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Review

Crop diversification through halophyte production on salt-prone land resources*

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Abstract

Rapid population growth in the less developed countries of arid and semiarid regions and concomitant decline in productivity of agricultural lands due to shortage of good-quality irrigation water and increasing soil salinity, are exerting enormous pressure on the dwindling supplies of human consumption for food. Equally or even more affected in some cases are other resources, such as fodder for animals and fuel wood for the rural poor. There is growing evidence that this trend is unlikely to reverse at least in the near future. The last quarter of the 20th century has seen an explosion of information leading to a better understanding of the biology of salt tolerance in plants. Most conventional crops have marginal salt tolerance and there is a need to explore alternate options for utilization of salt-affected lands and saline water resources. Research has indicated the potential of many halophytes to withstand high soil salinity and saline water irrigation, some even with seawater. This tolerance is achieved through a number of adaptations such as selective uptake and transport of ions, localization of ions in vacuoles, synthesis of compatible organic solutes for cytoplasmic balancing and protection of enzyme systems. As a consequence, these plants are able to reduce damage and exhibit sustained growth by establishing homeostatic conditions. A wealth of halophytic flora exists which can be exploited for an array of uses like food, fodder, fuel wood, oilseed, medicines, chemicals, landscaping, ornamentals, and environment conservation through carbon sequestration.

Keywords: Compatible solutes, Crop diversification, Halophytes, Ionic effects, Osmotic adjustment, Salinity, Salt tolerance

Review Methodology: We searched the following databases: CAB Abstracts, CAB Heritage, Agricola and Medline (keyword search terms used: Salinity, Salt tolerance, Halophytes, Amelioration, Environment, Arid lands). In addition we used the references from the articles obtained by this method to check for additional relevant material. We also spoke to colleagues and checked for any upcoming studies not yet published.

Introduction

Background: Water shortage, Irrigation Management and Increasing Salinity

Soil salinity and irrigated agriculture go hand in hand since ancient Babylonian times, and many old civilizations are known to have perished due to the onslaught of salinity on their agricultural lands [1]. Present-day agriculture is also facing the soil salinity hazard, which is mostly man-made and is largely brought about by lack of appropriate irrigation management [2]. Consequently, about a billion hectares of salt-affected lands have spread in Australia, India, Pakistan, Central and South Asia, the Middle East, North Africa, USA, Mexico, South America and an additional two million hectares go out of productivity worldwide each year due to secondary salinization [3, 4]. Good-quality irrigation water in these arid and semi-arid areas is scarce, underground water is generally brackish

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and rainfall is insufficient to leach out salts accumulated in the surface soil, because of high evapo-transpiration. Consequently, salt deserts (caused by lack of fresh water) and saline inland basins (caused by the rising level of saline groundwater as a result of leakage of drainage water) are being created in agricultural areas. Even if better-quality water is available, it is often mismanaged causing further soil deterioration and resulting in a direct loss of crop production. A burgeoning world population is also a cause of concern for sustained food supply [5].

Plants exposed to salinity initially experience osmotic stress followed by specific ion effects [6]. Sodium is generally the main culprit in such situations as it forms the bulk of the constituents of salinity, be it in water or soil. Brackish water of variable concentration exists over- and underground whereever saline soils occur, while seawater may contain 0.5–1.0 M salts depending on location and time of the year. The mention of seawater is relevant because of vast coastal areas of the world that are the natural habitat of diverse halophytic species with wide ranging succession of plants from seacoast (always wet with seawater) to inland, where seawater reaches only during high tide and salts concentrate in the root zone due to evaporation.

Plants have the ability to take up any salt present in rhizosphere. This uptake tilts in favour of sodium because of its abundance in saline soils and affects uptake of other more important ions; sodium is an essential mineral AQ1 nutrient only for C_4 and CAM plants and that too in small quantities [7]. High sodium in plants not only retards growth directly but also through interlinked metabolic processes starting from simple enzymatic reactions to more complex molecule building. In such situations, mineral nutrition is disturbed, chlorophyll content and their activity reduces affecting photosynthesis and a host of undesirable events start creeping up and create disturbance in growth and development of plant.

History: Measures Taken and the Degree of Success

Using saline lands for conventional agriculture requires either improving the soil or enhancing the salt tolerance limit of field crops, majority of which cannot survive with the levels of average soil salinity prevailing in the fields. These approaches, which have been applied with variable degree of success, involve engineering/reclamation and/or breeding crops for salinity tolerance. Engineering approaches include surface drainage, lining of canals and pumping of ground water, while reclamation of the salt-affected soils involves leaching with higher levels of irrigation, use of gypsum or acids, physical removal of salts and growing salt-tolerant plants. The results indicate an expensive and short-term solution to the problems. In many such studies, the plants used for rehabilitation were generally grasses that are known to exclude salts, thereby resulting in limited success.

Progress in breeding for salt tolerance through gene transfer has been slow, hampered by various factors, e.g. the character is under multigenic control, hence difficult to transfer and not many genes have so far been recognized to play with, not to mention the social acceptance of GM food. Some crops, however, have been bred for AQ2 salt tolerance through mutagenesis and conventional breeding [8, 9] but with limited success where salt tolerance was increased: but to the extent that it gave those species only a slight advantage in comparison to their less tolerant relatives. The existing levels of salinity in fields require further improvement in plants, which may not be forthcoming at least in the near future. However, utilizing the inherent ability of halophytes to complete their life cycle even under highly saline conditions seems a feasible option. Flowers and Yeo [9] have advocated that it is perhaps cheaper, easier and may be more successful to domesticate a wild salt-tolerant species than modify an existing crop to get gainful returns from a saline environment. History bears out success in the improvement of agronomic characters but not enhancement in salt tolerance comparable with even a sensitive halophyte.

Why Halophytes: Theoretical Arguments

There are numerous ways of defining halophytes. The best definition seems to be ‘plants that complete their life cycle in saline habitats’ [10], where concentration of soil solution is about 5 g/l of total dissolved solids (85 mM NaCl or 7–8 dS/m) [1]. They grow in habitats ranging from seacoast with salinity 0.5–1.0 M or higher to areas having slightly brackish water that is still not suitable for conventional agriculture. Several efforts have been made to compile a list of the halophytic flora of the world as well as a list of regional halophytes [1, 3], but the information is still far from complete.

The key to survival under saline conditions lies in the ability and capacity of a plant to minimize the effect of sodium and other harmful salts present. This can be achieved theoretically by restricting salt buildup in plant tissue (exclusion) or allowing it to a certain limit (inclusion); plants, depending on their genetic make-up, have the ability to do both. The ‘excluders’ are generally less tolerant as their capacity to exclude breaks at high substrate salt levels, whereas the ‘includers’, which are also prone to damage above a certain limit, continue to survive at considerably higher salt concentrations. The capacity to include or exclude salts breaks earlier in glycophytes, while the halophytes are able to do so over a wider range, thus making them more suited to these harsh environments.

The plants, in order to survive under such conditions, have to achieve osmotic adjustment and maintain a constant flow of water (and mineral nutrients needed for sustenance) from the rhizosphere to the growing parts. The soil solution here, because of accumulated salts, has a low water potential and in order to maintain transpiration flow, an even lower water potential is needed inside the plant. Again this is achievable through ion uptake and synthesis of compatible organic solutes. Excess ions, sodium for instance, are separated into cell vacuole and cytoplasm is balanced through accumulation of organic compounds which also help in proper functioning of metabolic processes and provide protection from damage under the adverse conditions.

Halophytes similarly achieve osmotic adjustment through inorganic ion accumulation and synthesis or accumulation of organic compounds, but the adaptation is to a greater extent than in glycophytes [11]. Betaine, for instance, is believed to function as a source of compatible solute for intracellular osmotic adjustment. Its accumulation occurs in the tissues of plants exposed to a saline substrate, and there is a positive correlation between betaine content and the amount of Na^+ and Cl^- in the cell sap. It is also estimated that about 200 mM/l of plant water or higher betaine concentration is needed to achieve osmotic adjustment successfully under saline conditions and a number of the Pakistani species, e.g. *Halopyrum mucronatum*, *Atriplex stocksii*, *Haloxylon stocksii* and *Suaeda fruticosa*, have levels of betaine concentration higher than this with a corresponding increase in salinity [12].

Halophytes also have other strategies to avoid water loss and reduce salt load. Faced with high salt uptake, they are able to excrete excess salts through specialized salt glands, governed by salt concentration of the growth medium, light, temperature, oxygen, pressure and the presence of metabolic inhibitors [2]. Active secreting glands have been listed in *Avicennia*, *Aeluropus*, *Aegiceras*, *Limonium*, *Rhizophora*, *Ceriops*, *Tamarix* and *Reaumuria* [13, 14]. A similar function of salt secretion is ascribed to bladder trichomes of some members of Chenopodiaceae, e.g. *Atriplex* species, which protects young developing shoots and leaves from toxic salt levels, first in the apoplast and then in the symplast.

Under physical or physiological stress conditions, their leaves develop certain xeromorphic adaptive characteristics such as succulence, reduction in surface area, thick cuticle or a cover of waxy layers on the epidermis, hairs on stem and leaves, sunken stomata, etc. [14]. The succulents often lack the ability to secrete salts, but thwart the rise of salt concentration through an increase in their cellular water content during development. *Arthrocnemum*, *Halogeton*, *Halopeplis*, *Halostachys*, *Haloxylon*, *Heliotropium*, *Salicornia*, *Suaeda*, *Salsola*, and *Zygophyllum* are prominent succulent halophytic genera. There is an abrupt reduction in surface area of leaves of some species (e.g., *Salsola imbricata*, *Trianthema triquetra* and *S. fruticosa*) under conditions of extreme salt stress. *S. fruticosa*, *S. imbricata*, *H. stocksii*, *Haloxylon salicornicum*, *Cressa cretica*, *Sporobolus ioclados*, *Urochondra setulosa*, and *Aeluropus lagopoides* are characterized by thick cuticle and a cover of waxy layer, while stems and leaves of the last five species remain covered with hair [11].

Salt tolerance in halophytes also varies with the stage of development. Some species, such as *S. fruticosa*, *H. stocksii*, *A. stocksii* and *Zygophyllum simplex*, are not highly salt-tolerant at germination, but show tolerance at the later growth stages [15], while other species like *Arthrocnemum macrostachyum* and *C. cretica* show a high degree of salt tolerance both at the germination and different growth stages [16–18]. Although an increase in salinity usually delays their germination [15] but when exposed to high salinity, the seeds of a halophyte may either germinate or remain viable for recovery during more favourable periods, as observed in many species [19]. However, it has also been observed that seeds of several perennial halophytic species from subtropical deserts progressively lost viability when soaked in highly saline water of coastal/inland marshes that are exposed to high temperatures [15].

History of Halophyte Utilization

Logic supports the contention that the present form of life or at least most of them had their origin in the waters of the ocean and even today the sea harbours a large flora. According to Boyko [20], 'it seems odd that such an enormous amount of plant material growing in the sea should not prove to be useful as a source of food' and Boyko suggested that the 'wayward ones that wandered out to the land should be returned to the sea to produce food'. Salinity and plants in fact do not seem to be incompatible, the only problem being of adaptation. Circumstantial and experimental evidence proves the superiority of halophytes in this regard.

Even when the ocean receded and continents appeared, plants continued to grow in the wild. Man, according to his need, domesticated some of these (the present-day agricultural crops), which in the process gained desirable attributes such as reduced seed dormancy in most species, synchronous flowering and ripening and increased yields, but they also lost or were left with reduced capacity to withstand the vagaries of wild environment. Most halophytes, on the other hand, continue to retain their wild nature. This has long been recognized and exploited by scientists, and the use of halophytes dates back to ancient times when *Alhagi maurorum* was used by the Sumerians as a soil ameliorant.

The Israelis should be credited to bringing this knowledge to the forefront in the recent past [21, 22]. Hugo Boyko may perhaps be regarded as pioneer of starting such activities, which later picked up not only in Israel but also spread to other countries [1]. In the foregoing we mentioned the destruction of civilizations due to salinity. The possibility of reversing this trend has aptly been demonstrated in Israel by Elisabeth Boyko [20]. She started planting suitable halophytic species using underground water of 6000–10 000 ppm for irrigation on barren gravel hills of a hot desert climate of less than

25 mm average yearly rainfall in an area which had no inhabitants. With greenery appearing, people started moving in and the population rose gradually from none in March, 1949 to 300 in November, 1949, 7000 in December, 1962 and 12 000 in December, 1964. Today, Eilat is an important port city and a winter resort of Israel boasting a population of about 30 000, which swells to over 50 000 during the peak tourist season, with the famous gardens of Eilat playing a pivotal role in bringing this change. This highlights the potential of using salt-tolerant plants in changing the ecology and environment of that area.

The upsurge in research on halophytes stems from the realization that improving the limited potential of our crops to sustain under adverse soil conditions remains elusive [23], whereas the increasing evidence in support of utilization of halophytes for various purposes keeps mounting [24]. Although, as yet, the commercial use of halophytes has not gained any appreciable momentum but they still provide relief to rural poor for various ailments, are a source of food for human consumption in certain places to a limited extent, certain halophytic grasses, in addition to their use in turf development, are a useful supplement for animal fodder during periods of scarcity and avenues are open to explore their potential for miscellaneous uses to benefit the mankind.

Utilization Potential of Halophytes

Salinity, at least at the moment, is of regional significance and has not reached the dimension that warrants emergency action to counter the damage. This is mainly because agriculture has so far managed to meet the demand. But with the present state of affairs, i.e. increasing population and decreasing crop yields due to salinity, warning bells should definitely start ringing and sooner the better. It may be too early to predict when we shall start to consume halophytic food as even part of our diet, given our long-established eating preferences. At present, 90% of human food comes from only 30 plant species and 50% from just four: rice, maize, wheat and potato. We do not know whether these are the best or just reached our dining tables accidentally, but one thing is pretty sure: that salt sensitivity of our staple food crops will ultimately make them redundant in the future. This could be decades or even more away, but is the most likely scenario to be faced by mankind.

For the time being, halophytes do not seem to have much potential in contribting to world food supply, although some are used by certain communities for this purpose [5]. Their potential as a land cover cannot be denied, which is not only aesthetically pleasing but also checks land erosion and degradation. The more important opportunities relate to reforestation or replanting and ecological recovery of saline areas that have fallen into disuse, coastal development and protection, production of cheap biomass for renewable energy, environment conservation through carbon (C) sequestration. Mangroves, a dominant vegetation form of many tropical and subtropical seacoasts, play an important role in stabilization of coasts and beaches; food chain and life support systems; aquaculture; agriculture; and support to development of wild-life sanctuary and recreation areas [25]. They also provide tannin; thatching material; fodder; fish poison; food products; medicine and wood for building purposes, fuel, and boat- and canoe-making for the residents of coastal areas [26]. About 100 halophytes are found on the coast of Sindh and Balochistan out of a total 410 reported from Pakistan, and about 51 could be used for extracting medicine, 48 as forage, 47 as fodder, 38 as food, 34 as ornaments, and others as fibres, timber and other usages of wood, and various chemicals [27]. Most examples given below rely heavily on information available on halophytes of Pakistan but other halophytes have also been mentioned at suitable places. For a more extensive coverage, Aronson's HALOPH is recommended [1].

Food-yielding Halophytes

The only conventional crops species consumed by human beings as food, which tolerate salinity to a certain extent are beets (*Beta vulgaris*), the date palm (*Phoenix dactylifera*) and barley (*Hordeum vulgare*), whereas there is an array of more salt-tolerant halophytic species with potential for use as human food and many of them are used for this purpose, albeit not on a very large scale. The seed-bearing species, which are used as food, include among others, *Salvadora oleoides*, *Salvadora persica*, *Trianthema portulacastrum*, *Oxystelma esculentum* and *Zizyphus nummularia* [5]. The young leaves, shoots, radicles of *Rhizophora mucronata*, *Ceriops tagal*, *Thespesia populnea*, *Hibiscus tiliaceus*, *Salicornia bigelovii*, *Salicornia brachiata*, *Sesuvium portulacastrum*, *Chenopodium album*, *Atriplex hortensis*, *Triglochin maritima*, *Arundo donax*, *Rumex vesicarius*, *Apium graveolens*, *Portulaca oleracea*, and *Suaeda maritima* have been used for vegetables, salads and pickles in various parts of Indo-Pakistan [27, 28]. Examples from elsewhere include use of *Aster tripolium* as vegetable in The Netherlands, Belgium and Portugal; *Salicornia* species and *Tripolium vulgare* as food in West Siberia, many mangroves including *Avicennia marina* and *Avicennia germinans* as food in Columbia; *Zizania aquatica* as a catch crop in western USA and Canada [29], *Distichlis* species for making bread, biscuits, etc. in many parts of the world [4].

Forages and Fodders

Without any prejudice to other uses, the greatest potential of halophytes probably rests with their utilization as forages and fodder [30]. The vast coastal areas around the world lie barren because of the shortage of good-quality water and there is no dearth of similar tracts inland, particularly in arid regions. Here, seawater (on the coasts) and underground water (inland) of a quality that may sustain or even promote growth of many halophytes is available for growing suitable fodder and forage species for cattle.

Animals browse most of the 68 halophytic grasses found in Pakistan. Aronson [31] recorded 1.26–2.09 kg/m^2 dry matter, and 15.5–39.5% fibre, and 10.2–19.5% crude protein in some species of *Atriplex*. *Kochia indica* has been field tested for domestic livestock and found to produce good fodder with fresh biomass of 8.5 kg per bush from March through August [28]. Kallar grass (*Leptochloa fusca*) has gained much attention as a fodder on salt-affected soils [32] and yields about 46 t/ha of green matter when planted in extreme alkali soil (pH>10) for five years.

Additionally, there are about 95 halophytic species that could be used as either forage or fodder and most prominent among them are mangroves. Camels relish the foliage of such species as *A. marina*, *Aegiceras corniculata*, *C. tagal*, and *R. mucronata* [25, 28]. Among trees, species of *Acacia*, *Prosopis*, *Salvadora* and *Zizyphus* are traditional fodder of arid regions. Many species of *Alhagi*, *Salicornia*, *Chenopodium*, *Atriplex*, *Salsola*, *Suaeda* and *Kochia* are common fodder shrubs [5]. Among grasses *L. fusca*, *Lasarius scindicus*, *Panicum turgidum*, *Dactyloctenium sindicum*, *Cynodon dactylon*, *Paspalum vaginatum*, *Sporobolus marginatus*, *Chloris gayana*, *Chloris virgata*, *Echinochloa turnerana*, *Echinochloa colonum* and *Puccinellia distans* are common species found in saline and alkaline areas and used as forages [27].

Oil Seeds

Production of vegetable oil from seed-bearing halophytes appears promising but needs extensive screening to ascertain the quantity and quality of oil from various species. Of special significance is the degree of saturation: presence of unsaturated fatty acids in excess quantities makes a particular oil better for human consumption. Seeds of various halophytes, such as *S. fruticosa*, *A. macrostachyum*, *S. bigelovii*, *S. brachiata*, *Halogeton glomeratus*, *Kochia scoparia*, and *H. stocksii* possess a sufficient quantity of high-quality edible oil, with unsaturation of 70–80% [33, 34]. Seeds of *S. oleoides* and *S. persica* contain 40–50% fat and are a good source of lauric acid. Purified fat is used for soap- and candle-making and is a potential substitute for coconut oil.

Fuel Wood and Timber

Practically any wood can be used as fuel for cooking and heating, except those emitting excessive smoke and undesirable odour, which are caused mainly due to the presence of certain chemicals. More than a billion people in developing countries rely on wood for cooking and heating. Quite often fuel wood is obtained from salt-tolerant trees and shrubs, which may include species of *Prosopis*, *Tamarix*, *Salsola*, *Acacia*, *Suaeda*, *Kochia*, *Capparis* and *Salvadora* [28]. In addition, species like *Dalbergia sisso*, *Pongamia pinnata*, *Populus euphratica*, *Tamarix* spp. could provide good-quality wood [27]. In coastal areas, the mangroves are used frequently for fuel and timber, which has contributed significantly to the deforestation of these habitats. Species of *Rhizophora*, *Ceriops*, *Avicennia* and *Aegiceras* are good fuel woods and also contribute to charcoal production [26].

Aronson [31, 35, 36] in a survey of over 1600 such plants has identified 290 species as being tolerant of 7–8 dS/m salinity. *Tamarix stricta* has been recorded as yielding 7.2 t DM/ha/yr, with a final density of 600 trees/ha after five years. Various species of *Prosopis*, *Casuarina*, *Eucalyptus* and *Acacia* have been evaluated for their salinity tolerance and biomass production. *Prosopis juliflora* could yield up to 52.3 t/ha biomass in six years. *P. juliflora*, *Acacia nilotica* and *Casuarina equisetifolia* have been found to be most alkali-tolerant; *Tamarix indica*, *Tamarix articulata*, *P. juliflora*, *Pithecellobium dulce*, *Parkinsonia aculeata* and *Acacia farnesiana* to be tolerant of salinity levels up to EC 25 to 35 dS/m; and *A. nilotica*, *Acacia tortilis*, *Casuarina glauca*, *Casuarina obesa* and *Eucalyptus calmadulensis* to be tolerant of salinity levels up to 15–25 dS/m. *A. corniculata*, *A. marina*, *C. tagal*, and *R. mucronata* trees could similarly be grown in areas with high salinity and high water tables.

Medicinal Uses

Herbal medicine has come of age and is gaining popularity. Almost all homeopathic drugs are based on plant extracts. Active ingredients of plants, many of which grow wild and may belong to halophytes, have inspired many allopathic medicines, though synthesized. Many workers have reported the medicinal uses of halophytes, while describing the economic importance of plants [27, 28]. Halophytic plants are known to provide relief in the following diseases: cold, 'flu' and cough (*Achillea mellifolium*, *Microcephala lamellate*, *Phylla nodiflora*, *Caesalpinea bonduc*, *Plantago lanceolata*, *Portulaca quadrifida*, *P. oleracea*, *Solanum surrattense*, *Withania sominifera*, *Tribulus terrestris*, *Capparis decidua*, *Z. simplex*, *S. persica* and *S. oleoides*): vermifuge (*Artimesia scoparia*, *P. quadrifida*, *Seriphidium brevifolium*, *Seriphidium quetenses*, *Cocos nucifera*, *P. oleracea*, *Evolvulous alsinoides*, *S. imbricata*, *S. tetrandra*, *Zygophyllum propinqum*, *Z. simplex*): stomach ailments (*Juncus rigidus*, *S. quetenses*, *T. populnea*, *Zaleya pentandra*): pain killer (*A. scoparia*, *Solanum surratense*): diuretic (*Plantago major*, *P. quadrifida*, *P. oleracea*, *W. sominifera*, *T. terrestris*, *J. rigidus*): snake bite (*R. vesicarius*, *Verbena officinalis*, *Z. pentandra*): gonorrhoea (*P. oleracea*, *Corchorus* *depressus*): sedative (*W. sominifera*): ulcer (*C. tagal*, *W. sominifera*): pneumonia (*C. depressus*): heart disease (*Ammi visnaga*, *T. terrestris*, *C. decidua*, *K. indica*, *Z. simplex*): skin diseases (*Centella asiatica*, *S. imbricata*): laxative (*Capparis deciduas*): eyes (*Z. simplex*): ear pain (*A. scoparia*): asthma (*E. alsinoides*, *Solanum incanum*): wound healing (*P. lanceolata*) and stimulant (*K. indica*) [1, 5, 27].

Source of Chemicals

Halophytes are the source of a variety of chemicals ranging from pharmaceuticals for health and beauty to chemicals for tanning or production of plastics. Most of the mangrove species are rich in tannin and its extraction from the bark has been a major use of mangroves [28]. A kind of soda is obtained in large quantities from *Suaeda*, *Salicornia*, *Salsola*, and *Haloxylon* species, which is used in soap-making and in the glass industry. Seeds of *Annona glabra* are a source of insecticide while Rotenon, an insect and fish/arrow poison is extracted from the roots of *Derris trifoliata* [29].

Landscaping

Recent research in the evaluation of halophytes for land reclamation and landscaping has taken a new dimension. Many halophytes, because of sustained growth under highly brackish water irrigation, provide useful vegetation cover for landscaping including turf development. *P. vaginatum* and *Sporobolus virginicus* may be suitable candidates for lawns and golf courses etc. [37] with the only precaution of protecting good-quality groundwater (if present underneath) from contamination. Many a beach-side hotels in Agadir, Morocco use mangroves (*A. germinans*) and *Atriplex halimus* as land cover to stabilize the shifting sand. Other examples include *S. portulacastrum*, which has enormous growth to cover large areas in a short time, and *Batis maritime*, which fills roadside ditches in a short time with dense biomass. The latter plant also tolerates saline water containing elevated levels of heavy metals. Similarly, *Casuarina stricta*, *Salicornia stricta*, *Spartina* species are used for dune stabilization and cultivating swamps [29].

Ornamental

Many halophytes are useful ornamentals because of their beautiful flowers and several leaf forms and growth patterns. Many halophytic trees, shrubs and tall herbs can provide beauty to front gardens. These include among others *A. tripolium*, *Limoniastrum monopetalum*, *Batis maritima*, *Tamarix nilotica*, *Tamarix amnicola*, *Cistanche fistulosum*, *A. halimus*, *S. portulacastrum*, *Noronhia emarginata* [29].

Carbon Sequestration

Accumulation of carbon dioxide (CO_2) in the atmosphere is a major environmental concern of modern times as evidenced by the increase in atmospheric CO_2 and subsequent global warming. According to a recent report [38], the net global carbon flux during the period 1850–2000 was 156×10^9 tons, about 63% of which was from the tropics, the greatest (48×10^9) from tropical Asia and least (3×10^9) from North Africa and Middle East. This trend can partly be reversed through the removal of CO_2 from the atmosphere and sequestration into long-lived pools of carbon in soil and plant, e.g. wood, leaf litter, root debris, etc.

The capacity of various halophytic species to produce considerable biomass including wood has long been established. It has been estimated that about 130 million ha of highly saline lands around the world may immediately be available to grow suitable halophytes with a capacity to assimilate 0.6–1.2 giga tons of C per year. Evidence from decomposition experiments suggests that 30–50% of this C might enter long term storage in soil [39]. N-fixing trees generally lead to increased accumulation of soil C, e.g. *Prosopis* and *Acacia* spp. are adapted to saline lands and may increase soil C by 2 tons/ha [40]. In North West India, *P. juliflora* grown on salt-affected lands has been reported to increase soil organic carbon pool from 10 to 45 tons/ha in an eight years period and *Prosopis cineraria* has similarly improved soil fertility, as well as sequestered extra C [41]. The potential of grasses in this regard should also not be under estimated as about 70 tons/ha C, comparable with values for forest soils, may be sequestered under grasslands [42] and a 12% increase in soil C could be obtained under *Panicum virgatum* on degraded lands in ten years [43].

Other Uses

Parts of the seeds of *Calotropis procera* are filled in pillows; many *Acacia* produce gums and the stem and leaves of *Juncus maritimus*, *K. scoparia*, *Aristida adscenscoinis*, *Imperata cylindrica*, *Phragmites australis* and *Typha domingensis* have been used since ancient times for the manufacture of mats, baskets thatching and cordage. *Pyrus betulaefolia* and *Malus sieversii* rootstocks are used for propagating pears and apples, respectively, and rootstock of *A. glabra* is used for producing high-quality *Annona* clones [29]. *Suaeda esteroa*, *S. bigelovii*, *Atriplex barclayana* have been successfully grown using saline wastewater discharged from aquaculture projects [44]. This also opens the possibility of utilizing urban and industrial wastes similarly.

Successes and Pitfalls

With the current pace of land deterioration due to spread of salinity and associated problems, a stage is fast approaching where conventional agriculture may not remain an economically feasible proposition in many parts of the world. This is particularly relevant to arid and semi arid regions where salt-affected soils are in abundance, drought is looming on the horizon and near famine conditions are spreading, for instance in some African countries. These adverse conditions impact badly the agricultural activities resulting in reduced crop yields. Many other countries, as a consequence, experience a shortage of agricultural commodities periodically and have to spend many millions from their valuable foreign exchange reserves to import food items, wheat for instance, from abroad. Putting this scenario in perspective, crop diversification through halophyte utilization to suit particular soil conditions seems inevitable.

Halophytes, because of their hardy nature, offer a natural alternative, but they may not easily find a place on our dining table, mainly due to hesitation on the part of consumers to change their eating preferences and because conventional agriculture has so far managed to meet the demand. Circumstances and exigencies may, however, force this change as observed in many communities and discussed in the foregoing. The success stories are few and far in between and the prominent ones include commercial exploitation of halophytic grass e.g., *P. vaginatum* and *S. virginicus* for landscaping and turf development [37], use of *Atriplex* spp. and some other shrubs as animal fodder [29], although the high oxalate content of *Atriplex* spp. poses serious health problems. Aggressive marketing of *S. bigelovii* by Arizonians [45, 46] has opened an avenue of introducing halophytes as cash-crops, but the commercial utilization of *S. bigelovii* as a source of edible oil remains questionable as the oil has yet to reach the market shelf. The process of taking a laboratory achievement to rigour of field conditions and making it a profitable venture is long, painstaking, tedious and difficult. It seems most failures may have come at this level. Biologists around the world are independently trying to develop cash-crop halophytes, but concerted efforts are needed to bring all of them together and devise a mechanism to foster links between them so that suitable species may be commercialized with coordinated international efforts.

Conclusions

There is no denying the fact that salt-affected lands and brackish water are precious resources available to mankind for beneficial exploitation. The knowledge of some of the mechanisms that the plants adopt to cope with salinity and the methods to deal with salt buildup in rhizosphere to minimize harmful effects on plants are available. Additional information on potential use of halophytes is accumulating and needs careful scrutiny to pick suitable species for particular purposes. Their should be no problem in saline culture of halophytes after establishing the need but great care has to be exercised to restrict such planting to areas where soils are already saline and the only water available for irrigation is brackish. In these ventures, it is advisable to choose crops and agronomic practice(s), which allow the minimum buildup of salts.

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Author Queries:

AQ1: Define CAM.
AQ2: Define GM.
AQ3: Please verify references [3, 5].
AQ4: Please provide year of publication for [38].