell formula	Void volume (%)	Channel dimensions (Å)	Thermal stability	Ion-exchange capacity (meq/g)
Analcime	$Na_{16}(Al_{16}Si_{32}OL_{96}) \cdot 16H_2O$	18	2.6	High	4.54
Chabazite	$(Na_2,Ca)_6(Al_{12}Si_{24}O_{72}) \cdot 40H_2O$	47	3.7×4.2	High	3.81
Clinoptilolite	$(Na_4K_4)(Al_8Si_{40}O_{96}) \cdot 24H_2O$	39?	3.9×5.4	High	2.54
Erionite	$(Na,Ca_5,K)_9(Al_9Si_{27}O_{72}) \cdot 27H_2O$	35	3.6×5.2	High	3.12
Faujasite	$Na_{58}(Al_{58}Si_{134}O_{384}) \cdot 27H_2O$	47	7.4	High	3.39
Ferrierite	$(Na_2,Mg_2)(Al_6Si_{30}O_{72}) \cdot 18H_2O$		4.3×5.5 3.4×4.8	High	2.33
Heulandite	$Ca_3(Al_8Si_{28}O_{72}) \cdot 24H_2O$	39	4.0×5.5 4.4×7.2 4.1×4.7	Low	2.91
Laumontite	$Ca_4(Al_8Si_{16}O_{48}) \cdot 16H_2O$		4.6×6.3	Low	4.25
Mordenite	$Na_8(Al_8Si_{40}O_{96}) \cdot 24H_2O$	28	2.9×5.7 6.7×7.0	High	2.29
Phillipsite	$(Na,K)_{10}(Al_{10}Si_{22}O_{64}) \cdot 20H_2O$	31	4.2×4.4 2.8×4.8 3.3	Low	3.87

Source: Mumpton [25].

Some potential uses of zeolites in developing country agriculture

Soil improvement

Most developing countries lie wholly or partly within tropical latitudes where rainfall is high and temperatures warm year round, consequently the soils are largely depleted of important plant nutrients. The composition of the highly weathered, acid soil and bedrock consists to a large degree of secondary minerals rich in silicon, aluminium, iron and water – certainly a sparse diet for many crops. In addition, those minerals have little ability to hold fertilizer nutrients in a form easily available to plants because the minerals have poor ion exchange properties. Where soil organic matter is low, costly nitrogen fertilizers leach quickly from soils providing little benefit to crops/farmers. Here, zeolites might play a beneficial role.

Mixing ground zeolitic rock with an infertile, acid soil could increase the soil's ion exchange properties and thus the soil's ability to hold nitrogen fertilizers (Chen *et al* [7]; Mumpton [25]) and other plant nutrients like potassium and calcium. One common zeolite species – clinoptilolite – is stable in acid soils having pH values as low as 2 (Flanigan [15]). In addition, zeolites themselves are likely to carry such nutrients in their natural state (see Table 1). Zeolites like clinoptilolite may contain small amounts of sodium which can be released to the soil during ion exchange. Sodium can adversely affect plants in some cases and, with its release, potassium might be removed from the soil by the zeolite (Lai, 1988, personal communication; Desborough, 1988, personal communication). Chemical monitoring to identify the beneficial or adverse effects of the addition of zeolites to the soil therefore is important throughout such field tests. (The Japanese have considerable experience in amending their soils with zeolites (Mumpton [25]; Minato and Utada [21]).

The Cuban Ministry of Basic Industries conducts extensive laboratory research and applied field testing of the zeolites clinoptilolite and mordenite for a wide variety of possible agricultural uses (Mumpton, 1988, personal communication). Cuban researchers report minor to major beneficial agricultural impacts of zeolite use during 10 years of investigation. Zeolite deposits exist in all Cuban provinces and the Cubans plan to construct four zeolite processing plants. The one deposit being mined today is composed of about 85% clinoptilolite and mordenite. The Cuban scientists report success using zeolites from this deposit in 'zeoponics' – a technique advanced by Bulgarian researchers that involves growing plants in a greenhouse on a mixture of zeolites, peat and vermiculite. This technique could find application in some arid/semi-arid developing countries.

Sandy soils in arid/semi-arid developing countries may also be deficient in ion exchange properties. Here again is a possible opportunity for zeolite application. Cooperative investigations of this application are now being planned by soil scientists of Egypt's Ain Shams University in cooperation with zeolite researchers at the US NASA Johnson Space Center in Houston, Texas (Ming, 1988, personal communication). Clinoptilolite deposits in western Egypt will be mined and the ground rock added to improve certain desert soils for agricultural use.

An additional benefit of zeolite additions to sandy soils is that zeolites are extremely effective at removing moisture from the air even where the humidity is low (Mumpton [25]). This moisture could benefit crops during extended periods of little rainfall. Such additions might also benefit highly leached, well-drained soils of the hot, wet tropics where rainfall may be seasonal.

Zeolites and rock phosphate

Phosphorus deficiency in soils inhibits productive agriculture in much of the developing world. Some developing countries, however, have rock phosphate deposits or other phosphorus-bearing mineral deposits, but cannot afford to build chemical facilities necessary to acid treat the rock to increase solubility and thus make the phosphorus available to plants. Over the past several years a few zeolite researchers have been investigating how ammonium-saturated zeolites, when mixed with ground rock phosphate or other phosphorus-bearing minerals of low solubility, can free significantly greater amounts of phosphorus (one to two orders of magnitude) for plants than when the phosphate minerals are mixed with the soil alone (Barbarick, Lai and Eberl [4]; Chesworth *et al* [12]; Lai and Eberl [19]).

Greenhouse experiments mixing ammonium-saturated clinoptilolite with ground rock phosphate in ratios of 3:1 to 4.5:1 show increased phosphorus uptake by plants and increased biomass production (Barbarick, Lai and Eberl [4]). Mixing farm-animal manures with zeolites like clinoptilolite and mordenite to achieve ammonium saturation on the farm provides opportunities for the farmers with few resources to produce their own fertilizers at low cost and to improve soil fertility. Farmers could add ammonia-saturated zeolites to farm soils as a slow-release nitrogen fertilizer and, where ground rock phosphate can be added as well, the phosphorus availability can be increased for crops. (Calcium from the rock phosphate released by the hydrogen ions of the ammonia is taken up by the zeolite and some phosphorus in turn is released to the soil for plant use.)

Fresh swine or chicken manure, both rich in nitrogen, probably will work best in charging zeolites with ammonia (van Straaten, 1988, personal communication). Fresh manure will work better than old manure because little ammonia will have had time to be lost by leaching or volatilization during storage. Further, pre-heating zeolite-bearing sedimentary rocks containing 50–70% clinoptilolite to 400–600°C before exposing them to animal wastes is suggested as a way to increase by 20 to 40 times the zeolite's ability to take in ammonia (Desborough, 1988, personal communication). However, many developing country farmers would be unable to heat-treat zeolites because of fuel and equipment costs associated with doing so.

Animal-waste management

Zeolites have a role in animal-waste management because they can adsorb ammonia from animal wastes (Mumpton [25]). Zeolites have a potential for use in developing countries to help minimize water pollution from agricultural runoff and to make animal manure easier to handle and to move from animal pens to agricultural plots. Applications of zeolites in swine production will be used below to illustrate the problems and opportunities in developing country animal-waste management.

Swine manure is malodorous and is composed only of about 10% solids (Minor and Stroh [22]) making it difficult and undesirable to handle. As such, in developing countries farmers wash a large percentage of the animal waste from swine pens into streams rather than use it on agricultural lands. Nevertheless, swine waste is a high quality source of plant nutrients when applied to agricultural plots. For example, a clinoptilolite-rich mudstone was used in a swine-raising activity in Japan to reduce the manure's offensive odour and to improve its handling characteristics. As a consequence, the zeolite-treated manure proved suitable as a fertilizer for rice cultivation (Honda and Koizumi [17]).

Other work in Japan on large hog farms also illustrates the usefulness of zeolites (Nishimura [27]). A zeolite filter composed of granular mordenite (grains 2–5 mm in diameter) used to process contaminated water remaining after initial manure/water filtration, removed the ammonium ions, other micro-substances, and trapped much of the remaining suspended solids. Transparency of the effluent showed marked improvement after zeolite treatment (see Table 2).

Recently, Romanian researchers (Marton and Marculescu [20]) showed similar results to those of the Japanese. They used non-activated, ground volcanic tuff containing 67% clinoptilolite in a series of filters, each with a different zeolite size fraction ranging from 0.5–10 mm. The ammonia–nitrogen content decreased 91.3% and the nitrate–nitrogen content decreased 99% from the initial metallic screens through the final zeolite filter.

Such studies illustrate that zeolites can play an important role in animal-waste management by trapping ammonia. Clinoptilolite, for example, could be spread on the floor of swine enclosures to trap ammonia and reduce the odour, and moisture content of manure. The manure might become a resource of fertilizer for agricultural plots rather than a pollutant in surface-water resources. Pits containing zeolites could be constructed near swine pens into which manure could be washed. The liquid overflow would be

Table 2. Zeolite (mordenite) treatment of liquid swine wastes in Japan (Nishimura [27]).

Sample	Nitrogen (ppm)	COD (ppm)	BOD (ppm)	Cm of transparency
A	554	1907	3600	0
B	142	240	610	2
C	19	24	21	24

Note: A = original solution
B = solution after initial separation
C = solution after treatment with zeolite (mordenite)
BOD = biological oxygen demand
COD = chemical oxygen demand

reduced in ammonium by the zeolites and the trapped sediment could be spread on agricultural lands as a nitrogen-rich fertilizer.

Zeolite amended diets, in the case of poultry, have been able to reduce the moisture content of poultry faeces by 25% (Willis, Quarles, Fagenberg and Shutze [38]). Such moisture reduction could improve the farmer's desire and ability to collect and transport the nutrient-rich fertilizer to his agricultural plots. Swine fed a 5% clinoptilolite diet produced more compact and less malodorous faeces than control groups (Vrzgula and Bartko [36]).

The Netherlands, although not a developing country, has severe air and water pollution problems arising from the significant level of swine production – 14 million pigs, a number equal to its human population (Armstrong [3]). The People's Republic of China in 1985 had 331.5 million pigs (Wittwer *et al* [39]), one for every three persons in China. Here too, animal-waste disposal has caused serious, widespread water pollution problems. Disposal of the manure from Hong Kong's 570 000 pigs and 6.7 million chickens is adversely affecting Hong Kong's streams, rivers, beaches and near-shore marine waters (Wong [40]; Anon [1]; Bingham [5]). Daily, some 2000 tons of untreated animal manure enter its streams and rivers. The problem is so severe that Hong Kong's government is considering actions that may tightly restrict swine- and chicken-raising activities in the Colony (Anon [2]). China has large zeolite resources (Huang [18]) having potential if used wisely, to alleviate China's own swine-waste problem and perhaps also that of neighbouring Hong Kong.

Heavy metals and animal feeds

Trace amounts of copper and zinc are commonly added to the diets of pigs as artificial supplements, copper to promote weight gain and zinc to offset copper toxicity. This practice is used in China, Hong Kong and many other countries as well. The individual pig retains only about 5–10% of these metal supplements, and the rest is expelled in the manure. When the manure is spread as fertilizer, high levels of copper (and sometimes other trace metals) can concentrate in the crops over time (Wong [41]) and ultimately in humans, sometimes to toxic levels. Clinoptilolite will absorb copper, zinc and cadmium from soil in preference to calcium and sodium (Weber, Barbarick and Westfall [37]). Thus, additions of clinoptilolite to swine manure would tend to tie up potentially toxic heavy metals preventing them from rapid movement in the soil and endangering humans. However, if the soils are acid, the heavy metals ultimately will become mobile.

Animal nutrition and health

Mixing zeolites in animal diets has had some interesting results that may have some future applications in developing country agriculture. Nevertheless, as with other applications of zeolites to agriculture, research results are mixed and further research on the impacts of zeolites on animal nutrition, weight gain, and health is clearly needed. Thus far, no adverse impacts on common farm animals (swine, poultry and ruminants) and products derived from them have been observed where zeolite additions have been made to the animal diets. Research shows that replacing 1–2% of the feed with ground clinoptilolite can produce a small, reproducible improvement in feed conversion and in some cases increases in animal body weight (Quarles [32]).

Zeolites used by Romanian researchers (Marton and Marculescu [20]) to treat swine waste-water became enriched in ammonia, organic matter, and other nutrients during the process. The zeolites subsequently were dried and powdered and as much as 15% was added as dietary supplements to animal rations. The Romanian zeolite scientists are convinced of the usefulness of zeolites as beneficial dietary additives for animal feeds.

The beneficial impacts of zeolite diet supplements on animal health are varied (Mumpton [25]). For example, the results summarized by Mumpton on experiments of feeding swine zeolite supplements show decreases in death rate, incidence of disease, gastric ulcers, pneumonia and heart dilation. Further, zeolite supplements reduced the outlay for animal medicines and had pronounced beneficial impacts on slowing or eliminating diarrhetic animal ailments like scours. Here again zeolites appear to fill another important need of the developing country farmer, that of improving animal health, and careful research is needed to verify and explain the actions of zeolites in animal health and nutrition.

Exploration for zeolites

Many extensive zeolite deposits occur as surface or near-surface, flat-lying, relatively soft beds of altered volcanic tuffs of relatively young geologic ages, some of which may contain 90% zeolites (Mumpton, 1988, personal communication). Because the crystal size of zeolites is so small, field identification of such deposits is difficult. Final determination requires x-ray, chemical, and electron microscope analysis. Once identified, stratigraphic and paleogeographic reconstructions can help guide further geological exploration.

Several geophysical and remote-sensing techniques could help in zeolite exploration. Geophysicists use field electrical resistivity measurements in the search for hydrothermal ore deposits (Stanley, 1988, personal communication). Large halos of clay-rich country rock commonly surround such ore deposits. Outer halos may be rich in smectite clay minerals and in zeolites, two kinds of minerals that hold large quantities of water. Electrical resistivity is characteristically very low over such water-bearing mineral halos and, thus, can be used to help identify potential zeolite deposits. Stanley has made measurements, available in his laboratory, which show electrical resistivity differences for a variety of zeolite species.

Considerable attention is being given to the search for hydrothermal ore deposits using special equipment carried in satellites and in aircraft (Podwysocki, 1988, personal communication). However, near-infrared satellite imagery of arid regions from the Landsat-4 Thematic Mapper has not been able to resolve spectral differences between common clay minerals and zeolite minerals surrounding ore deposits (Ehmann and Vergo [14]). Similarly, spectral differentiation using the older airborne multispectral scanner (MSS) could not be achieved (Podwysocki, Segal and Abrams [29]). It seems likely, however, that by using the newer Airborne Imaging Spectrometer, an aircraft-mounted instrument having high-resolution sensors, remote-sensing specialists should be able to separate the two types of geological materials in arid regions from the air (Ehmann and Vergo [14]). Improved remote sensing techniques would help in the broad search for minerals like zeolites to the benefit of developing country agriculture. Even so, geological field and laboratory work ultimately will be needed to make the final zeolite mineral identification (Podwysocki, Power and Jones [30]).

Developing country geological surveys

Developing country geological surveys commonly lack the needed laboratory equipment (eg x-ray diffractometers, electron microscopes) to carry out thorough analyses of geologic materials, especially fine-grained, non-metallic mineral resources like zeolites and clays. Such institutions generally lack even the more fundamental resources necessary to conduct field work (eg vehicles, fuel, adequate numbers of trained staff, funds, etc). Further, the training of developing country geologists to assess non-metallic mineral resources is weak and needs strengthening at the university level. Those and other associated problems hinder developing countries from determining whether zeolite deposits exist in their countries.

Another problem needing attention is that geoscientists and agricultural scientists generally have little interdisciplinary contact in their work. Such a separation increases the likelihood that should zeolite deposits be discovered, the find could go unnoticed by the agriculturalists or the geologists might not realize that the discovery could have significant benefits to local farmers.

Conclusions

Research information assembled in the volume *Zeo-Agriculture: Use of Natural Zeolites in Agriculture and Aquaculture* (Pond and Mumpton [31]) and in the paper 'Using zeolites in agriculture' (Mumpton [25]) provides an excellent starting point for the agriculturalist and natural resource specialist who may be interested in learning how zeolites work so that he or she might apply that knowledge effectively to the special problems of developing-country agriculture. Clearly, additional research is needed before zeolites can be used extensively in developing countries. Nevertheless, those reports may whet the appetite of the biological researcher and physical scientist. The reports contain information hinting at an array of interesting and potentially important zeolite uses that may be relevant to developing-country agriculture and where obvious additional research is needed.

Field testing zeolite use in agriculture in developing countries is long overdue for many applications. It is here that rapid advances probably will occur especially if the work is conducted by interdisciplinary teams of biologists, chemists, geologists/mineralogists, soil scientists and agronomists.

. . . many agricultural scientists working with zeolite materials are poorly informed on the chemistry, structure, and physical properties of the very minerals they are using in their experiments. Their lack of knowledge of the similarities and differences among the several natural zeolite species showing promise for agriculture useage has led to less than optimal experimental designs. For example, the lack of knowledge of the inherent chemical and mineralogical differences (and therefore, e.g., of ion-exchange reactivity) that might exist from deposit to deposit or even

Table 3. Reported occurrences of sedimentary zeolites in certain developing countries.

Country	Zeolite species	Minable deposit	Minor occurrence	Chances for finding deposit
Turkey	Clinoptilolite	XX		Excellent
	Erionite		XX	Excellent
	Chabazite		XX	Excellent
	Analcime	X		Excellent
Cuba	Clinoptilolite	XX		Excellent
	Mordenite	X		Excellent
Guatemala	Clinoptilolite	X		Excellent
Mexico	Clinoptilolite	XX		Excellent
	Mordenite	XX		Excellent
	Analcime		X	Good
	Erionite	X		Excellent
	Phillipsite		X	Excellent
Panama	Clinoptilolite	X		Excellent
West Indies	Wairakite		X	Poor
	Clinoptilolite		X	Excellent
Angola	Clinoptilolite		X	Good
Botswana	Clinoptilolite		X	Good
Burundi	?	X		?
Congo	Analcime	X		Good
Egypt	Heulandite		X	Good
Ethiopia	?	X		?
Kenya	Phillipsite	X		Excellent
	Erionite	X		Excellent
Northwest Africa	Analcime	X		Good
	Mordenite		X	Good
	Clinoptilolite	X		Excellent
Tanzania	Erionite	X		Excellent
	Chabazite	X		Excellent
	Phillipsite	X		Excellent
	Analcime	X		Excellent
	Clinoptilolite	X		Excellent
Iran	Clinoptilolite	X		Excellent
Pakistan	Analcime		X	Good
China	Clinoptilolite	XX		Excellent
	Mordenite	X		Good
Taiwan	Laumontite		X	Poor
	Analcime	X	X	Good
Argentina	Clinoptilolite	XX		Excellent
	Analcime	X		Excellent
	Laumontite		X	Poor
Chile	Clinoptilolite		X	Excellent

Source: Mumpton [25]; additional data from van Straaten [35]; Huang [18]; and Su and Dai [34].

within a single deposit is particularly troublesome. Second, many geological and chemical scientists, experts on zeolites in their own right, seem to be poorly informed on the profound genetic and physiological variabilities that exist from animal to animal or from plant to plant, or of the chemical complexities of a plant-soil system or within an animal's digestive tract. Considering these deficiencies, it is no wonder that many of the zeo-agricultural results obtained to date lack agreement (Parham [28]).

These are common zeolite research problems in developed countries so it is important that developing country scientists avoid such problems from the start to assure reproducible research results and to avoid following false trails.

The findings from zeolite research to date, though not as comprehensive as one might like, offer encouragement to those persons working with farmers in developing countries. If used properly, zeolites might lead to increased food security for those farmers. Interdisciplinary zeolite research among geologists, biologists, and agricultural scientists is starting to grow and the term 'agrogeology' is developing a following in universities and other research institutions in Canada and the USA (Sheppard [33]; Pond and Mumpton [31]; Lai and Eberl [19]; Chesworth [8,9,10,11]; van Straaten [35]; Chesworth, van Straaten, Smith and Sadura [12]; and Gough [16]). Additional activities that strengthen and expand such linkages will be needed if zeolites' agricultural potentials are to be reached in developing countries.

Nevertheless, agricultural scientists and others are quite aware that from time to time 'magic elixirs' come on the market that claim to solve all of the farmer's soil problems overnight. Rarely does sound research support the promoter's claims. With the growing body of research on zeolite uses in agriculture, however, it is becoming increasingly clear that their role in agriculture generally, but more particularly in developing country agriculture, holds real promise.

Today, we know that zeolite deposits occur in at least 20 developing countries (Table 3). Finding other zeolite deposits in other developing countries and assessing their properties for agricultural use still needs increased attention from the geological surveys of those countries. Certainly, here is an area for increased cooperation between geological institutions of the developed and developing world.

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