Innovations in Utilization of Poor-Quality Water for Sustainable Agricultural Production

R.K. Yadav and J.C. Dagar

Abstract

To meet the requirements of food and other agricultural commodities for the burgeoning population is a big challenge for the agricultural community. With the increasing demand for good-quality land and water for urbanization and development projects, agriculture will be pushed more and more to the marginal lands, and the use of poor-quality waters for irrigation is inevitable. Groundwater aquifers in the most of arid and semiarid regions are saline, and therefore cultivation of conventional arable crops with saline irrigation has not been considered sustainable in these regions. However, concerted research efforts have shown that the degraded lands can be put to remunerative alternative uses (through agroforestry) including salt-tolerant forest and fruit trees, crops, forage grasses, medicinal and aromatic and other high-value crops, and adopting appropriate planting (e.g., subsurface planting) and other management techniques (furrow irrigation). Such uses have additional environmental benefits including carbon sequestration and biological reclamation. Agroforestry is not only a necessity for increasing tree cover and hence decreasing pressure on natural forests but also a most desired land use especially for reclaiming and rehabilitating the degraded lands, especially in arid and semiarid rainfed areas underlain with saline groundwater as source of irrigation. In developing countries like India, there seems to be little scope for bringing the fertile lands under forest cover. It may be emphasized that we can bring unproductive wastelands and waterlogged areas under forest cover and take agroforestry tree plantation on non-forest community and farmlands utilizing poor-quality water including drainage and wastewaters. The long-term studies conducted show that salt-affected and waterlogged areas and saline water (including seawater) can be utilized satisfactorily in raising forest and fruit tree species with

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improved techniques, forage grasses, conventional and nonconventional crops, oil-yielding crops, aromatic and medicinal plants of high economic value, petro crops, and flower-yielding plants.

Out of 356 km^3 $years^{-1}$ of total wastewater generated across all the continents, only 50 % is treated to primary level. In developing countries of the Middle East and North Africa (MENA), Latin America, and Asia, only 8 %, 18 %, and 32 %, respectively, of total wastewater generated is treated. Overall, about 20 million hectares of agricultural land is irrigated with treated and untreated wastewater throughout the world. Such practice has resulted in the potential health risks due to pathogen, salt, nutrient, and toxic element contamination of the food chain and environment. Controlled irrigation of wastewater, in plantations based on water, nutrient, and pollutant (metals) assimilation capacity, can help in productive utilization and safer disposal of wastewater. Several tree species have the potential to accumulate appreciable concentrations of Cd, Cu, Ni, and Zn in their root tissues when irrigated with wastewater or grown on metal-contaminated soils. In woody species, additional wood and bark formed every year are important sinks for biologically available metals. Since these tissues are slow to enter the decomposition cycle, accumulated metals remain immobilized for a considerable longer period. Urban plantations and green areas with nonedible crops like cut flowers and aromatic grasses in combination with constructed wetlands also offer many economic, social, recreational, and biodiversity conservation benefits over its use in agriculture and disposal in water bodies. Opportunities for raising nonconventional but remunerative crops and alternate land uses through use of saline underground and wastewaters are discussed in this chapter.

Introduction

With 97 % of the total global water being brackish, the remaining only 3 % is fresh in nature. While the world's oceans are unbounded, the freshwater available to mankind is virtually the most finite. Of this 3 % freshwater, 69.0, 0.3, 0.7, and 30 % is found as glaciers and snow; in lakes and rivers; as soil moisture and biological water; and as groundwater, respectively (Shiklomanov 1993). To meet the food and other requirements for the ever-increasing population, irrigation, "the most important sector," uses >70 % of the global freshwater withdrawals and 90 % of the total consumptive uses (Siebert et al. 2010). At the global level, out of the total irrigated area of ~310 million ha (Mha), 117 Mha (38 %) is irrigated with groundwater (FAO 2012). Poor-quality water includes saline groundwater, saline drainage effluents, sewage, and other types of wastewater for irrigation. Groundwater surveys indicate that the extent of poor-quality water use ranges between 25 % and 84 % of the total groundwater development in different states in India (Minhas 1998). In some states of India, area underlain by saline groundwater is very high (26 % in Haryana and 41 % in Rajasthan). Many more areas with good-quality aquifers are endangered with contamination as a consequence of excessive withdrawals of groundwater.

Further, the twentieth century witnessed very rapid urbanization and industrialization at a global scale. Urban population increased from 13 to 34 % during 1900–1960 and further to

54 % by the year 2014. Fast-emerging urban, industrial, and other nonagricultural sectors consume only <15–20 % of the total water supplies with the remaining 80–85 % returning as deteriorated-quality wastewater (Yadav et al. 2003; Minhas and Samra 2004). Increasing supply of water to meet the expanding demand of nonagricultural sectors consequently results in generation of increasing volumes of wastewater commensurate to the rapidly increasing population, urbanization, improved living conditions, and economic development (Lazarova and Bahri 2005; Asano et al. 2007). In the most of developing countries, urban drainage and disposal systems are common, so urban wastewater consists of effluents from residential, institutional, commercial, and industrial establishments and urban runoff water arising from rains or storms. Estimates by Raschid-Sally and Jayakody (2008) suggest that about 20 million hectares of agricultural land throughout the world is irrigated with treated and untreated wastewater. The use of wastewater for irrigation has been found effective in the establishment of trees, for shade, amenity, urban greening, and shelterbelts along roads in Iran, the Near East, and the United States (Armitage 1985), for woodlots in India and Egypt (El-Lakany 1995), and for urban greening, landscape, and environmental protection in the United States, Australia, Kuwait, and India (Armitage 1985; Minhas et al. 2015). Similarly, controlled irrigation of wastewater in a mixed stand plantation of oaks (*Quercus* spp.), red pine (*Pinus resinosa*), and white spruce (*Picea glauca*) has been found to effectively filter out nitrogen (~150 kg N ha^{-1}), phosphorus (12 kg P ha^{-1}), and other constituents per year in Australia (CSIRO 1995). However, wastewater also contains a variety of contaminants. Long-term uncontrolled direct use of untreated wastewater or polluted water from rivers and streams for irrigation poses potential risks of pathogen (Minhas et al. 2006) and toxic chemical contamination of crops (Yadav et al. 2003), soil (Violante et al. 2010) and groundwater pollution (Lal et al. 2008; Drechsel and Evans 2010), and ultimately the food chain through sewage-soil-crop-animal-human system (Qadir et al. 2010; Yadav et al. 2015). Though, after appropriate treatment, wastewater can be productively used in all purposes for which freshwater is used, viz., irrigation of crops and aquaculture, landscape, urban and industrial uses, recreational and environmental uses, and artificial groundwater recharge, irrigation in urban and peri-urban agriculture is the most prevalent practice. Wastewater provides an assured source of irrigation and supplements nutrients to crops (Ullah et al. 2011; Ghosh et al. 2012) and is thereby considered as a reliable and inexpensive alternative for wastewater treatment and disposal (Feigin et al. 1991). Several tree species have potential to accumulate appreciable concentrations of Cd, Cu, Ni, and Zn in their root tissues. Additional wood and bark formed every year in woody species, the important sinks for biologically available metals with slower decomposition cycle, immobilize accumulated metals for a considerable longer period. However, to ensure optimal plantation growth and environmental protection, loading rates of wastewater and its constituents should match the water and nutrient requirements of proposed plantations. Controlled use of wastewater for irrigation in plantations based on their water, nutrient, and pollutant (metals) assimilation capacity could be a productive alternative for safer disposal of wastewater. Urban plantations and green areas with nonedible crops like cut flowers and aromatic grasses in combination with constructed wetlands also offer many economic, social, recreational, and biodiversity conservation benefits over its use in agriculture and disposal in water bodies.

Efficient use of poor-quality water is imperative to sustain agricultural development for meeting the increasing demands of food, forage, fuel wood, timber, and other necessities for the ever-increasing population and protection of the environment under limited availability of good-quality water. Therefore, an attempt has been made in this chapter to compile information on poor-quality water (saline groundwater, saline drainage effluents, sewage, and other types of wastewater) availability, efficient use, and management for irrigation and environmental protection.

Saline Groundwater Occurrence and Use for Crop Production

Beneath many of the world's deserts are reserves of saline water. The reserves of saline groundwater are found to occur in the Thar Desert of the Indian subcontinent, the Arabian Desert of the Middle East, the Sahara Desert in North Africa, the Kalahari Desert in Southern Africa, the Atacama Desert in South America, the California deserts in North America, and in the West Australian deserts. The information for saline water use on the global prospective is reported from at least 43 countries, which are using saline water for irrigation in one or other forms. These countries are virtually from the semiarid and arid regions, except some developed nations, which make use of the wastewater for irrigation. Rhoades and his associates explored the use of saline water in irrigation (Rhoades et al. 1992). With increasing demands of food, forage, fuel wood, timber, and other necessities for the ever-increasing population and the limited availability of good-quality water, the saline water irrigation is now considered as an imperative necessity for the sustainable agricultural development, which includes the use of saline groundwater, saline drainage water, and sewage wastewater for irrigation. Groundwater surveys in India indicate that poor-quality water being utilized in different states is 25–84 % of the total groundwater development – more in arid and semiarid regions. It is 84 % in Rajasthan, 62 % in Haryana, 47 % in Uttar Pradesh, 38 % in Karnataka, 30 % in Gujarat, 32 % in Andhra Pradesh, and 25 % in Madhya Pradesh (Minhas 1998). Many more areas with good-quality aquifers are endangered with contamination as a consequence of excessive withdrawals of groundwater.

FAO (2012) published the standard water-quality criteria for saline irrigation. Ragab (1998) critically examined the possibilities and constraints in the use of brackish water for irrigation and also the merits of sprinkler and drip irrigation for saline water use, while Kandiah (1998) derived strategies to minimize adverse environmental impacts of saline water use in agriculture. Rhoades et al. (1992) in their FAO paper on "Saline Water for Irrigation" classified saline waters (Table 1) in terms of salt concentration, which is the major quality factor generally limiting the use of saline water for crop production.

For assessing quality of irrigation water, main parameters determined are salt content (EC, $\mathrm{dS\ m^{-1}}$), sodium adsorption ratio ($\mathrm{SAR} = \mathrm{Na^{+}}/\sqrt{[(\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})]}$, $\mathrm{mmol l^{-1}}$), residual alkalinity [$\mathrm{RSC} = (\mathrm{CO_3^{2-}} + \mathrm{HCO_3^{-}}) - (\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})\ \mathrm{meql^{-1}}$], divalent cation ratio ($\mathrm{DCR} = \sum \mathrm{M^{2+}}/\sum \mathrm{M^{n+}}$), and presence of specific ions such as $\mathrm{NO_3}$, F, B, and Se. Based on the characteristic features of the majority of groundwater in use by the farmers in different agroecological regions and the above indices, irrigation water has been broadly grouped (Minhas and Gupta 1992) into good water (ECiw <2 and SAR <10), saline water (ECiw >2 and SAR <10), high SAR saline water (ECiw >4 and SAR >10), and alkali water (ECiw variable, SAR variable, and RSC >2.5).

The adaptability of irrigation with saline water is decided by crop salt tolerance limit, nature of soil particularly its leaching characteristics, quality of saline water, intensity of rainfall, availability of freshwater, methods of

Table 1 Classification of saline water

Water class	EC ($\mathrm{dS\ m^{-1}}$)	Salt concentration ($\mathrm{mg\ l^{-1}}$)	Type of water
Nonsaline	<0.7	<500	Drinking and irrigation
Slightly saline	0.7–2	500–1500	Irrigation
Moderately saline	2–10	1500–7000	Primary drainage water and groundwater
Highly saline	10–25	7000–15,000	Secondary drainage water and groundwater
Very highly saline	25–45	15,000–35,000	Very saline groundwater
Brine	>45	>35,000	Seawater

Source: Rhoades et al. (1992)

application of irrigation water, climate of the area, soil-water-crop environment and human resource management, and the saline water irrigation economics (Tanwar 2003). Various aspects of the problems related to the use of poor-quality waters have been researched for long in different soil and agroclimatic conditions in India as well as other countries, and results of these studies have been compiled (Minhas and Gupta 1992; Manchanda 1998; Minhas 1996, 1998; Tyagi and Minhas 1998; Bajwa et al. 1998; Minhas et al. 1998; Tanwar 2003). Rhoades et al. (1992) and Minhas and Gupta (1992) created the standard water quality criteria for saline water irrigation. Ragab (1998) critically examined the possibilities and constraints in the use of brackish water for irrigation and merits of sprinkler and drip irrigations for the saline water use. Kandiah (1998) derived strategies to minimize adverse environmental impacts of the saline water use in agriculture. The guidelines recommended for productive use of saline irrigation water are given in Table 2.

The saline water irrigation program also includes the irrigation with the drainage effluent water and the wastewater, which have been alternatively developed in many countries (Minhas et al. 2015). Boyko (1966) was among the pioneers to draw attention to the possibility of crop production using seawater for irrigation. Mass (1985, 1990) produced the exhaustive research data for the limits of salt tolerance in field crops, grasses, and fruit crops. Based on this work, Tanwar (2003) compiled the consolidated information on salt tolerance and yield potential of selected crops as influenced by irrigation water salinity, while in India, very useful information was generated on salinity limits of irrigation water for different arable crops through the All India Coordinated Research Project in the Central Soil Salinity Research Institute (2000–2009) particularly for arid and semiarid regions (Table 3). These crops may also be cultivated in agroforestry systems using saline irrigation. In recent years, however, several researchers have promoted the use of halophytes and demonstrated their economic potential to produce a large and diverse number of traditional and new products using saline water including drainage and wastewaters, seawater for irrigation, and marginal land resources. The use of saline or seawater to irrigate various food, feed, fiber, fodder, and industrial crops has been reported by several researchers (Aronson 1989; NAS 1990; Lieth and Al Masoom 1993; Jaradat 2003; Dagar 2003, 2014; Dagar and Singh 2007; Dagar et al. 2013; Meena et al. 2014) to obtain economic yields of grains, oilseeds, vegetables, fodder, fuel and fibers, fruits, pharmaceuticals, and other products. Some of these crops can also be successfully cultivated as constituents of agroforestry systems.

Table 2 Guidelines for saline irrigation waters (RSC <2.5 me l^{-1}) in India

Soil texture (% clay)	Crop tolerance	Upper limits of ECiw (dS m^{-1}) in rainfall (mm) region		
		<350 mm	350–550 mm	550–750 mm
Fine soil (>30 %)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine soil (20–30 %)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse soil (10–20 %)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse soil (<10 %)	Sensitive	–	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

Source: Minhas and Gupta (1992)

Table 3 Salinity limits of irrigation waters for arable crops in India

Crop	Location	Soils	Years	Previous crop	ECiw (dS m^{-1}) for relative (%) yield		
					100	90	75
Wheat	Agra	Sl	6	Pearl millet	6.6	10.4	16.8
	Agra	Sl	2	Toria	4.3	6.6	11.0
	Dharwar	Scl	5	Sorghum	3.4	7.0	12.9
	Hisar	Sl	5	Sorghum/fallow	6.1	8.7	13.0
	Indore	Cl	8	Maize	4.7	8.7	15.2
	Jobner	Ls	4	Fallow	8.3	11.7	17.5
	Karnal	S	5	Fallow	14.0	16.1	19.5
Barley	Agra	Sl	2	Fallow	7.2	11.1	18.0
Rice	Bapatla	Scl	6	*Kharif* rice	2.2	3.9	6.8
	Bapatla	Scl	3	*Rabi* rice	1.8	2.9	4.8
Maize	Dharwar	Scl	5	Sorghum	3.7	7.8	14.5
	Indore	Cl	7	Wheat	2.2	4.7	8.8
Pearl millet	Agra	Sl	4	Wheat	5.4	9.0	15.0
Italian millet	Bapatla	S	5	Sunflower	2.4	4.6	8.2
	Bapatla	S	4	Italian millet	2.5	4.9	8.7
Sorghum	Agra	Sl	3	Mustard	7.0	11.2	18.1
	Dharwar	Scl	6	Wheat	2.6	5.1	9.1
Mustard	Agra	Sc	6	Sorghum	6.6	8.8	12.3
	Bapatla	Scl	5	Soybean	3.8	7.9	14.7
	Jobner	Ls	2	Cluster bean	6.6	13.5	–
Sunflower	Dharwar	Scl	5	Maize	3.3	6.8	12.6
	Bapatla	Sl	3	Mustard	3.5	7.2	13.4
Groundnut	Bapatla	S	5	Italian millet	1.8	3.1	5.3
Soybean	Bapatla	Scl	3	Mustard	2.0	3.1	5.0
Pigeon pea	Agra	Sl	6	Onion	1.3	2.3	3.9
Cluster bean	Bapatla	Sl	3	Variable	3.2	4.5	6.8
	Jobner	Ls	2	Mustard	3.9	6.6	11.1
Berseem	Agra	Sl	5	Rice/sorghum	2.5	3.2	4.4
Onion	Agra	Sl	5	Pigeon pea	1.8	2.3	3.3
	Bapatla	S	5	Variable	5.1	6.0	7.5
Potato	Agra	Sl	5	Okra	2.1	4.3	7.8
Tomato	Bapatla	S	3	Variable	2.4	4.1	6.9
Okra	Agra	Sl	5	Potato	2.7	5.6	10.5
	Bapatla	S	3	Variable	2.1	3.9	6.7
Brinjal	Bapatla	S	2	Variable	2.3	4.1	7.1
Fenugreek	Jobner	Ls	3	Pearl millet	3.1	4.8	7.6
Chillies	Bapatla	S	2	Variable	1.8	2.9	4.9
	Jobner	Ls	3	Variable	4.5	7.5	12.5
Coriander	Bapatla	S	3	Variable	2.9	5.8	10.7
Bitter gourd	Bapatla	S	3	Variable	2.0	3.4	5.8
Bottle gourd	Bapatla	S	3	Variable	3.2	4.5	6.8

Source: AICRP CSSRI (2000–2009). For scientific names, please see Subject Index

In dry regions, due to lack of good-quality water for irrigation, the most of the lands remain barren. Rehabilitation of these barren dry lands is limited to two possibilities: (i) exploiting plants native to arid environments and (ii) devising efficient cropping systems and techniques for using limited saline groundwater resources judiciously. In the past, efforts toward utilization of saline water were mainly aimed at enhancing the production of annual arable crops, and the notion of irrigated forestry or fruit trees, growing forages, and other non-conventional high-value crops has been considered to be less attractive leading to poor economic production. Efforts have proved that we can successfully grow salt-tolerant forest and fruit trees, forages, and other high-value crops utilizing the saline groundwater for economic use of abandoned arid lands (Tomar et al. 2003a, b, 2010; Dagar et al. 2008, 2012, 2013, 2015; Dagar 2014). Some of these results obtained under different agricultural systems are discussed in this paper.

Afforestation/Agroforestry with Saline Irrigation

The traditional approach for sustaining the use of saline water is to irrigate the arable crops more frequently and provide adequate leaching requirements. Nevertheless, such practices demand the application of additional quantities of saline water and thereby also result in enhancement of salt loads in soils. Frequent irrigation is usually advocated for shallow-rooted crops in arid environments mainly because the added salts get pushed below the rooting zone. Optimizing saline water irrigation requirement of a particular crop is a very important aspect of saline agriculture. But in deep-rooted tree plantations, the additional salts going into the soil through enhanced frequency of irrigation during their establishment, which may rather aggravate the problem as salts are likely to persist within their expanding rooting zones and subsequently hinder the growth of trees. Therefore, irrigation with saline water should aim to create favorable niches for the better establishment of saplings and also eliminate the excessive salinity buildup. This could be achieved by using subsurface planting and furrow irrigation technique irrigating only the limited area under furrows planted with tree saplings. The success of the system was attributed to both the reduced salt load and their significant leaching by concentration of rainwater through runoff into these furrows. Along with suitable irrigation management of saline water, growing of viable and salt-tolerant crops of high economic value such as fruit trees and medicinal, oil-yielding, and petro-crops is of immense importance. These crops must not only be tolerant to salinity and drought stresses but also be well adapted to the local agro-climate. Therefore, afforestation or agroforestry involving trees, shrubs, grasses, and low-water-requiring crops (when using saline water for irrigation) is considered an ideal land use for utilization of degraded lands using saline water (Tomar et al. 2003a, b, 2010; Dagar et al. 2008, 2013, 2015; Dagar 2014). Even the common-property lands can be brought under farm forestry. Besides providing fuel, fodder, and timber, afforestation will also lead to bio-amelioration of salty lands. Afforestation of these lands will not only help in ecological and environmental considerations but also be useful in relieving pressure on traditionally cultivated lands and forests.

Planting Techniques

In a traditional approach of sustaining saline water irrigation, more frequent irrigation is applied to meet the leaching requirements. However, such practice demands additional quantities of saline water use and thereby results in increased salt loads in soils. Such approaches have been advocated for shallow-rooted crop plants in arid environments mainly because the added salts could be pushed beyond the rooting zone. But in deep-rooted tree plantations, the additional salts going into the soil through enhanced frequency of irrigation during their establishment may rather aggravate the problem as these are likely to persist within their expanding rooting zones and may subsequently hinder the growth of trees. Therefore, irrigation with saline water should aim to create favorable niches for the better establishment of saplings and also eliminate the excess buildup of salinity. This could be achieved by irrigating only the limited area under furrows planted with tree saplings both of forest and fruit trees. In this technique, furrows (15–20 cm deep and 50–60 cm wide) are created at 3–5 m intervals with a tractor-drawn furrow maker. Auger holes (0.2 m diameter and 1.2 m deep) are dug at the sill of these furrows spaced at 2–3 m intervals. These are refilled with the mixture of original soil plus 8 kg of farmyard manure, 30 g superphosphate, 15 g zinc sulfate, and 15 g of iron sulfate. Six-month-old tree saplings are transplanted during the rainy season (July–August) at dug auger-hole sites, and saline water irrigations are given in only furrows. The technique is known as subsurface planting and furrow irrigation system (SPFIM). In the case of forest trees, the irrigation may be provided for the initial 3 years (four to six times in a year), and, thereafter, plantations may be irrigated once during the winter only. Salt storage in soil profile may increase during the irrigation period, but the added salts get distributed in soil profile as a consequence of seasonal concentration of rainfall during monsoons and some episodic events of rainfall during the following years. The interspaces can successfully be utilized for growing low-irrigation-requiring crops such as barley (*Hordeum vulgare*), taramira (*Eruca sativa*), cluster bean (*Cyamopsis tetragonoloba*), pearl millet (*Pennisetum typhoides*), sesame (*Sesamum indicum*), and seed spices like dill (*Anethum graveolens*), fennel (*Foeniculum vulgare*), etc. during initial years. Medicinal isabgol (*Plantago ovata*) was found doing well under partial shade. The soil is enriched with organic carbon (>0.4 % in upper 30 cm) under the promising tree species. Thus, rehabilitation of arid soils with the promising tree species using the available saline waters would not only render the abandoned soils to be productive but also ensure conservation and improvement in the environment for long-range ecological security on these lands.

Afforestation and Agroforestry Practices with Saline Irrigation

Many workers in India (Tomar et al. 1998, 2003a, b; Dagar 2003, 2014; Dagar and Singh 2007; Dagar et al. 2015) reported important salt-tolerant plants used for fuel wood and forages, which can be cultivated successfully through irrigation with saline water (ECiw 8–12 dS m^{-1}). *Acacia nilotica*, *A. tortilis*, *A. modesta*, *A. farnesiana*, *Azadirachta indica*, *Cordia rothii*, *Prosopis juliflora*, *P. cineraria*, *Tamarix articulata*, *Cassia* spp., and *Ziziphus* spp. among trees and *Brachiaria mutica*, *Cynodon dactylon*, *Echinochloa colonum*, *Leptochloa fusca*, *Panicum antidotale*, *P. laevifolium*, *P. maximum*, *Pennisetum purpureum*, *P. polystachion*, *Sporobolus helvolus*, *S. marginatus*, *Cenchrus ciliaris*, *C. setigerus*, *Dactyloctenium aegyptium*, *D. scindicum*, etc. among grasses along with other forages form viable silvopastoral agroforestry systems in various regions.

Tomar and Yadav (1980) observed that the seed germination of species like *Acacia nilotica*, *A. tortilis*, *Albizia lebbeck*, and *Prosopis juliflora* was not affected when irrigated with water of EC_{iw} 4 dS m^{-1}. The detrimental effects of sodicity (SAR_{iw}) increased with salinity, whereas RSC was not that detrimental. In general, water of EC_{iw} 8–10 dS m^{-1} and SAR up to 30 did not influence the growth of *P. juliflora* and *A. tortilis*; those of EC_{iw} 4–6 dS m^{-1} and SAR up to 15 were for *A. nilotica*, *Parkinsonia aculeata*, *A. lebbeck*, and *Pongamia pinnata*. Tomar et al. (1996) also observed that nursery of *Acacia* spp. could be raised without any effect on its growth with saline water of EC_{iw} 4 dS m^{-1}. They further observed that initial survival and growth of *A. nilotica* and *P. juliflora*, when planted in saline waterlogged soils in furrows, could be ensured with moderate saline water irrigation (EC_{iw} 12–29 dS m^{-1}) with some reduction in biomass. In an experiment to evaluate the irrigation requirements using subsurface planting and furrow irrigation technique, Minhas et al. (1996) observed that irrigation quantities equaling 10 % of the open pan evaporation, though saline, sufficed for the optimal growth of *A. nilotica* and *Dalbergia sissoo* on a highly calcareous soil with little subsoil water storage.

A large number of salt-tolerant species, besides those mentioned above, can be used as agroforestry crops with saline irrigation;

however, these exhibit large differences in salt tolerance based on a number of factors, including life cycle, frost tolerance, soil type, and climatic factors. For example, grains and oilseed crops as the eelgrass (*Zostera marina*) and Palmer salt grass (*Distichlis palmeri*), rich in starch and protein, grow well in saline conditions of the Gulf of California; pearl millet (*Pennisetum typhoides*) grows well with saline (EC_{iw} 27–37 dS m^{-1}) water irrigation on sandy soil (NAS 1990); annual quinoa (*Chenopodium quinoa*) with protein rich nutritious seeds used as a staple food by South Americans and perennial seashore mallow (*Kosteletzkya virginica*) can produce 2.5 and 1.5 Mg ha^{-1} grains, respectively with irrigation using water containing 2.5 % salt (Jaradat 2003). Likewise, tubers and foliage crops such as *Eleocharis dulcis, Sesuvium portulacastrum, Beta vulgaris* and *B. maritima*; fruit-yielding trees like *Ziziphus mauritiana, Achras zapota, Carissa carandas, Manilkara hexandra, Phoenix dactylifera, Emblica officinalis, Psidium guajava*, and *Aegle marmelos*; sources of liquid fuels as *Beta vulgaris* and *Nypa fruticans*; many gum/oil/resin-yielding species of *Acacia, Sesbania*, and *Grindelia*; a source of sperm whale oil as *Simmondsia chinensis*; source of natural rubber as *Parthenium argentatum*; and bioactive derivative-yielding plants like *Calophyllum inophyllum, Balanites roxburghii, Azadirachta indica* and *Catharanthus roseus* are some important crops already adopted under saline irrigation in many parts of the world (NAS 1990; Jaradat 2003; Dagar 2003, 2014). Kefu et al. (1995) reported utilization of halophytes in China as sources of starch and protein (species of *Zostera*, *Chenopodium*, *Atriplex*), oil (*Salicornia*, *Suaeda*), food and therapeutic value (*Limonium bicolor*), fiber (*Apocynum venetum*), medicine (*Ephedra sinica*, *Lycium barbarum*, *Kochia scoparia*, *Xanthium sibiricum*, *Glycyrrhiza uralensis*, *Artemisia stelleriana*), essential oil (*Aster*, *Artemisia*), and valuable fodder for domestic animals (*Agropyron sibiricum*, *A. mongolicum*, *Pennisetum alopecuroides*, *Spartina anglica*, *Nitraria sihirwa*, *Elaeagnus angustifolia*, *E. umbellata*), which are cultivated in agroforestry systems in saline environments.

During the past few decades, a number of well-designed species evaluation trials were established on saline waterlogged soils (Tomar et al. 1994, 1998; Tomar and Minhas 1998; Jeet Ram et al. 2010), and species of trees such as *Eucalyptus*, *Prosopis*, *Tamarix*, *Salvadora*, *Casuarina*, etc. have been recommended for their salt tolerance. However, it appears that in addition to salt tolerance, tolerance to aridity (water stress) also affects the performance under arid situations where mostly saline groundwater exists. Typical examples are of *Casuarina equisetifolia*, *Pongamia pinnata*, and *Terminalia arjuna* that could not come up under these experimental conditions, though otherwise known for their salt tolerance under waterlogged saline soils. Ahmad et al. (1985) reported that plants of *Melia azedarach* showed more rapid growth than *Azadirachta indica* when irrigated with saline water (ECiw 4.5–14.0 dS m^{-1}), while Chaturvedi (1984, 1985) observed that plants of *Prosopis juliflora*, *Acacia nilotica*, *Terminalia arjuna*, *Syzygium cumini*, *Albizia lebbeck*, *Pongamia pinnata*, *Cassia articulata*, *Adhatoda vasica*, and *Cassia siamea* performed well when irrigated with water of salinity ranging from EC 4.0 to 6.1 dS m^{-1}. Jain et al. (1983, 1985) noticed that *P. juliflora* and *T. articulata* tolerated irrigation water salinity of 8 dS m^{-1}, whereas *Eucalyptus hybrid* and *Leucaena leucocephala* are only moderately tolerant to saline (~6 dS m^{-1}) water irrigation. Dagar et al. (2004, 2005, 2006, 2012) reported successful performance of *Salvadora persica*, *Catharanthus roseus*, *Cordia rothii*, *Euphorbia antisyphilitica*, and *Adhatoda vasica* when irrigated with water of high salinity (up to EC 12 dS m^{-1}). It may be pointed here that even the saline groundwater resources in arid areas are too limited to sustain long-term irrigation requirement of tree plantations. Moreover, salt input into soils has to be the minimum to ensure a better growth of trees. Thus, the strategies have to be only to establish plantations with saline irrigation and let these subsequently thrive under natural agro-climatic conditions. Earlier also, it has been reported that furrow planting method (Minhas et al. 1996, 1997; Tomar et al. 1998, 2003b; Dagar et al. 2008, 2014) helped in harvesting most of rainwater in furrows as a result of runoff from the inter-row area and infiltrated through this zone only, thereby pushing the salts beyond the rooting zone of transplanted tree saplings. This implied the need for long-term evaluation trials for evaluating tree species for their suitability to site conditions.

Long-Term Saline Irrigation: Some Case Studies

Case Study 1: Afforestation of Calcareous Soils

For sustaining viable wood production enterprise under saline irrigation situations, tree species should be not only tolerant to salinity and drought but also well adapted to the local agroclimate. Though sufficient information, from pot and short-term field studies, exits about the tolerance of tree species to salinity (Tomar and Yadav 1985; Yadav 1991; Gupta et al. 1995; Tomar and Minhas 1998), however, due to lack of longer period field trials over a range of climate, cultural practices, soil types, and soil conditions (e.g., calcareousness goes along with aridity), it is very difficult to draw conclusions about the performance of individual tree species in the field.

It may be also pointed out here that besides salt tolerance as the selection criteria for specific sites, the socioeconomic and ameliorative roles of trees have to be accorded due consideration in afforestation programs. Thus, a longtime field experiment was conducted on a highly calcareous soil (*Typic Haplustalf*) at Bir Reserved Forest, Hisar, India (29°10′ N and 75° 44′ E with altitude of 220 m above MSL). The climate at the site is semiarid monsoon type with an average annual rainfall of about 498.6 ± 165.3 mm (average from 1991 to 2011), the most (70–80 %) of which occurs during July–September. The average annual open pan evaporation during the study period was 1887.7 ± 242.7 mm. The low ratio of precipitation to open pan evaporation at ~0.26 and high interannual rainfall variability suggest that the area is almost arid with complete dry land conditions. The annual maximum and minimum daily temperature during the study period was 31.32 ± 0.77 °C and 16.14 ± 0.81 °C, respectively.

Six-month-old saplings of three dozens of tree species were transplanted in the refilled auger-hole pits at 2.5 × 2.0 m spacing (2000 trees ha^{-1}) during the rainy season and irrigated with tube well water having an electrical conductivity (EC_{iw}) of ~10 dS m^{-1}. Irrigation was applied only in the furrows for the initial 3 years, and, thereafter, for the next 5 years, a single irrigation was applied every year during winter to protect the plants from frost injury. To optimize maximum biomass and getting regular firewood, close-planted trees were pruned at initial stage (at 2 years of growth), and then harvested alternate trees and rows (at 5 and 8 years of growth, respectively). Sufficient biomass (9–73 Mg ha^{-1}) was obtained, which could be utilized as firewood. Remaining trees were harvested for timber and firewood after 16–20 years. Fodder trees (namely, species of *Acacia*, *Azadirachta*, *Cordia*, *Prosopis*, *Salvadora*, *Feronia*, and *Ziziphus*) were lopped successfully for fodder which is always scarce in dry regions. Planting trees on these degraded lands of arid areas would be helpful in augmenting fodder, food, timber, and fuel wood and improving ecological sustainability through enhanced carbon sequestration in both wood and soil.

After 8 years of planting, to give more space to trees, one fourth of the trees were harvested, and the highest biomass was obtained from *Tamarix articulata* (73.5 Mg ha^{-1}) followed by *Acacia nilotica* (22.4 Mg ha^{-1}), *Prosopis juliflora* (20.2 Mg ha^{-1}), and *Eucalyptus tereticornis* (14.8 Mg ha^{-1}). Trend in the total biomass after 20 years of growth in remaining trees was almost similar with *Tamarix articulata*, *Acacia nilotica*, *A. tortilis*, *Eucalyptus tereticornis*, *Prosopis juliflora*, and *Azadirachta indica* outyielding the other species (Fig. 1).

Litterfall from the most of tree species resulted in an improvement in organic carbon

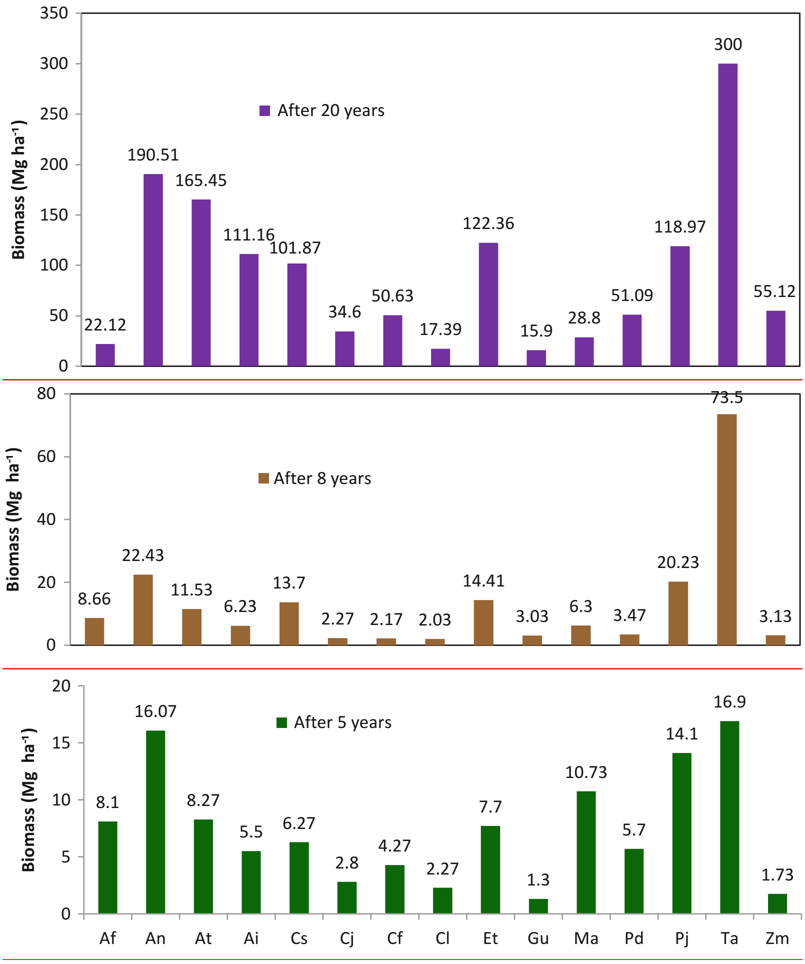

Fig. 1 Biomass of trees harvested after 5, 8, and 20 years of growth. Depictions: *Af Acacia farnesiana*, *An Acacia nilotica*, *At A. tortilis*, *Ai Azadirachta indica*, *Cs Cassia siamea*, *Cj C. javanica*, *Cf C. fistula*, *Cl Callistemon lanceolatus*, *Et Eucalyptus tereticornis*, *Gu Guazuma ulmifolia*, *Ma Melia azedarach*, *Pd Pithecellobium dulce*, *Pj Prosopis juliflora*, *Ta Tamarix articulata*, *Zm Ziziphus mauritiana* (Source: Based on Dagar et al. unpublished)

content of the underlying soils gradually. *Acacia nilotica*, *A. tortilis*, *Azadirachta indica*, *Eucalyptus tereticornis*, *Feronia limonia*, *Tamarix articulata*, and *Guazuma ulmifolia* species increased organic carbon content (>0.5 %) considerably as compared to other species (Fig. 2). The effects of such species were vividly more in the upper 0–30 cm layer as compared to the lower layers. It is evident from the results that firewood species such as *Acacia farnesiana* and multipurpose species such as *Moringa oleifera* may get required results in 8–10 years, but species like *Tamarix articulata*, *Acacia nilotica*, *Azadirachta indica*, and fruit tree *Ziziphus mauritiana* go on adding biomass regularly and require long-term growth as has been proved in present investigation as well.

Case Study 2: Agroforestry with Fruit Trees

At the same site (as described in case study 1), 6–9-month-old saplings of fruit trees (grown in poly bags through grafting) of karonda (*Carissa carandas*), Indian gooseberry (*Emblica*

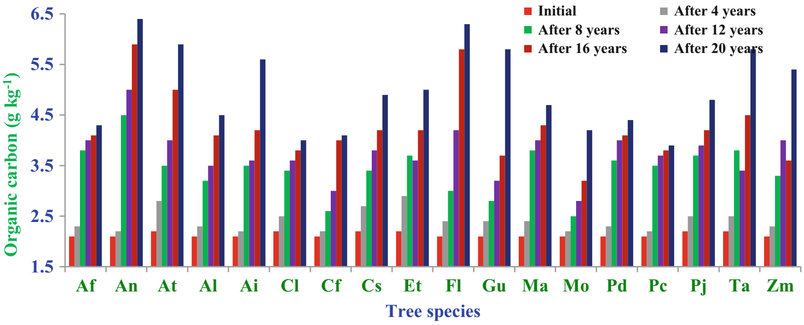

Fig. 2 Development of organic carbon in soil under different tree species at different intervals of time. Depictions: *Af Acacia farnesiana*, *An Acacia nilotica*, *At A. tortilis*, *Al Albizia lebbeck*, *Ai Azadirachta indica*, *Cl Callistemon lanceolatus*, *Cf C. fistula*, *Cs Cassia siamea*, *Et Eucalyptus tereticornis*, *Fl Feronia limonia*, *Gu Guazuma ulmifolia*, *Ma Melia azedarach*, *Pd Pithecellobium dulce*, *Pj Prosopis juliflora*, *Ta Tamarix articulata*, *Zm Ziziphus mauritiana* (Source: Based on Dagar et al. unpublished)

officinalis), and bael (*Aegle marmelos*) were transplanted in the refilled auger holes at the site during July 2002. The saplings were basin irrigated with low-salinity water (EC_{iw} ~4–6 dS m^{-1}, SAR 18), alternately irrigated with water of low and high salinity (EC_{iw} 8.5–10.0 dS m^{-1}, SAR 21), and irrigated with water of high salinity. In total, there were ten treatment combinations consisting of three fruit tree species irrigated with three levels of saline water irrigation and one control treatment of low-salinity water-irrigated arable crops without trees. Karonda was planted at row-to-row distance of 5 m and plant-to-plant 2 m, whereas Indian gooseberry and bael were planted at a distance of 5 m × 4 m. Only arable crops were grown in inter-spaces between tree species and the control treatment of low-salinity water without trees.

Pearl millet (*Pennisetum typhoides* cv. HHB 68) was cultivated in the interspaces between rows of trees during the *kharif* (rainy) season during the first year of establishment, i.e., 2002, followed by adoption of barley (*Hordeum vulgare* cv. BH 375)-cluster bean (*Cyamopsis tetragonoloba* cv. HG 365) cropping sequence during the years 2003–2007 and mustard (*Brassica juncea* cv. CS 54)-cluster bean crop rotations during the years 2008–2011. Though during the first year the performance of the pearl millet crop was very good, it had to be replaced with cluster bean during the next year because of the problem of birds' damage (being surrounded by forest trees). In general, *kharif* season crops were sown after the onset of monsoon without pre-sowing irrigation except in the years when the onset of monsoon was unduly delayed. However, before sowing of *rabi* (winter) season and *kharif* crops in delayed monsoon years, a pre-sowing irrigation of about 6 cm was given using the water of respective treatments. Before sowing of *rabi* crops, about 10 Mg ha^{-1} of farmyard manure was applied each year. All the crops were cultivated following the recommended package of agronomic practices for the respective crops.

Performance of Fruit Trees

Under all water quality irrigation treatments, *karonda* and *bael* recorded complete (100 %) and 90–98 % survival, respectively, at 3 years. However, the low survival of 80, 86, and 90 % was recorded in gooseberry under irrigation with high-, alternate-, and low-salinity water, respectively. Gooseberry was damaged severely due to frost during winter of 2006, and despite of regeneration, it could not bear fruits; however, *karonda* produced about 0.95 Mg ha^{-1} of fruits with slight reduction in high-salinity water, and *bael* also started bearing fruits and produced 2.32, 1.85, and 0.96 Mg ha^{-1} of fruits when irrigated with water of low, alternately of low and high, and of high salinity, respectively (Table 4).

Table 4 Yield of fruits (Mg ha^{-1}) when fruit trees are grown along with intercrops

Fruit trees	Saline water	2005[a]	2006[a]	2007	2008	2009	2010	2011
Carissa carandas	Low	0.93	1.10	1.38	1.54	1.68	1.72	1.59
	Low/high	0.84	0.92	1.13	1.42	1.46	1.54	1.62
	High	0.80	0.83	1.00	1.25	1.34	1.42	1.48
	Mean	0.86	0.95	1.17	1.39	1.49	1.56	1.56
Emblica officinalis	Low	–	–	0.24	0.42	0.52	0.58	0.52
	Low/high	–	–	0.19	0.31	0.38	0.46	0.49
	High	–	–	0.14	0.22	0.26	0.32	0.43
	Mean	–		0.19	0.32	0.39	0.45	0.48
Aegle marmelos	Low	–	2.32	3.28	4.50	3.98	4.06	3.81
	Low/high	–	1.85	2.24	3.60	3.36	3.85	3.58
	High	–	0.96	1.48	1.68	2.08	3.08	3.17
	Mean	–	1.71	2.33	3.26	3.14	3.66	3.52

[a] Frost years (Source: Dagar et al. 2015)

Performance of Intercrops

Pearl millet cultivated in inter-spaces between the rows of fruit trees during the *kharif* season in the first year of establishment of fruit trees produced grain yield of 2.34, 2.20, and 1.96 Mg ha^{-1} when irrigated with low-, alternate low- and high-, and high-salinity water, respectively. No significant difference in yield was noticed with different fruit trees, and no reduction was noticed in straw yield with application of any of the saline water treatments. As pointed out earlier, due to bird problem, this crop was replaced with cluster bean during the *kharif* season of following consecutive years. In the *rabi* season of 2003, there was very good yield of barley with mean grain and straw yield of 2.46 Mg ha^{-1} and 2.95 Mg ha^{-1}, respectively, with no significant difference in yield among treatments of saline water irrigation showing the tolerance of barley crop to high-salinity water. The yield of cluster bean in subsequent years (from 2003–2006 to 2009–2011) decreased when cultivated with water of high salinity or when irrigated alternately with water of low and high salinity (Table 5). Other fruit trees which find place with saline water irrigation include *Feronia limonia*, *Ziziphus mauritiana*, *Psidium guajava*, and *Phoenix dactylifera*. These have been found quite successfully grown in sandy soil irrigating with water up to EC_{iw} 10 dS m^{-1}.

Soil Salinity Development

When the soil data were compared critically for its salinity, it was found that during summer after the harvest of *rabi* crops, there was development of salinity in upper 0–1.2 m soil depth because of application of saline irrigation both in fruit trees and crops, more so when irrigated with water of higher salinity. As there was almost normal rainfall during all the years (>450 mm) except in 2004 and 2006, when it was below normal (321 mm and 340 mm, respectively), during the rainy season, the salt leached down in the profile. During these 2 years, the salinity in soil profile was higher than other years (Fig. 3). As such, there was not much development of salinity due to saline irrigation showing the sustainability of saline irrigation in this region. There was direct negative correlation between rainfall and salinity development in soil profile due to saline irrigation (Fig. 4).

Performance of Grasses in a Silvopastoral System

In one experiment on sandy loam soils, Tomar et al. (2003a) observed that forage grasses like *Panicum laevifolium* and *P. maximum* were the most suitable species under high-salinity water irrigation and produced annually 14–17 Mg ha^{-1} of dry forage (Fig. 5) showing their potential as silvopastoral grasses if grown in protected conditions.

Table 5 Yield (Mg ha^{-1}) of inter-crops grown with fruit trees

Fruit trees	Treatment	Average of 5 years (2003–2007)		Average of 4 years (2008–2011)	
		Barley	Cluster bean[a]	Mustard	Cluster bean[b]
	Control	3.55 ± 0.31 (3.82 ± 0.23)	1.41 ± 0.27 (2.22 ± 0.36)	1.58 ± 0.14 (3.16 ± 0.29)	0.96 ± 0.15 (1.55 ± 0.19)
Cc	Low	3.43 ± 0.34 (3.75 ± 0.29)	1.36 ± 0.27 (2.10 ± 0.32)	1.41 ± 0.09 (2.88 ± 0.16)	0.77 ± 0.02 (1.35 ± 0.06)
	Low/high	3.32 ± 0.33 (3.63 ± 0.18)	1.28 ± 0.28 (1.93 ± 0.30)	1.33 ± 0.07 (2.76 ± 0.13)	0.71 ± 0.02 (1.30 ± 0.04)
	High	2.99 ± 0.25 (3.26 ± 0.15)	1.21 ± 0.28 (1.90 ± 0.35)	1.18 ± 0.08 (2.61 ± 0.10)	0.69 ± 0.02 (1.26 ± 0.02)
Eo	Low	3.56 ± 0.34 (3.89 ± 0.25)	1.38 ± 0.29 (2.27 ± 0.42)	1.73 ± 0.08 (3.61 ± 0.17)	0.83 ± 0.08 (1.43 ± 0.13)
	Low/high	3.29 ± 0.28 (3.42 ± 0.26)	1.27 ± 0.26 (2.09 ± 0.35)	1.66 ± 0.07 (3.48 ± 0.12)	0.78 ± 0.07 (1.39 ± 0.13)
	High	3.04 ± 0.22 (3.16 ± 0.22)	1.16 ± 0.26 (1.87 ± 0.30)	1.58 ± 0.06 (3.36 ± 0.10)	0.73 ± 0.06 (1.33 ± 0.11)
Am	Low	3.27 ± 0.31 (3.50 ± 0.22)	1.30 ± 0.29 (2.14 ± 0.38)	1.26 ± 0.07 (2.68 ± 0.12)	0.78 ± 0.13 (1.41 ± 0.22)
	Low/high	3.08 ± 0.30 (3.30 ± 0.24)	1.25 ± 0.27 (1.99 ± 0.33)	1.21 ± 0.08 (2.55 ± 0.15)	0.72 ± 0.12 (1.34 ± 0.21)
	High	2.78 ± 0.24 (2.99 ± 0.19)	1.14 ± 0.25 (1.79 ± 0.28)	1.11 ± 0.07 (2.33 ± 0.08)	0.66 ± 0.14 (1.26 ± 0.24)

Cc Carissa carandas, *Eo Emblica officinalis*, *Am Aegle marmelos*, *Control* inter-crop raised with low saline water without plantations [Source: Dagar et al. (2015)]

[a] Average of 4 years

[b] Average of 3 years. Deviation from mean (±) is between the mean yields of the years

Values in paranthesis are of straw yield

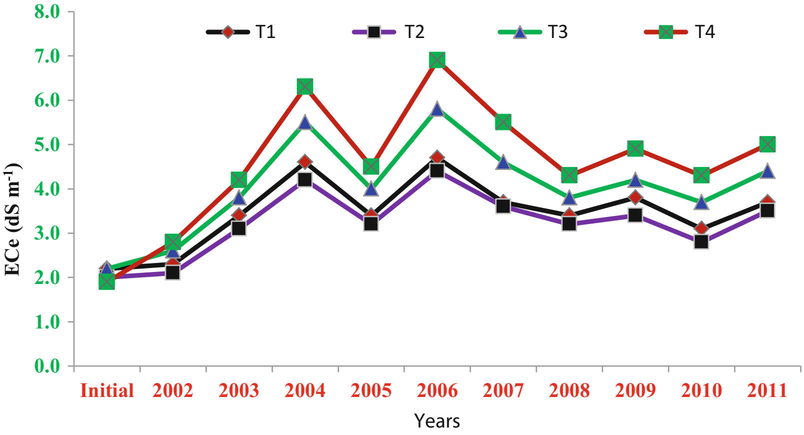

Fig. 3 Soil salinity (ECe dS m^{-1}) developed in soil profile (1.2 m) during different years when irrigated with water of different salinities. Depictions: T_1- when crops were irrigated with water of low salinity without any tree; T_2- when fruit trees and crops were irrigated with water of low salinity; T_3- when fruit trees and crops were irrigated alternately with water of low and high salinity; T_4- when fruit trees and crops were irrigated with water of high salinity

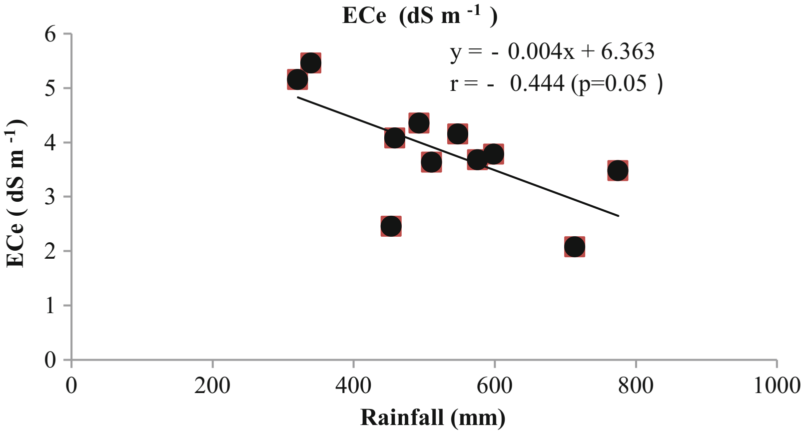

Fig. 4 Relationship between soil salinity (ECe dS m^{-1}) and corresponding annual rainfall (mm) during different years. Values in equation depict y = ECe of soil profile (dS m^{-1}), x = annual rainfall (mm) at the site

About 25–30 % of total forage was also available during the lean period of summer when most of the people become nomadic along with their cattle. The water use efficiency was also highest in these two species. These grasses along with native *Cenchrus setigerus* and *S. ciliaris* can successfully be grown with trees like *Acacia nilotica*, *A. tortilis*, *A. ampliceps*, *A. farnesiana*, *A. modesta*, *Azadirachta indica*, *Feronia limonia*, *Prosopis juliflora*, *P. cineraria*, *Tamarix articulata*, *Cordia rothii*, *Salvadora persica*, and *Cassia siamea*, and one irrigation with saline water which is always available during summer can produce reasonably good biomass for livestock in dry regions (Dagar et al. 2008). In dry regions, preference may be given to forage trees so that those may contribute toward forage requirements of the people.

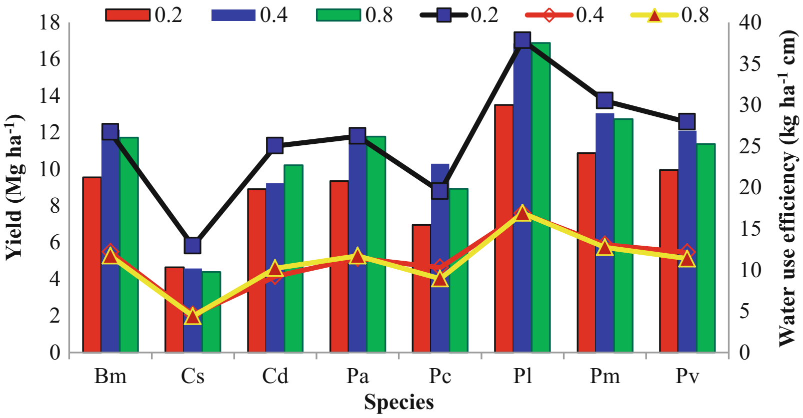

Fig. 5 Dry biomass yield and water use efficiency of different grasses when irrigated with different Diw/CPE ratios of saline water. Depictions: *Bm Brachiaria mutica*, *Cs Cenchrus setigerus*, *Cd Cynodon dactylon*, *Pa Panicum antidotale*, *Pc P. coloratum*, *Pl P. laevifolium*, *Pm P. maximum*, and *Pv P. virgatum* (Source: Tomar et al. (2003a))

Performance of Non-conventional Crops

In a series of experiments conducted at the same site, the performance of several low-water-requiring nonconventional salt-tolerant crops such as castor (*Ricinus communis*), taramira (*Eruca sativa*), dill (*Anethum graveolens*), medicinal and aromatic plants, petro crops, and winter annual flowers provided a viable alternative to effectively utilize the degraded calcareous lands using saline water (ECiw 8–10 dS m^{-1}) for irrigation. Tomar and Minhas (2002, 2004a, b), Dagar (2003, 2009, 2012, 2014), Tomar et al. (2005, 2010), Singh and Dagar (2009), and Dagar et al. (2005, 2006, 2008, 2009, 2013) in a series of experiments evaluated the performance of aromatic and medicinal plants and winter annual flowers under saline irrigation in isolation as well as in partial shade of trees. Among the species tested for medicinal value, the most promising was psyllium (*Plantago ovata*) with an average seed yield of 1050 kg ha^{-1}, and it did not show any adverse impact when compared with canal water irrigation. When different frequencies of irrigation were compared using water of low salinity (ECiw 4.0 dS m^{-1}), high salinity (EC 8.6 dS m^{-1}), and low and high salinity alternately, the average un-husked seed yield was found to be 1102, 885, and 1159 kg ha^{-1}, respectively, showing significant advantage when the crop was irrigated alternately with water of low and high salinity. There was an increase in yield with increase of frequency of irrigation. Among eight varieties, the best performance was shown by variety JI-4 followed by Sel-10, Niharika, HI-5, GI-2, GI-1, local, and HI-34, in descending order (Tomar et al. 2005, 2010). Psyllium did not show any yield reduction with *Acacia nilotica* trees even at later stages showing its suitability for partial shade tolerance. Likewise, lemongrass (*Cymbopogon flexuosus*) was also found as a promising crop with saline irrigation (Dagar et al. 2013). The average fresh foliage yield was found to be 12.0–13.0, 6.7–8.3, and 9.1–9.8 Mg ha^{-1}, respectively, when irrigated with water of low salinity (ECiw 4.0 dS m^{-1}), high salinity (ECiw 8.6 dS m^{-1}), and alternately (Table 6).

There was an increase in yield with increase in irrigation schedule (Diw/CPE ratio). Furrow planting was a superior planting technique than other methods including flat planting. The comparative yield in furrow, flat, and top of bund was 9.1, 5.7, and 3.1 Mg ha^{-1}, respectively. Among the cultivars tested, RRL-16 and OD-58 showed better performance followed by Praman and Krishna (Dagar et al. 2013). The overall results indicated the possibilities of raising lemongrass on degraded calcareous soil using saline water up

Table 6 Impact of different irrigation schedules on fresh yield[a] (Mg ha^{-1}) of lemongrass when irrigated with water of different salinities during 2006–2007 and 2007–2008 (yield average of 2 years)

	Irrigation schedule (Diw/CPE ratio)			
Salinity of irrigation (Iw/CPE)	0.2	0.4	0.6	0.8
Low	10.9	12.0	13.0	14.3
Low/high	7.7	8.6	10.0	11.5
High	4.3	7.1	8.5	10.1
LSD ($p = 0.05$)				
Between water of different salinity: 2.4				
Between different frequencies of irrigation: 0.98				
Interaction (salinity × frequency): NS				

[a]Total of four cuttings each year. Source: Dagar et al. (2013)

to EC 8.6 dS m^{-1} without buildup of soil salinity if normal rainfall occurs once in 3–4 years. There was no impact on quality of oil due to salinity. Aromatic grasses such as vetiver (*Vetiveria zizanioides*), lemongrass, and palmarosa (*Cymbopogon martinii*), when irrigated with saline water (EC 8.5 dS m^{-1}), produced on an average 90.9, 10.4, and 24.3 Mg ha^{-1} of dry biomass, respectively (Tomar and Minhas 2004a). Different cultivars of vetiver could produce 72.6–78.7 Mg ha^{-1} of shoot biomass and 1.1–1.7 Mg ha^{-1} of root biomass. The roots are used to extract aromatic oil.

Medicinal crop *Aloe barbadensis* was also equally tolerant and produced 18 Mg ha^{-1} fresh leaves under partial shade. *Ocimum sanctum* produced 910 kg ha^{-1} dry shoot biomass. In a separate trial, dill (*Anethum graveolens*), taramira (*Eruca sativa*), and castor (*Ricinus communis*) could produce 931, 965, and 3535 kg seeds per ha, respectively, when provided with three irrigations of saline water of EC 10 dS m^{-1} (Dagar et al. 2008). The average seed yield of castor var. DCS-Jyoti-2 was found to be 2.68, 3.46, and 2.74 Mg ha^{-1} when irrigated with water of high (EC_{iw} 10 dS m^{-1}), low (EC_{iw} 5 dS m^{-1}), and alternately low and high salinity, respectively. There was an increase in yield with increase of frequency of irrigations. Increased application of nitrogen and phosphorus alone or in combination also increased the yield. Among the cultivars, DCS-Jyoti-2 showed better performance as compared to HISAR CH-1 and the local perennial variety. These results suggest that castor can successfully be cultivated in dry regions utilizing the saline water for irrigation.

Cassia senna and *Lepidium sativum* could also be successfully cultivated using saline water up to 10 dS m^{-1} for irrigations. Even spice fennel (*Foeniculum vulgare*) produced average seed yield with high-salinity water use (1.56 ± 0.02 Mg ha^{-1}) showing its suitability for saline irrigation. Average seed yield of fennel under inorganic and organic input treatments ranged from 1.4 to 1.7 Mg ha^{-1} (Meena et al. 2014). Ornamental flowers such as *Chrysanthemum*, *Calendula*, and *Matricaria* produced 13.2, 4.7, and 3.5 Mg ha^{-1}, respectively, of fresh flower yields when cultivated irrigating with water of EC up to 5 dS m^{-1} (Tomar and Minhas 2002). Irrigation with good-quality water for establishment followed by consequent saline irrigation increased the yield of flowers significantly. All these high-value crops could successfully be grown as inter-crops with forest and fruit trees at least during the initial years of establishment (Dagar 2009; Dagar et al. 2006, 2008, 2009, 2013).

Among petro crops, *Jatropha curcas* though established well could not tolerate frost. *Euphorbia antisyphilitica*, a succulent laticiferous shrub, commonly known as candelilla and wax plant, was found to be a potential hydrocarbon-yielding petro-crop. It yields 8–10 % of total biomass as biofuel. It can be grown successfully on most degraded sandy and calcareous soils in arid and semiarid regions. It produced about 23 Mg ha^{-1} of dry biomass in 2 years with saline irrigation and proved to be a low-nutrient-requiring crop (16 and 40 kg ha^{-1} of P and N). It is also low-water requiring and produced 17.5 Mg ha^{-1} and 15.25 Mg ha^{-1} of dry biomass with saline water (12 dS m^{-1} irrigation at Diw/CPE ratio of 0.1 and

0.2, respectively) as compared to 10.9 Mg ha^{-1} under rainfed condition (Dagar 2012). Some medicinal crops including edible cactus (*Opuntia ficus-indica*) have been evaluated and found suitable under saline environment and irrigating with saline water (Gajender et al. 2014).

Agroforestry for Saline Vertisols with Saline Irrigation

The salty vertisols are generally either contemporary or of secondary origin. The contemporary salty soils exist in the topographic situation having poor drainage conditions. However, the soils that have become sodic due to injudicious use of irrigation water can be encountered in the irrigation command areas. In a long-term experiment, *Prosopis juliflora*, *Salvadora persica*, and *Azadirachta indica* were found as the most successful tree species after 14 years of plantation on these soils as compared to other tree species. However, among grasses, *Aeluropus lagopoides*, *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana*, *Dichanthium annulatum*, *Bothriochloa pertusa*, and species of *Eragrostis*, *Sporobolus*, and *Panicum* were most successful.

Aromatic grasses such as *Vetiveria zizanoides* and *Cymbopogon martinii* can also be grown easily. *Matricaria chamomile* can withstand both high pH and ESP. In a separate fruit tree trial on vertisols with ESP 25, 40, and 60 %, it was found that gooseberry (*Emblica officinalis*) and ber (*Ziziphus mauritiana*) are the most successful plantations. Oil-yielding bush *Salvadora persica* in combination with forage grasses such as *Leptochloa fusca*, *Eragrostis* spp., and *Dichanthium annulatum* produced satisfactory forage yield in addition to oil on clay loam waterlogged (0.5–2.0 m water table) saline (with pH ranging from 7.2 to 8.9 and ECe from 25 to 70 dS m^{-1}) vertisols in Gujarat. These grasses could produce on an average 3.72, 1.0, and 1.8 Mg ha^{-1} of forage, respectively. During the fourth year, the seed yield of *Salvadora persica* ranged from 1.84 to 2.65 Mg ha^{-1} with oil contents ranging from 576 to 868 kg ha^{-1} at different salinity levels (Gururaja Rao et al. 2003). The experiments conducted in sodic vertisols with ESP 40 growing grasses like *Leptochloa fusca*, *Brachiaria mutica*, and *Vetiveria zizanioides* showed that all these grasses performed well and the forage biomass increased during the second year. Besides producing biomass, the silvopastoral system helped in amelioration of soil in terms of reducing soil pH, EC, and ESP and increasing organic matter.

Opportunities

With increasing competition for good-quality lands and water resources, agriculture will be pushed more and more into marginal environments. Water will be a major constraint, and with more and more use of poor-quality water (PQW), the area under salinity and waterlogging will increase. Moreover, in the scenario of climate change, the problem of salinity is expected to aggravate due to sea level rise when many coastal areas may go under seawater. Hence, it is a well known fact that in the future, agriculture in semi-arid and arid regions will increasingly depend on use of poor-quality groundwater, while brackish water aquaculture will be more prominent in coastal regions experiencing seawater intrusion. There is, therefore, an urgent need to have comprehensive understanding and better contingency plans based on resource-efficient, socioeconomically viable, and environmentally safe technologies to deal with salt-degraded soils and to improve productivity of such marginal lands using saline water for irrigation.

Looking ahead at the existing and new challenges in the coming decades and to develop a comprehensive strategy in order to fulfill our goals of sustaining the agricultural productivity, we need to prepare a perspective research plan for 2050 addressing all the issues in an interdisciplinary approach. Our research attention needs to concentrate in the following thrust areas:

- Management of waterlogged saline soils in different canal commands through engineering and biological approaches of subsurface and bio-drainage and their integration

- Management of poor-quality water, including domestic, drainage, and agro-industrial effluents
- Resource inventories on waterlogged, salt-affected soils and poor-quality waters for land use planning
- Bioremediation through integrated approach to tackle salinity problems of serious nature including soil and water pollution
- Crop improvement for salinity, alkalinity, and waterlogging stresses
- Alternate land uses of salt-affected soils and waterlogged areas utilizing the poor-quality waters
- Reclamation and management of coastal saline soils using seawater judiciously

The opportunities for salinity research due to the size and diversity of problems are enormous, where all types of salt-affected soils and water of varying qualities are encountered and require specific solutions. The following areas show that biosaline agriculture is an opportunity in disguise:

- The vast extent of salt-affected soils, which are yet to be reclaimed, and areas undergoing secondary salinization represent an opportunity for us to demonstrate our technology and bring benefits to the global community. There are opportunities to exploit renewable resources of amendments via the biological route including microbial approach for reclamation of salty soils and utilization of poor-quality water.
- Large areas undergoing secondary salinization provide an opportunity to test the scope of strategies like irrigation system improvement interventions and other preventive strategies to check the spread of salinity and waterlogging.
- Increasing industrialization due to economic liberalization will lead to increasing environmental problems and have adverse effects on soils and water quality, requiring us to develop newer technologies.
- Enormous biodiversity of plant resource, liberalization in government policy for exchange of germplasm, and newer tools like remote sensing, biotechnology, etc. create additional research opportunities.
- A common fund needs to be developed for skill development of scientific talent, particularly among institutes already working in salinity-related problems. Our research experiences and ability to replicate our successes in other situations in different parts of the world will give us an edge to proceed ahead and wherever possible we may utilize consultancy opportunities for reclamation and remediation work in different countries.
- Different funding organizations may come forward for reclamation of salt-affected lands and waterlogged areas on a large scale for implementation programs.
- Modern technologies (such as nanotechnologies) related to salt land reclamation and use of poor-quality waters will provide unique opportunities for alleviation of poverty, particularly among small and marginal farmers.
- An important trend observed during recent years is crop diversification especially regarding preference of horticultural crops, and domestication of halophytic new crops has gradually gained pace along with industrial and infrastructural development. This has provided opportunity to work with these crops in the marginal lands.
- Salty soils with high groundwater table offer challenges to increase the water productivity through integrated approaches of rearing fish, dairy animals, and agricultural and horticultural crops through a multi-enterprise approach.
- Identification of biofuel and energy plantations and aromatic and medicinal high-value crops for common lands, wastelands, etc. and developing their agronomic practices offer a unique opportunity to contribute to the energy resources.

Wastewater Generation, Treatment, and Use

Published and online wastewater reports suggest that out of 181 countries, only 55 have estimates on its generation, treatment, and use. Statistics on wastewater generation, treatment, and use is available for only 113, 103, and 62 countries, respectively; and even this available information is not up to date. As such, approximately 356 km ^{3} years^{-1} of wastewater is generated across all the continents; but of this, only 50 % is treated to primary level. However, the disparity among contents becomes alarming when continent-wise data are analyzed as only 8 %, 18 %, and 32 % of total wastewater generated is treated in developing MENA countries, Latin America, and Asia, respectively, in comparison to 73 % and 67 % in America and Europe, respectively. Because investments in treatment facilities have not kept pace with persistent increases in urban population and the wastewater volumes generated, so on an average, wastewater treatment is limited to <27 % in the most of developing countries of Latin America, the Middle East and North Africa, and Asia (Sato et al. 2013).

In India; only 31 and 22 %, respectively of the total sewage (38,254 million liters per day- MLD) and industrial wastewater (83,000 MLD) generated are treated. Treating such huge volumes of wastewater up to the desirable levels using conventional sewage treatment processes is not economically feasible (Kumar 2003), and the situation is pretty similar or worse in almost all developing countries. As far as wastewater use in agriculture is concerned, it ranges from a low of only <3 % in America and Europe to as high as 11 and 16 % of total generated in developing nations of Asia and the MENA region. Overall estimates of Jimenez and Asano (2008) suggest that the wastewater-irrigated area in the world is ~4.5 million ha; but as per Raschid-Sally and Jayakody (2008), >200 million farmers use treated and untreated wastewater to irrigate crops on 20 million ha. Though there are large variations in estimates on use of wastewater for irrigation, it is certain that wastewater accounts for about 1.5–6.6 % of the total global irrigated area of 301 million ha (Drechsel and Evans 2010) and is likely to increase further with rapid increase in urbanization, particularly in water-scarce areas. Following the modified FAO regional classification of countries in developing regional estimates of water use (FAO 2012), the extent of wastewater generation, treatment, and use at the regional and country scale is summarized in Table 7. This situation is likely to continue in all the resource-starved developing countries where urbanization and industrialization is outpacing the development of technical solutions that can ensure the safe distribution and management of wastewater. Therefore, we need to develop the better technical methods and policy guidelines for handling untreated wastewater on farms and recommendations for its use in plantation-based agroforestry for protecting farmworkers and consumers from the potentially harmful pathogens and chemicals.

Wastewater Typology

Sources of generation and availability of wastewater determine its typology. It may be classified into municipal wastewater, domestic wastewater (i.e., spent water from communities after a variety of uses in domestic houses, commercial buildings, and institutions), and industrial wastewater from manufacturing plants of a variety of commodities including thermal power plants. The primary parameters of importance for irrigation (Ayers and Westcot 1985) are total salt concentration or total dissolved solids, electrical conductivity, hydrogen ion activity (pH), SAR, toxic ions (boron, chloride, and sodium), trace elements, and heavy metals. However, the major concern with wastewater use for irrigation in agriculture arises due to more than the safe limits of pathogenic and organic and inorganic contaminants.

Problems Associated with Use in Agriculture

Wastewater contains various pathogenic organisms, i.e., bacteria (fecal streptococci, clostridium), viruses (enteroviruses, rotaviruses), helminthes, parasites, salmonella, and intestinal nematodes. These pathogens cause various diseases such as diarrhea, cholera, viral infections, and other ailments in human beings and animals. In addition to these pathogens, wastewater also contains more than the safe limits of organic and inorganic contaminants. Generally, organic chemicals like aldrin, benzene, chlordane, chloroform, DDT, hexachlorobenzene, lindane, and

Table 7 Wastewater generated, treated, and used in different regions where the information is available

Regions	Countries and numbers	Wastewater volume (km^3 years^{-1}) Generated	Treated	Used
North America	Canada and the United States **(2)**	84.97	61.12	2.35
Latin America	Antigua and Barbuda, Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rice, Cuba, the Dominican Republic, Ecuador, El Salvador, Guatemala, Mexico, Nicaragua, Panama, Paraguay, Peru, and Venezuela **(19)**	29.75	5.47	0.55
Europe	Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Kosovo, Luxemburg, Malta, Monaco, Montenegro, the Netherlands, Poland, Portugal, Republic of Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom **(31)**	52.44	34.86	1.38
Russia and the former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan **(15)**	27.48	20.16	0.99
Middle East and North Africa (MENA)	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Syria, Tunisia, Turkey, the United Arab Emirates, and Yemen **(20)**	22.64	1.90	3.69
Sub-Saharan Africa	Botswana, Burkina Faso, Djibouti, Eritrea, Ethiopia, Ghana, Lesotho, Mauritania, Mauritius, Namibia, Senegal, Seychelles, South Africa, Swaziland, and Uganda **(15)**	3.71	3.29-	0.06
Oceania	Australia and New Zealand **(2)**	2.09	2.33	0.35
Asia	Bangladesh, Bhutan, Cambodia, China, India, Japan, Laos, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, the Philippines, Republic of Korea, Singapore, Sri Lanka, Thailand, Vietnam **(19)**	133.12	42.17	14.403
Total	123	356.23	181.29	23.77

Source: based on compilations from various sources by Sato et al. (2013)

tetrachloroethylene and inorganic constituents cadmium, chromium, nickel, arsenic, cyanide, fluoride, lead, mercury, nitrate, and selenium are the major contaminants in wastewater (Table 8). Though these organic and inorganic constituents are present in low concentrations, their ingestion over prolonged periods also causes detrimental effects on human and animal health. The WHO included limit values in health guidelines for organic and toxic substances.

Food Safety and Health Concerns

In the most of developing countries, 80–90 % of wastewater is discharged with little or no treatment in natural water bodies (rivers, lakes, ponds, wetlands). It makes them highly polluted for sustainability of aquatic life and causes >2.0 million human deaths annually from diarrhea (Qadir et al. 2007). Farmers in urban and peri-urban areas use untreated wastewaters for irrigation. Many studies have shown a range of food safety and health risks stemming from vegetable or fruit crops irrigated with untreated wastewaters (Qadir et al. 2010). Waterborne diseases, such as diarrhea, originated from untreated wastewater and have affected children in several parts of the world (Opryszko and Majeed 2010). There are many studies which have shown the adverse effect of wastewater irrigation not only on farmers' exposure and risk of intestinal nematode infections but also on actual and possible links between the

Table 8 Potential contaminants in wastewater and hazards associated with its use in agriculture

Contaminants	Parameters	Hazards/concerns
Pathogens	Bacteria (*E. Coli*, fecal coliforms, *Salmonella*, *Shigella*, *Vibrio cholera*, *Clostridium*, *Bacillus*), viruses (polio, hepatitis, Coxsackie, rota), helminths (*Ascaris*, *Trichuris*, *Ancylostoma*, *Schistosoma*), protozoa (*Entamoeba*, *Giardia*), nematodes, and parasites	Communicable diseases such as diarrhea, cholera, typhoid, food poisoning, salmonellosis, dysentery, gastroenteritis, polio, hepatitis, Coxsackie infection, ascariasis, trichuriasis, ancylostomiasis, schistosomiasis, amoebiasis, giardiasis, etc.
Biodegradable and stable organics	Biological oxygen demand (BOD), chemical oxygen demand (COD), phenols, pesticides, chlorinated hydrocarbons	Depletion of oxygen demand, development of septic conditions, hindrances in aquatic ecosystem, hazards to habitats, persistent toxicity in environment, hazards for irrigation, etc.
Suspended solids	Volatile compounds, suspended and colloidal impurities	Anaerobic conditions with deposition of sludge, clogging of sprinklers and drippers
Heavy metals	Cd, Cr, Ni, Pb, Zn, As, Hg, etc.	Accumulation in soils, crops, and aquatic organisms, ingestion by humans and animals, contamination of the food chain and environment

consumption of crops irrigated with untreated wastewater and the risk of hookworm and *Ascaris* infections or the increased risk of enteric disease (Trang et al. 2005; Qadir et al. 2010). Besides pathogens, chemical contaminants can be of concern especially in those countries where industrial effluents enter domestic wastewater and natural streams. Heavy metals get on accumulating in the human body through the food chain (fish, vegetables, fruits, nonvegetarian food, etc.) to the extent of non-tolerable limit causing untimely mortality.

Metal Accumulations

Wastewater use in agriculture has both opportunities and problems. Opportunities include cheap disposal option, reliable source of irrigation, conservation, and supplementing supply of water and nutrients for agriculture (Hoeks et al. 2002; Yadav et al. 2006; Lopez et al. 2006; Qadir et al. 2007). However, adoption of more disposal-oriented and unscientific irrigation practices simultaneously poses health risks to farmers and consumers. The potential problems associated with wastewater use in agriculture are transmission of diseases from excreta-related pathogens, vectors, and skin irritants (Minhas et al. 2006; Keraita et al. 2007); and the pollution of the environment through accumulation of salts (Yadav et al. 2003), toxic chemicals like heavy metals (Rattan et al. 2005; Yadav et al. 2015), and pesticides in soils, surface water bodies, and groundwater (Minhas and Lal 2010; Murtaza et al. 2010).

Irrigation of crops using raw or partially treated sewage and industrial effluents has been cited as the main reason for accumulation of heavy metals (HMs) in the vegetables because >40–60 % of the HMs remain in wastewater even after primary-level treatment. Uses of such effluents have been found to enhance the availability of metals in agricultural soils by 2–130 times (Pescod 1992; Nan et al. 2002; Minhas and Samra 2004; Mapanda et al. 2007; Yadav et al. 2006) and ultimately lead to significant contribution toward contamination of the food chain through their accumulations in vegetables and other food crops grown on such soils. Though maximum accumulations of metals, depending on species of metals and crops, seem to occur in roots followed by stalks and leaves (McBride 2003; Gupta et al. 2008), Pb, Zn, Cd, Cr, and Ni contents in vegetables were found beyond the safe limits in wastewater-irrigated sites at Titagarh, West Bengal (India).

Mapanda et al. (2007) recorded Cd, Cr, Ni, Pb, Cu, and Zn concentration of 0.7–2.4, 1.5–6.6, 2.5–6.3, 0.7–5.4, 1.0–3.4, and 18–201 mg kg^{-1}

Table 9 Contents of heavy metals in different wastewater-irrigated crops

Metals/plant	$\mu g\ g^{-1}$ dry weight of crop					
	Cd	Cr	Ni	Pb	Zn	Cu
Mitra and Gupta (1999)						
Lettuce	13.4	61	52	35	171	25
Mint	10.4	68	54	22	139	26
Cauliflower	13.8	87	59	31	97	16
Celery	12.0	35	43	24	93	21
Spinach	14.6	96	69	50	154	34
Coriander	14.0	48	51	31	136	25
Chinese onion	11.5	46	47	34	125	18
Radish	17.8	78	63	58	139	28
Yadav et al. (2015)						
Beet (root)	3.14	1.89	1.72	6.42	–	–
Faba bean (pod)	1.84	NT	0.96	1.34	–	–
Cauliflower (curd)	0.92	NT	NT	1.48	–	–
Brinjal (fruit)	1.18	NT	NT	1.87	–	–
Okra (pod)	1.43	1.06	1.37	3.19	–	–
Bottle gourd (fruit)	1.65	0.52	0.64	2.86	–	–
LSD ($p \leq 0.05$)	0.60	NS	0.47	1.24	–	–
Safe limits[a]	1.5	20	2.5	50	30	1.5

[a]Source: Awashthi (2000); *NT* stands for non-traceable. For scientific names of crops, please see Subject Index

dry weight, respectively, in wastewater-irrigated leafy vegetables at Mukuvisi and Pension, Harare (Zimbabwe). From consumption of the vegetables with such concentrations of HMs, estimated intakes come to be 0.02–0.04, 0.05–0.1, 0.05–0.1, 0.05–0.09, 0.04–0.05, and 0.6–3.3 mg day^{-1} for Cd, Cr, Ni, Pb, Cu, and Zn, respectively, with Cd intake rates crossing recommended minimum risk levels (MRLs) and Cu, Ni, Cr, and Pb reaching >60 % of their respective MRLs at both sites. Similarly, in Hyderabad (India), presence of 12–40 times more than the safe limits of Cd, Cr, Ni, Pb, and Fe in milk of cows fed with wastewater-irrigated para grass (*Brachiaria mutica*) fodder suggests their transfer from wastewater (Minhas and Samra 2004). Long-term use of wastewater and its conjunctive use with groundwater have been found to cause toxic accumulations of Cd, Pb, Ni, and Cr, particularly in leafy vegetables and legumes (Yadav et al. 2015). Mitra and Gupta (1999) recorded that heavy metals in different crops under wastewater irrigation were beyond safe limits (Table 9). On the basis of several studies, it can be concluded that wastewater-irrigated vegetables accumulate 2–40-fold higher contents of HMs (Rattan et al. 2002; Minhas and Samra 2004; Yadav et al. 2015).

Environmental Problems

Metal pollution has a harmful effect on biological systems because they are biologically nondegradable and tend to accumulate in toxic levels, thus causing various diseases and disorders even in relatively lower concentrations (Pehlivan et al. 2009; Tangahu et al. 2011). All countries have been affected with waste disposal-related pollution, though the area and pollution severity vary enormously. In Western Europe, 1.4 million sites were reported to be affected by heavy metals (McGrath et al. 2001), of which over 300,000 were contaminated; and the estimated total number in Europe could be much larger, and same is true about countries like the United States. In China, about one sixth of arable land has been polluted by heavy metals arising due to wastewater irrigation (Liu et al. 2010). The problem is very severe in India, Pakistan, and Bangladesh, where small industrial units are pouring their untreated effluents in surface drains near agricultural fields, and in these countries, the raw sewage is often used for agriculture (Liu et al. 2010). Excess supply of plant nutrients with wastewater use in agriculture for irrigation also poses serious environmental pollution. In a long-term irrigation with sewage water from municipal origin, Yadav et al. (2003) observed that buildup in total N was up to 2908 kg ha^{-1}, available P 58 kg ha^{-1}, total P 2115 kg ha^{-1}, available K 305 kg ha^{-1}, and total K 4712 kg ha^{-1} in surface soil with variable vertical distribution. Traces of NO_3-N (up to 2.8 mg l^{-1}), Pb (up to 0.35 mg l^{-1}), and Mn (up to 0.23 mg l^{-1}) could also be observed in well waters near the disposal point, thus indicating initiation of groundwater contamination.

Management Interventions for Risk Reduction Using Wastewater

The risks of using untreated or partially treated wastewater in agriculture can be reduced through wastewater treatment and nontreatment options or a combination of both (WHO 2006). These include:

- Water quality improvements
- Human exposure control
- Technical interventions (phytoremediation) before use
- Farm-level wastewater management
- Harvest and post-harvest interventions

Water Quality Improvements

The first and foremost step for improvement in wastewater quality is primary treatment. This is simply a sedimentation process in which organic and inorganic solids are allowed to settle and then removed. The process reduces the biological oxygen demand (BOD) by 25–50 %, the total suspended solids 50–70 %, and the oil and grease contents by 55–65 %. Some organic nitrogen, phosphorus, and heavy metals are also removed. Primary treated effluents may be of acceptable quality for irrigation of trees, orchards, vineyards, fodder crops, and some processed food crops.

Secondary treatment can be implemented using methods such as waste stabilization ponds, constructed wetlands, infiltration-percolation, and upflow anaerobic sludge blanket. Storing reclaimed water in reservoirs improves microbiological quality and provides peak-equalization capacity, which increases the reliability of supply and improves the rate of reuse (Qadir et al. 2010). Constructed wetlands also serve as habitat for wildlife and anthropogenic wastewater discharge and treatment and stabilize other related ecological disturbances. Aquatic plants such as *Typha latifolia*, *Phragmites karka*, *Eichhornia crassipes*, *Salvinia molesta*, *Pistia stratiotes*, *Scirpus tabernaemontani*, *Colocasia esculenta*, *Azolla filiculoides*, etc. established in wetlands can also be used for paper pulp. The wetland acts as a biofilter, removing sediments and pollutants such as heavy metals from the water. Groundwater recharge with deep percolation through soil aquifer treatment (SAT), as practiced in Tula Valley (Mexico), can remove microorganisms, provided soil properties are appropriate and the process is properly managed.

Human Exposure Control

Protective measures such as wearing of gloves, boots, and mask, washing hands properly, and changing irrigation methods can reduce farmers' exposure. The sprinklers should not be used for irrigation. It also requires awareness campaigns against diseases that can be transmitted through wastewater use.

Technical Interventions (Phytoremediation)

Phytoremediation is an emerging technology using selected plants to clean up the contaminated environment from hazardous

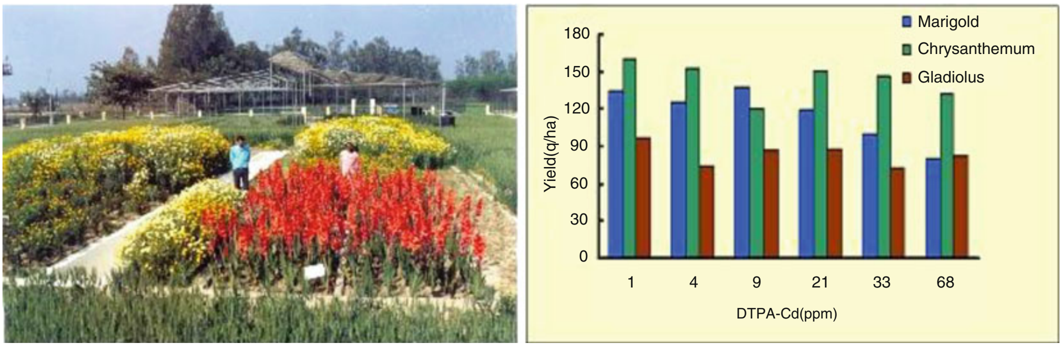

Fig. 6 Flower crops grown with their yield under variable metal concentration-contaminated wastewater irrigation at Karnal (Haryana), India

contaminants to improve the environment quality. HMs, the most potential contaminants in wastewater, cannot be degraded biologically but only transformed from one oxidation state or organic complex to another (Gaur and Adholeya 2004). To identify plants with the ability to accumulate HMs, 300 accessions of 30 plant species were tested by Ebbs et al. (1997), and it was found that many species of *Brassica* (*juncea*, *napus*, *rapa*) exhibited moderately enhanced Zn and Cd accumulation. While reviewing the uptake of heavy metals (As, Pb, and Hg) by plants, Tangahu et al. (2011) reported that the fern *Pteris vittata* was capable of accumulation of As to the extent that only 0.7 mg g^{-1} dry weight of plant and aquatic *Azolla caroliniana* and terrestrial *Populus nigra* could accumulate 0.2 mg As g^{-1} dry weight of plant root. Some species have shown hyperaccumulation of different metals, as *Brassica campestris*, *B. carinata*, *B. juncea*, and *B. nigra* >100 mg Pb g^{-1} dry weight; *B. napus*, *B. oleracea*, and *Helianthus annuus* >50 mg Pb g^{-1} dry weight; and *B. juncea* >1 mg Hg g^{-1} dry weight, with every chance of food chain contamination. However, if cultivated for fuel wood, trees as component of agroforestry can serve the purpose of phytoremediation. Similarly, Lal et al. (2013) recorded 16 % higher biomass yield of lemongrass (*Cymbopogon flexuosus*) and increasing plant Cd, Cr, Ni, and Pb concentrations from 1.54 to 1.85, 3.27 to 4.04, 4.35 to 5.58, and 3.53 to 4.46 mg kg^{-1} dry biomass but without any contamination of essential oil under varying wastewater irrigation regimes of irrigation depth: cumulative pan evaporation (ID/CPE) at 0.6, 0.8, 1.0, 1.2, and 1.5, respectively, as compared to groundwater. In their similar studies conducted earlier, Lal et al. (2008) observed that cut flowers such as marigold (*Tagetes erecta*), chrysanthemum (*C. indicum*), and gladiolus (*Gladiolus grandiflorus*) have promise in Cd-contaminated environment (Fig. 6). *Jasminum sambac*, *Jasminum grandiflorum*, and *Polianthes tuberosa* are the other ornamental and cut flower species suitable for urban greening and avenue culture with wastewater irrigation (Augustine 2002). Significance of these studies is that we can successfully grow these remunerative crops in isolation or in agroforestry systems utilizing contaminated wastewaters.

Table 10 Number of plant species that are reported to have hyper-accumulation traits (metal concentration >1000 mg kg^{-1} dry weight)

Metals	Number of species	Metals	Number of species
As	04	Pb	14
Cd	01	Se	20
Co	34	Zn	04
Cu	34	Hg	01
Ni	>320		

Source: Lone et al. (2008) and Tangahu et al. (2011)

Lone et al. (2008) stated that more than 400 plant species have been identified as metal hyperaccumulators (Table 10). These include either high-biomass plants such as willow (*Salix* spp.) or those that have low biomass but high hyper-accumulating characteristics such as species of *Thlaspi* and *Arabidopsis*.

Farm-Level Wastewater Management

Improved wastewater irrigation management at farm level includes suitable practices such as crop selection, irrigation management, and other soil-based interventions. Such interventions can reduce potential health and environmental risks to only some extent. However, global survey suggesting 32 % and 27 % use of diluted and untreated wastewater in vegetables and cereals, respectively (Raschid-Sally and Jayakody 2007), points toward a very dangerous trend for food chain contamination as many of the vegetables are consumed raw and also contain metals beyond the permissible levels. As will be discussed later, a safer alternative could be the production of urban forestry, agroforestry, avenue and roadside plantations grown for fuel and timber, and aromatic (e.g., lemon and vetiver grasses) and cut flower-yielding (*Chrysanthemum*, *Gladiolus*, *Jasminum*, and *Polyanthus*) species in urban green areas, which do not come directly in the food chain.

When choosing irrigation methods, farmers should consider the quality of water supply to manage use and the associated potential health and environmental implications due to pathogenic and metal contamination of crops. Furrow and irrigation, especially subsurface drippers, provide higher health protection to farmers and consumers as compared to flooding (Minhas and Samra 2004). An additional possibility is the cessation of irrigation, prior to harvest to allow pathogens' natural die-off.

Soil-based interventions without the production of edible plants are important, particularly in the case when wastewater is contaminated with heavy metals, which usually accumulate in surface soil layers. For moderate levels of metals and metalloids in wastewater, there is no particular management needed if the soils are calcareous; however, there can be problem in acidic soils, which require lime treatment, and when irrigating with wastewater containing elevated levels of sodium, soil structure deterioration may occur, and we require application of calcium source such as gypsum (Qadir et al. 2010). Care has also to be taken regarding detrimental effects of salts, nitrates, metals, and pathogens reaching groundwater; the shallower is the water table, the more is the danger.

Harvest and Post-harvest Interventions

These interventions involve the process of harvest, post-harvest cleaning, handling during transport, marketing, storage, and preparation in kitchens. Minhas et al. (2006) gave details of these processes and also suggested to harvest cereal and fodder crops above a certain height from ground to minimize pathogens. They also advocated the introduction of low-cost relatively safer practices as washing and post-harvest handling methods to reduce the pathogenic load of wastewater-irrigated crops.

Tree Plantations/Agroforestry Interventions for Wastewater Use

The use of wastewater for irrigation is probably as ancient as cultivation of land; however, large-scale controlled irrigation in established sewage farms in Europe, Australia, India, and the United States for disposal and prevention of pollution in surface water bodies dates back to only the last century. Although crops were produced on these farms, crop production was a secondary consideration. The El-Gabal El-Asfar sewage farm (Egypt) established in 1911 to dispose of Cairo City's untreated wastewater covered 200 ha tree plantations and expanded to 1260 ha in mid-1980 with conversion of forest to citrus along production of cereals and vegetables (Braatz and Kandiah 1998). Pioneering studies on the application of treated municipal wastewater on forest lands as a means of purification and groundwater recharge were also carried out in central Pennsylvania, USA, during 1963–1977.

Table 11 Growth parameters of 15-year-old *Pinus eldarica* when irrigated with wastewater and well water

Irrigation type	DBH (cm)	Height (m)	Basal area (cm^2)	Standing volume (m^3)
Wastewater	17.95 (1.33)	10.04 (0.15)	264.20 (30.02)	0.139 (0.013)
Well water	13.50 (0.50)	9.02 (0.10)	135.0 (20.5)	0.65 (0.090)

Source: Tabari et al. (2011). Values in parenthesis are ± SE

Studies examining the effects of wastewater irrigation on tree plantations in Victoria, Australia, commenced in 1973 provide the benchmark potential productivity of wastewater-irrigated 14-year-old *Eucalyptus grandis* and *E. saligna* in terms of mean annual increment (MAI) in wood volume of 41 and 31 m^3 ha^{-1} year^{-1} (Duncan et al. 1998). Wastewater-irrigated 4-year-old *E. globulus* plantations at 1333 and 2667 stems ha^{-1} stocking density also produced average volume growth and MAI of 126 and 91 m^3 ha^{-1} and 27 and 36 m^3 ha^{-1} year^{-1}, respectively, while the corresponding MAI values for *E. grandis* were 19 and 26 m^3 ha^{-1} year^{-1}. Lone et al. (2008) also observed MAI of 33 m^3 ha^{-1} year^{-1} for *E. saligna* at 1500 stems ha^{-1} and 31 m^3 ha^{-1} year^{-1} for *E. grandis*. This indicates that short-rotation coppicing of these two species can serve as a suitable option for wastewater disposal.

Untreated sewage is used to irrigate *Acacia salicina*, *Eucalyptus camaldulensis*, and *Tamarix aphylla* (Armitage 1985); mixed hardwood stand consisting mainly of oaks (*Quercus* spp.), red pine (*Pinus resinosa*), and white spruce (*Picea glauca*) (Braatz 1996) in Australia; and neem (*Azadirachta indica*) and date palm (*Phoenix dactylifera*) in the United Arab Emirates, forestry plantations for urban greening. In Murray-Darling Basin (Australia), the area under wastewater-irrigated tree plantations increased from 500 to 1500 ha in >60 variable size effluent sites (CSIRO 1995). Most of these studies were aimed at handling the problem of wastewater disposal; however, to utilize the nutrient potential of wastewater, economic gains are also considered in recent plantations. For example, in Egypt, Omran et al. (1998) observed better growth of orange trees; increase in water and nutrient availability through effluent application influenced the growth of trees such as *Pinus radiata*, *Eucalyptus grandis*, *Populus deltoides*, *E. tereticornis*, and *Leucaena leucocephala* (Das and Kaul 1992); *Casuarina glauca*, *E. camaldulensis*, and *Tamarix aphylla* (El-Lakany 1995); *Hardwickia binata*, *Acacia nilotica* trees, and olive tree *Olea europaea* (Aghabarati et al. 2008); *Casuarina equisetifolia* (Kumar and Reddy 2010); *Pinus eldarica* (Tabari et al. 2011); and *E. tereticornis* (Minhas et al. 2015).

All these studies indicate that due to the availability of sufficient quantity of nutrition in wastewater, most of these plantations gained advantage. Tabari et al. (2011) observed in afforested *Pinus eldarica* (15 years old) stands that trees showed better growth ($p < 0.01$) in the field irrigated using municipal water than in plots irrigated with well water, as indicated by the increased diameter at breast height (DBH), basal area, and standing volume of trees in wastewater-irrigated fields (Table 11).

It is now evidenced by several studies (Yadav et al. 2003; Mapanda et al. 2007; Kumar and Reddy 2010; Tabari et al. 2011) that sufficient availability of water and nutrients through wastewater helps to increase growth of trees. However, excess than needed supply of nutrients in wastewater needs to be taken care by selection of fast-growing tree species and better planning of plantation projects producing more biomass and development of urban and peri-urban green spaces and greenbelts around the cities.

The use of tree plantations continues to be investigated globally for sustainable disposal or reuse of wastewater (Myers et al. 1995), improving livelihood security of millions of smallholders (Qadir et al. 2007, 2010), impact on soil fertility (Yadav et al. 2003; Kumar and Reddy 2010; Tabari et al. 2011), phytoremediation (Tangahu et al. 2011), soil reclamation (Lone et al. 2008), creation of wetlands for improving biodiversity

(Qadir et al. 2010), environmental services (Dagar 2014), and potential as a climate change adaptation measure.

A major concern with wastewater irrigation is the fate of excess than plantation sequestration potential of nitrogen (N) and phosphorus (P) in the environment as these cause pollution of surface and groundwater. While P will not usually be a problem in short to medium term, particularly on soils with high P adsorption capacity, there is always a potential risk for leaching of N (as nitrate) to groundwater. Fast-growing trees initially accumulate significant amounts of N, but the net N requirement declines after canopy closure stage of plantation when recycling sets in via decomposition of litter and internal translocation. Therefore, removal of N and other nutrients by plantation can be maximized by growing trees in short rotations. However, short rotations (<6 years) may compromise water use and also limit the potential products to biomass for fuel rather than higher-value wood. Across *Eucalyptus* species, aboveground elemental uptake (mainly N, P, K) by coppiced or original trees generally increases in proportion to biomass accumulation with > half of N being in foliage. Duncan et al. (1998) observed that under high-N strength wastewater irrigation (15 mg L^{-1}), maximum amount of N was sequestered in the potentially harvestable biomass of 3-year short rotations, while longer rotations (12 years) could achieve a similar balance of inputs through assimilation of N equivalent to supply from only lower-strength effluents (5 mg L^{-1}).

Another more serious concern associated with wastewater irrigation in agriculture is the management of metallic pollution. The tree species for urban greening should be selected on the basis of nature of elements present in wastewater to be used. *Acacia*, *Mimosa*, *Anadenanthera*, and *Salix* are efficient in absorbing Cd; *Eucalyptus* and mangroves are efficient in Pb accumulation; *Genipa americana* is efficient in Cr absorption; and *Salix viminalis* can remove up to 20 % Cd and 5 % Zn.

Benefits of Wastewater Irrigation in Urban Plantations

There are many potential benefits of wastewater irrigation in tree plantations. These include relatively safer and low-cost treatment and disposal; augmenting nutrient and water supplies; environmental services such as climate improvement, soil enrichment, biodiversity improvement, and carbon sequestration, hence mitigating climate change; and livelihood security through various products such as timber, fuel wood, food, and employment. Some of these benefits are discussed here in brief.

Safe, Low-Cost Treatment and Disposal

The cost of conventional methods of treatment of entire wastewater will be very high, prohibitively so for most developing countries. As a result, these countries depend on other forms of relatively cheaper disposal and treatment options. Among these, use in urban tree plantations and greening areas can be one such alternative. However, long-term sustainability of wastewater irrigation in tree plantations also depends on site-specific soil, climate, species, application techniques, and sociopolitical environment. There should be balance between wastewater disposal rates and evapotranspiration and nutrients/pollutants carrying capacity of the plantations grown at the site. Controlled application of wastewater in forestry plantations at 2.5 cm per week effectively filtered out excess N, P, and other constituents and made it acceptable for crop production and even drinking. Availability of nutrients from wastewater also improved tree growth by 80–186 % (Braatz and Kandiah 1998). In many cases, wastewater when passed through created wetlands was purified enough for irrigation of arable crops and agroforestry.

These observations demonstrated that low-strength municipal wastewater can be recycled through urban forestry plantation ecosystems with the benefits of increasing tree growth, restoring the water quality, and recharging groundwater reserves.

Livelihood Source

Wastewater use in urban forestry plantations supports livelihoods of the urban poor in many parts of the world. It is a common reality in urban and peri-urban areas of more than three fourths of the cities of developing nations in Asia, Africa, and Latin America. The majority of the urban poor in these cities have an urgent need for improvement in quality of life with employment opportunities, provision of shelter, potable water, and recreation. In these regions, care should be taken to design urban plantations and green areas to supplement these needs and improved quality of life. An important aspect of urban greening is the jobs for poor, skilled, and unskilled laborers. Urban greening projects are often labor-intensive and provide both initial jobs as soil preparation, planting, etc. and more permanent employment in the form of maintenance and management of plantations and green areas. Project managers of the forestry component of the urban greening program in Mexico City have estimated that the program needed 3380, 3700, 800, and 100 workers to produce and transport plants, for working in the plantations, for management, and for protection and surveillance, respectively, in existing green areas (IDB 1992). In addition to basic amenities, urban green space also satisfies diverse basic human needs as food, fuel, and shelter from trees and shrubs, because tree products, if sold, provide direct cash benefits; if used within the household, they provide indirect cash benefits by freeing cash income for other uses. Trees themselves can improve existing savings/investments, secure tenure, or increase property value. As such, urban greening has many indirect benefits in terms of conservation of land and environment, controlling floods and erosion, saving energy, providing habitat for wildlife in addition to recreation, and health and other material benefits. However, in this chapter, our main focus remains on more safer and beneficial use of wastewater through plantations and urban green areas.

Environmental Benefits

Urban plantations and green areas provide some direct and other indirect benefits related to improvement in quality of life. In addition to direct benefits as fuel wood, food, fodder, and poles, these improve air, water, and land resources and are also safer outlets for disposal of urban wastes which help in improvement of health, recreation, environmental education, aesthetics, and enhancement of landscape, especially for the urban poor. Plantations also help in controlling erosion, urban water supplies, and habitats for wildlife. Depending on management objectives of urban plantations, the focus is quite different in developed cities and relatively poorer urban dwellings; however, multipurpose urban plantations are beneficial in all conditions. Urban plantations and green areas should be designed on the basis of needs and desires of local populations so that these can serve maximum possible benefits. Overall, the term urban agroforestry including urban greening using plantations involves the management of urban and peri-urban plantation in a planned, integrated, and systematic manner to achieve the maximum environmental, social, and economic well-being of the urban society.

Carbon Sequestration

Tree plantations offer additional advantage of mitigating predicted increase in atmospheric carbon concentration through their potential to carbon absorb more efficiently (Hunter 2001; Kurz et al. 2009). Eucalyptus plantation can play an important role as carbon sinks and contribute significantly to the removal of CO_2 from the atmosphere. During the process of photosynthesis, the atmospheric CO_2 is utilized by the leaves

Table 12 Temporal changes in carbon sequestration (Mg ha^{-1}) potential of wastewater-irrigated variable stocking density *Eucalyptus* populations

Density (stems ha^{-1})	165		520		1990		6530	
Plantation age (year)	WW	TW	WW	TW	WW	TW	WW	TW
3	19.9	21.0	117.0	113.4	83.2	82.3	150.4	144.2
7	41.7	39.6	264.7	253.8	156.2	151.5	193.4	181.1
10	52.0	46.6	351.0	328.6	237.6	229.1	214.8	196.4

Source: Minhas et al. (2015)

WW and *TW* stand for wastewater and tube well water, respectively

to produce photosynthates, which get stored either in the roots or bole. The carbon absorption by tree plantations in a given area varies with plantation age corresponding to variations in growth as well as plantation density. Carbon absorption is also expected to increase with better tree growth caused by essential plant nutrients supplied through sewage irrigation. Minhas et al. (2015) recorded that the rate of increments in stock volumes of wastewater-irrigated *Eucalyptus tereticornis* plantations increased with plantation density and age; and for densities <2000 stems ha^{-1}, it peaked during the sixth year of growth as compared to earlier in higher densities. Stock volumes attained with wastewater and tube well water irrigation at the end of the tenth year were 1800 and 1421 m^{3}ha^{-1}, respectively. The overall carbon temporal sequestration potential of different densities of wastewater- and tube well water-irrigated *Eucalyptus* plantations varied from 19.9 Mg ha^{-1} for wastewater irrigation in the third year of growth to 351 Mg ha^{-1} (Table 12). This suggests that wastewater irrigation in plantations can help in increasing the carbon sequestration potential of urban plantation.

Improvement in Climate and Energy Savings

While air pollution indices in many cities in more developed countries have dropped over the years, air pollution levels have been also rising in cities throughout much of Latin America and the Caribbean. Carter (1993) reported that the average level of particulate suspension in the atmosphere of Mexico City increased from 615 % between 1974 and 1990. Those most affected by such detrimental air contaminants are children, the elderly, and poor people with respiratory problems. Therefore, in these cities, an aggressive and multifaceted approach to combating pollution is all the more urgent. Growing plantations and developing green areas reduce air pollution and also improve city beautification. Air pollution is directly reduced when dust and smoke particles are trapped by the plantations. In addition, plants absorb toxic gases, especially vehicle exhausts, which are a major component of urban smog (Nowak et al. 1996). The temperature-moderating effect of urban plantations can reduce temperature extremes and thus reduce the smog formation arising with the rise in temperature (Kuchelmeister 1991). Carbon dioxide, a major component of air pollution and greenhouse effect, can also be reduced through photosynthesis and reducing heat island effect with urban greening and plantations.

Urban plantations influence climate in two distinct manners, depending on the size, spacing, and design of plantations and green areas, first directly through effect on human comfort and second indirectly through effect on the energy budget of buildings in cities where air-conditioning is used. Plantations increase human comfort by influencing the degree of solar radiation, air movement, humidity, and air temperature and providing protection from heavy rains. Plantations and other vegetated areas also have an important impact on the energy budgets of buildings and, in turn, of entire cities. Plantations have been found to reduce the average air temperature in buildings by as much as 5 °C. Studies in Chicago suggest that an increase of 10 % plantation cover can reduce the total energy requirements of the city by equal extent (McPherson et al. 1994). Urban plantations also supply renewable energy in the form of fuel wood and other substitutes of fossil fuels. Treating wastewater in plantations eliminates the need for major sewage treatment plants that need fuel for their operation. Similarly, organic municipal solid waste serves as composted fertilizer, mulch for green areas, and animal feed, thereby reducing the energy and transport.

Reducing Noise Pollution

Noise pollution has been consistently rising with increase in heavy industry and commercial and traffic corridors and often reaches unhealthy levels in all big cities. Poor people living in dwellings without insulation against noise and close to industries and traffic corridors are the most exposed to the highest levels of noise. Plantations, urban green areas, and vegetation can help reduce noise pollution by sound absorption, deflection, reflection, refraction, and masking (Miller 1988). Higher-frequency noise is the most distressing to people, and plants absorb high-frequency noise more than lower ones, thus becoming advantageous. The optimum planting design to lessen noise pollution is dense vegetative cover in a range of heights. Using wastewater, such plantation barriers can be developed around industries and along traffic corridors.

Flood and Erosion Control

Urban plantations, green area parks, and wetlands form important components of flood control system of cities. They increase the permeable surface area to absorb floods arising due to storms and also reduce flow rates as compared to nonvegetated asphalt surfaces and thus apparently help in reducing damage to buildings or settlements. The Durban park system in Durban, South Africa, retains storm runoff water in upland ponds and marshes and in downstream wetlands (ICLEI 1995). Similarly, in Tulsa, Oklahoma (USA), certain plantation species tolerant to a week or more waterlogging have been planted in urban parks designed for flood control. Since the 1980s, the Curitiba City of Brazil has been utilizing urban green area parks with a lake in the middle for controlling the frequent flood devastations. As per estimates of Lone et al. (2008), about 3.0 million people used to live on the steep hills surrounding Rio de Janeiro City where risk of landslides has been reduced by planting hardy soil-binding species using trickle irrigation. In Bogotá, Colombia, an environmental rehabilitation project includes the reforestation of 4450 ha in the watershed of the Bogotá River, reducing erosion and sedimentation over about 6800 ha (IDB 1990).

Solid Waste and Land Reclamation

Urban greening can also help in reducing the solid waste disposal problem. Many forms of waste and nutrient recycling are already in use in some parts of the world. In Asian countries, organic wastes, settling pond sludge, and wastewater are used as fertilizer and irrigation for agriculture, urban plantations, and aquaculture. Composting of city organic wastes in urban plantations and green areas can be another viable alternative to reduce volume of urban refuse and thus waste disposal expenses. In Milwaukee, Wisconsin (USA), the sewage is passed through a special vegetated treatment facility which turns it into a highly valued very cost-effective soil amendment named Milorganite. Likewise, unused or degraded lands and landfills can be reclaimed through urban greening activities.

Some urban areas in semiarid and arid regions require strategic perennial plantations to reduce the salinization problem. Planting selected trees depending upon the interactions between trees, water, and salt is seen as a better way of using wastewater to reduce “leakage” into the groundwater system. Strategic planting of deep-rooted HRTS trees like *Eucalyptus* can check seepage of salts and pollutants. This is because trees develop extensive root systems to trap the water, which is then used for tree growth or returned to the atmosphere through evaporation and transpiration. Estimates suggest that the amount of water that percolates below the root zone of arable crops and pastures can be 10–100 times more than that percolating below trees. Trees and other deep-rooted tolerant plants can help stabilize the site, improve aesthetics and biodiversity, and provide fodder for drought proofing.

Urban Plantations for Wastewater Use

Selection of plantation species for urban agroforestry or greening with beneficial use of wastewater will depend on the prevailing environmental conditions for which they are planned. However, after due consideration of given local climate, soils, and wastewater quality and quantity, the following important traits should be considered in species selection:

- Fast growth, although it is relative to the quality of the wood or other products produced. Generally, fast growth is suitable for pulpwood and materials for panel products but not for sawn wood products because of the often lower density of fast-grown wood. Some species (e.g., *Populus* and *Eucalyptus*) that traditionally have been grown fast in plantations can be managed for sawn wood by lengthening rotations, aggressive thinning, and early pruning. However, for wastewater use, urban tree species should have the following characteristics:
- Tolerance to soil conditions, i.e., reaction, salinity, metal load, and excess water
- Tolerance to climatic conditions like temperatures, insolation, and wind conditions
- Ease of propagation, including a reliable seed supply if seedlings are used
- Evergreeness, which allows the plantation to utilize higher quantities of wastewater

In Egypt, substantial volumes of wastewater generated in cities and villages are used in forest plantations (MSEA 2006). Zalesny Jr. et al. (2015) recommended some plantation species, based on their suitability, growth potential, use, and economic value, for wastewater irrigation in different regions of Egypt. These are pine (*Pinus* spp.), eucalyptus (*Eucalyptus* spp.), and poplar (*Populus* spp.) for pulpwood or sawn wood; mahogany (*Khaya ivorensis*) and teak (*Tectona grandis*) for high-value products; and beechwood (*Gmelina arborea*) for only pulpwood. *Salix* has an excellent capacity to take up metals as cadmium and cesium (Cs-137) from the soil and could be used for environmental protection. Cesium and potassium have been found to compete in the metabolism of the plant, and thus uptake of cesium could be increased by reducing potassium fertilization. Salt tolerance will also be an important criterion for potentially saline effluent disposal on urban sites and environments, while water use is the main consideration in controlling groundwater pollution. Information on salt tolerance of different plantation crops can be obtained from Mass and Hoffman (1977). Marcar et al. (1995) provided detailed information on salt tolerance limits of 30 tree species, and other authors (Slavich et al. 1999; Morris and Collopy 1999; Benyon et al. 1999; Shah et al. 2000; Myers et al. 1999; Minhas et al. 2015) have investigated water use of different tree plantations, bushes, and grasses under a range of conditions. *Eucalyptus* species are generally considered to be effective for wastewater utilization purposes. *Eucalyptus camaldulensis* is a hardy tree that grows under a wide range of climatic conditions and soil types. Some provenances of the species even tolerate saline water and soil conditions quite well. *Acacia nilotica*, *Dalbergia sissoo* and *Tecomella undulata*, *Populus*, and *Tamarix* are other species and genera that have performed quite well in plantations under excess soil moisture conditions (Bhutta and Chaudhry 2000). In addition to the abovementioned two general considerations of quantity and composition of wastewater to be used, economic benefits accruing from urban plantations is another major factor that decides the choice of plantation species.

There are many species of trees adapted to urban and suburban growing conditions, such as *Leucaena leucocephala*, that provide high-quality fodder for livestock. Similarly, a large percentage of urban dwellers, especially the poor, use firewood as their primary cooking and heating fuel and depend on nearby green areas for their source of wood. Urban greening can provide sustainable fuel wood plantings to meet the needs of these urban residents. Fruits, nuts, and fiber are some of the other forest products that could be harvested from wastewater-irrigated urban and suburban plantations and green areas. Most trees that provide these products are found in private lots and gardens. Generally, the ornamental value is the main consideration of selecting suitable horticultural plantation species for greening public urban areas as these are less subject to damage and theft.

In the peri-urban areas of Hubli in Karnataka state of India, all farmers bordering the wastewater *nalla* engage in less water-requiring wastewater-irrigated agroforestry plantations on their private properties which reduces exposure to wastewater. In some areas, the main wastewater-irrigated agroforestry land uses are orchards and agro-silviculture which consists of spatially mixed tree-crop combinations. The two important tree species are sapota (*Achras zapota*) and guava (*Psidium guajava*), and other common species are coconut, mango, areca nut, and teak. Species found on farm boundaries include neem (*Azadirachta indica*), tamarind (*Tamarindus indica*), *Eucalyptus* spp., poplar (*Populus deltoides*), *Acacia* spp., coconut (*Cocos nucifera*), and teak (*Tectona grandis*). About 20–25 % yield advantage has been observed from wastewater irrigation in comparison to tube well water-irrigated fields (Bradford et al. 2003).

Recycling Solid Waste and Wastewater Through Urban Plantations

Forestry plantations used for urban greening help to improve local site ecosystem water availability in an integrated manner. As most of the cities in the developing world face acute deficiency of wastewater treatment, the integration of stabilization and lagoon ponds into urban plantations with green parks could allow wastewater reuse in the plantations. In addition to this, plantations can also offer a beneficial use for solid waste landfill sites. Huge amount of solid wastes produced in the cities in the developed world, which is also gradually increasing even in urban communities of developing countries, has become a serious problem. Urban plantations with green areas offer some solutions in the form of possible sites for composting. Recycling of waste from urban forest can play a major role in solid waste management, especially in cities in developing countries, and should be encouraged not only to reduce the need to dispose of vast amounts of waste but also to secure new raw materials from extraction for reuse. Unused and degraded land and landfill sites can be reclaimed through plantations and development of green areas as practiced in Hong Kong (Chan et al. 1996; IDB 1997).

In the cities of developing countries, more than 90 % of raw or partially treated wastewater is discharged directly into rivers, lakes, and seas. Disposal of wastewater remains a problem even in developed world cities. Wastewater use for irrigation to plantations in urban green areas has been suggested as a safer and relatively more productive alternative in arid zone countries like Egypt and Iran (Braatz 1993). Reused city wastewater not only recharges aquifers but also reduces the demand exerted on scarce freshwater reserves. The practice of at least partially treating wastewater in stabilization ponds integrated into park systems and other green areas must be considered as an economic and ecological alternative to conventional urban wastewater treatment. Recycling wastewater through oxidation ponds and wetlands into green areas in Battambang, “the second largest city of Cambodia,” has been found more environment friendly than disposal in surface water bodies and also economical to conventional waste treatment (IDB 1997). Large land requirement is the major disadvantage of this practice, but making the open space economically attractive through multiple uses can counteract this problem.

Wastewater Use Potential in Urban Plantations

Land application of domestic and industrial wastewater is getting attention because it provides primary, secondary, and tertiary treatment to the waste in a single operation, with recycling and reuse benefits of wastewater and nutrients for biomass production (Idelovitch and Michael 1984; Witherow and Bledsoe 1986), besides preventing the pollution of streams and lakes. Wastewater-irrigated urban forestry/agroforestry plantations have been recognized as a strategy to use urban wastewater while also rehabilitating and greening wastelands. The availability of permanent streams of wastewater has enabled urban farmers to diversify their cropping practices. Spatial distribution of plantations, flowers, or agroforestry systems results from a combination of availability and composition of wastewater, labor, soil type, area, and its landscape within urban or peri-urban areas. As such, the present scenario of wastewater use in close urban and peri-urban areas of developing countries includes adoption of a year-round intensive vegetable system. Further away from the cities, less intensive farming systems are practiced, without consideration of adverse effects of wastewater irrigation. However, the wastewater still offers advantages in terms of early-season irrigation and increasing growth and production from green plantations, flower crops, and fruit trees in agroforestry systems. Plants such as *Eucalyptus*, poplar (*Populus* spp.), pine (*Pinus* spp.), bamboo (*Bambusa arundinacea*), acacia (*Acacia mangium*), neem (*Azadirachta indica*), and Indian rosewood (*Dalbergia sissoo*) which have high transpiration rate system (HRTS) can be effectively utilized as a safer alternative for beneficial disposal of wastewater. Such plants can transpire higher quantum of wastewater than the potential evapotranspiration possible from the site soil matrix alone. The higher wastewater use in plantations is due to the combination of deeper rooting, extended growing seasons, and higher inputs of radiant energy because of lower albedos as compared to herbaceous covers or crop lands (Nosettoa et al. 2012). Khanzada et al. (1998) monitored the water use of *Acacia nilotica*, *A. ampliceps*, and *Prosopis pallida* on 3–5-year-old plantation sites with contrasting soil and water quality conditions in the Indus Valley in Pakistan. *A. nilotica* used the maximum water, which varied from 1248 to 2225 mm depending upon plantation growth conditions. They suggested that trees can evaporate large volumes of water provided the salt accumulation remained within tolerable limits of the species. *Eucalyptus* and poplar with high demand for water and nutrients also have capacity to remediate nutrient-rich raw or dilute municipal wastewater.

Although water use could be as high as 2500 mm annually in a 6 -year-old plantation, the exact amount of water and nutrients taken up by *Eucalyptus* depends upon climate and plantation vigor (Rockwood et al. 1996, 2004; Minhas et al. 2015). Under tropical semiarid conditions of northwest India, Minhas et al. (2015) have continuously recorded the maximum potential monthly mean daily transpiration rates of wastewater-irrigated *Eucalyptus* plantations. They have suggested that *Eucalyptus* hybrids at a stand density of ~550 stems/ha have mean daily transpiration rates within 6 mm day^{-1} in contrast to the earlier reported very high rates of 20 mm day^{-1}. However, total annual transpiration rates gradually increased from 392 to 1417 mm during the third to seventh year of growth, which did not increase much further till the plantation age of 10 years. Transpiration rates also increased with density especially during the initial years of growth, e.g., the average annual transpiration at ~2000 stems ha^{-1} varied from 768 to 1628 mm from the third to seventh year of growth (Fig. 7). This implies that wastewater can be used beneficially by planting the trees at high density during early growth and thinned appropriately as the growth picks up.

This study suggested that *Eucalyptus* can safely use wastewater up to 0.56 × open pan evaporation (OPE) during summer months (April–June), 1.24 × OPE during August–October during maximum growth period, and 1.12 × OPE during winter. Similarly, at Wagga

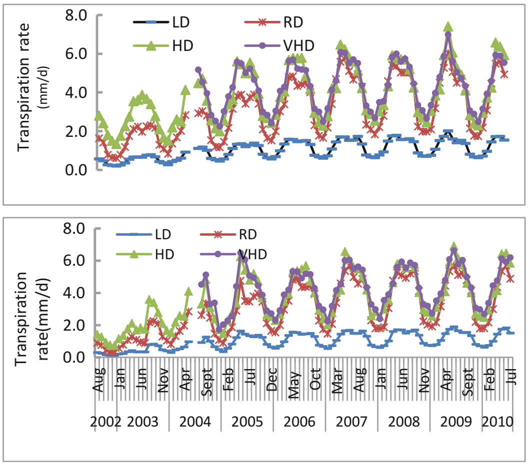

Fig. 7 Monthly average of mean daily sap flow (transpiration rate) values per hectare (mm/day) for TW- and SW-irrigated plantations

Wagga, Myers et al. (1999) observed that *Eucalyptus grandis* attained faster early growth and closed canopy in 2 years compared to an estimated 4 years for *P. radiata*. Though *Eucalyptus* plantation water use during specific period of time was higher than that of the pines but the plantations of two species with similar stage of canopy development and growing on same site have comparable water use. So, *Eucalyptus* at closed canopy, which has a maximum monthly mean daily water use rate of <8 mm day^{-1} and an annual crop factor between 0.84 and 0.93 times pan evaporation, is not inherently a more profligate consumer of water than pines when soil water is not limiting. Even though tree plantations may not have significantly higher water use potential than arable crops, they have definite advantage of consistent use throughout the year.

To avoid the groundwater contamination, due to wastewater use in plantations, the wastewater application should be regulated as per the evapotranspiration and nutrient use potential of the site plantations. Nutrients present in the wastewater should be used by the plants and partly retained in the soil matrix without affecting the soil ecosystem. Since, it is not always possible to work out actual evapotranspiration (ET) of plantations at every site (Domec et al. 2012); however, ET can be estimated precisely using certain models (Ge Sun et al. 2010). Based on the data of the AmeriFlux sites, forests across the United States, Canada, Brazil, and Costa Rica, Joshua et al. (2005) concluded that certain potential evapotranspiration (PET) models as Penman-Monteith, Penman, and Priestley-Taylor can be used with good precision to work out maximum possible wastewater disposal rates at a given site under specific stage of the plantations.

Heavy Metal Recycling Potential of Urban Plantations

To tackle the limitations of conventional wastewater treatment systems and avoid food chain contamination due to use in agriculture, alternate low-cost, eco-friendly methods need to be evolved for safer disposal and desired level of treatment. Phytoremediation, a cost-effective "green" technology, mainly relies on nutrients, salts, and metal-accumulating plants to remove polluting metals from soil or water (Salt et al. 1998). A list of about 400 terrestrial plants species, having 100–1000 times more accumulation potential for one or more HMs than those normally accumulated by plants grown under the same conditions, has been prepared by Hooda (2007). In comparison to food arable crops, wastewater irrigation in plantations is relatively safer, cost-efficient, and an environmentally sound way to treat and dispose wastewater (Armitage 1985). On wastewater-irrigated soils, *Acacia nilotica*, *Dalbergia sissoo*, and *Acacia modesta* accumulated relatively higher HMs than several bushes and grass species. HM concentrations in these species varied as per the composition of wastewater in the order of Fe > Zn > Cr > Pb > Ni > Cd > As. All the species exhibited higher HM composition in the root as compared to shoot (Irshad et al. 2015). Though there is lack of reports on symptoms of HM toxicities in tree species, it also indicates their tolerance mechanisms to withstand higher HM concentrations than agricultural crops (Riddell-Black 1994). It has been observed that even those trees which are not selected for metal tolerance generally survive in metal-contaminated soil but with reduced growth rate (Dickinson et al. 1992). Beneficial effects of organic load in wastewater and sludge on tree growth processes have been found to far outweigh any adverse impacts of the added metals. Prolonged sewage irrigation markedly increased the amount of Fe, Zn, Mn, Cu, Pb, and Ni in the leaves and fruits of *Citrus* and olive without adversely affecting their growth and accumulation of metals beyond the safe limits in fruits (Khalil 1990; Maurer et al. 1995; Aghabarati et al. 2008). Therefore, use of low-strength wastewater did not pose any threat to *Citrus* and olive trees and consumers from heavy metal accumulation. Batarseh et al. (2011) found the accumulation being independent of the heavy metal concentration in the wastewater, suggesting a selective uptake of the metals by the olive plants. Also the trend of heavy metal transfer from soil to olive fruits, and leaves, was almost the same, showing a consistency of transfer. Dinelli and Lombini (1996) observed that metal concentrations were generally higher in the early vegetative growth stage, due to a relatively high nutrient uptake compared to growth rate. This was followed by a period of vigorous growth, which diluted the concentrations until the flowering stage, in which the minimum values for almost all elements were obtained. Several tree species grown on sludge-amended spoil had the highest concentrations of Cd, Cu, Ni, and Zn in root tissues. Wood and bark are important sinks for biologically available metals, with additional sink tissue being formed each growing season. These tissues are slow to enter the decomposition cycle; accumulated metals can, therefore, be immobilized in a metabolically inactive compartment for a considerable period of time (Lepp 1996). Massive root systems of trees upon establishment bind the soil, thus promoting soil stabilization. Moreover, addition of litter to the surface quickly leads to an organic cover over the contaminated soil. In addition, transpiration by the trees reduces downward and lateral flow of water in the soil, thus reducing the amounts of heavy metals transferred to groundwater and surface water. Deep-rooting plants could reduce the highly toxic Cr(VI) to Cr(III), which is much less soluble and, therefore, less bioavailable (James 2001). It could be because of organic products of root metabolism, or resulting from the accumulation of organic matter, could act as reducing agents (Pulford and Watson 2003). Proper management of municipal effluent irrigation and periodic monitoring of soil and plant quality parameters are required to ensure successful, safe, long-term municipal effluent irrigation.

Wastewater Treatment and Nutrient Removal by Urban Plantations and Green Areas

Sewage treatment plants are established in large cities only, and as such, there are no or a very few wastewater treatment facilities available in small and medium urban settlements of most of third world countries. Apparently for these areas, decentralized natural treatment systems such as urban plantations with green areas and constructed wetlands could prove cost-effective and environment-friendly alternative wastewater treatment. Urban plantations in combination with the constructed wetlands (CWL) remove higher nitrogen (66–73 %) and phosphate (23–48 %) compared to unvegetated wetlands (Juwarkar et al. 2005). Similarly, treatment performance and removal efficiencies of various types of CWL for BOD, TSS, and nutrients (total P, total N, and NH_4-N) were compiled by Vymazal (2010). Under sewage irrigation and compost mulch application, *Eucalyptus* biomass yields were found to increase more than twice in comparison to those of *Populus* after 3 years of growth at Orlando (USA), revealing better performance of *Eucalyptus* both in terms of environmental and economic implications. Rockwood et al. (2004) observed that, under sewage irrigation, *Eucalyptus* can reduce N and P leaching by 75 %. Relative concentrations of N, P, and K in *Eucalyptus* plant tissues were reported to be in the order of foliage > stem bark > branches > stem wood. HRTS plantations could remove N by 60–76.2 %, whereas the removal of phosphate was comparatively less than nitrogen, and it ranged from 17.7 % to 70.3 %. It was further observed that due to profuse growth of *Casuarina equisetifolia*, its N removal efficiency was relatively more as compared to *Dendrocalamus strictus*. In addition to N removal, these plantations also reduced wastewater biological oxygen demand (BOD) with removal efficiency ranging from 80.0 % to 94.3 % (Thawale et al. 2006). Urban greening in the form of agroforestry system plantations has many advantages, which include sink potential for water and air pollutants, aesthetics, and biomass generation for energy.

The ponds, rivers, and wetlands with plantations as part of natural treatment of wastewater also serve for recreation, wildlife habitat, aesthetics, and educational use. Wetlands, the most biologically diverse ecosystems, a resource for tertiary wastewater treatment, increase habitats for flora and fauna in and along the waterways. The biological functions and physical aeration occurring in the wastewater during the passage of wastewater in the waterways remove many of the toxic effluents from the wastewater (ICLEI 1995). These plantations with wetlands in urban park systems are the low-cost wastewater treatment facilities for low-income cities. There are several alternatives to wastewater treatment and disposal that can be incorporated in green areas. As such, wastewater can be used to irrigate urban and suburban agriculture and forests, horticultural projects (flowers for export), city landscaping and parks, and tree farms. All of these options provide for a safe and productive means of wastewater disposal (Braatz 1993). This reuse of wastewater not only recharges the aquifer but also reduces the demand on scarce freshwater resources. Controlled recycling wastewater into urban plantations and green area parks or forested, farmed, and degraded lands may also be more economical than finding ways to dispose it of somewhere else.

Urban plantations and green areas have following additional benefits in addition to low-cost treatment and remuneration in terms of livelihood security for the urban poor.

Material Benefits Accruing from Urban Plantations

Maintaining small gardening plots using diluted or treated wastewater can help urban growers, especially the poor, to provide food for their own families. In Arlington town of Virginia (USA), residents have been given rights to plant food on community garden land located on sides of the city highways. This serves dual purpose of food production and maintenance of the green areas. In the ancient Aztec system of chinampas, the wastewater streams between the chinampas provided irrigation, transportation, aquaculture, recreation, and tourism. Similarly, in Xochimilco Plantation Park, extension specialists have been imparting training on apiculture to neighborhood people and encouraging beekeeping (UNDP 1996). Such integrated systems of wastewater use in urban plantations could prove beneficial to growers, consumers, and the city amenities.

Urban plantations can provide significant material benefits in areas where poles, firewood, and fodder are in high demand. Tree species that produce poles for fence posts are highly valued, especially in arid regions where low-cost fencing materials are scarce. Poles are also used in construction, furniture making, and crafts. There are many species of trees adapted to urban and suburban growing conditions, such as *Leucaena leucocephala*, that provide high-quality fodder for livestock. Similarly, a large percentage of urban dwellers, especially the poor, use firewood as their primary cooking and heating fuel and depend on nearby green areas for their source of wood. Urban green park areas developed using wastewater can provide sustainable fuel wood plantings to meet the needs of these urban residents. Most trees that provide fruits, nuts, and fiber can be grown in private gardens.

Social Benefits of Urban Plantations

Although difficult to quantify, the benefits of urban plantations and greening to human health are considerable. Urban plantations and green parks improve air quality, contribute toward aesthetically pleasing and relaxing environment, and thus have positive impacts on health in terms of decrease in respiratory illnesses and reduction in stress. Urban forests provide a connection between people and their natural environment that would otherwise be missing in a city. This connection is important for everyday enjoyment, productivity, and general mental health of workers (Nowak et al. 1996). Plantations also reduce ultraviolet light exposure thereby lowering the risks of harmful health effects such as skin cancer and cataracts (Heisler et al. 1995).

Green areas provide recreational sites, especially for lower-income residents who tend to frequent city parks more than wealthier citizens because of financial constraints and restrictions on leisure time. The urban poor generally have few affordable options for recreation and thus place a high value on green areas. Parks and other green areas also provide educational opportunities to learn about the environment and natural processes.

Aesthetic value of plantations and green areas, though not considered as important as food and shelter, is also very meaningful to urban residents. Vegetation reduces sun glare and reflection, complements architectural features, and tones down the harshness of large expanses of concrete. Rehabilitating lands with vegetation is often more attractive and cost-effective than constructing buildings. Aesthetically pleasing green areas help in enhancing the property values. For example, the vegetated beautification of Singapore and Kuala Lumpur has been adjudged as a major factor in attracting huge foreign investment and their rapid economic growth (Braatz 1993). Similarly focused urban greening along roadways and railway lines in the Black Country district of England, a region of polluted lands, helped to attract huge investments (Jones 1995). The range of benefits that urban greening provides is both practical and comprehensive and addresses many of the social, environmental, and economic problems most cities face. Though urban plantations and green park areas are not the panacea for every urban problem, nonetheless these can significantly improve many of them and create a much more desirable environment to live.

Conclusions

Wastewater has enormous irrigation, nutrient, and labor employment potential, which is likely to increase at a high pace commensurate to increasing urbanization with provision of water supply and sewerage. Therefore, the wastewater needs to be considered as a resource rather than a menace by the urban planners and policy makers, especially in freshwater-scarce urban situations.

Wastewater also contains salts, pathogens, heavy metals, and other pollutants. Therefore, the benefits of wastewater use can be offset by the associated adverse health and environmental impacts in the long run, especially in developing countries where large volumes of raw or diluted wastewater are used in high-value vegetables, food grains, and fodder crops in peri-urban agriculture.

To overcome the hazards associated with wastewater use in agriculture, the chapter emphasizes on low-cost appropriate alternative measures like urban plantations and green area parks and some guidelines for selection of suitable species. Under the situations where land has been already contaminated and food crops are not permitted, the establishment of urban plantations such as poplar, eucalyptus, mahogany, willow, salix, etc. and green area parks in cities and greenbelts along traffic corridors or around cities can prove safer in terms of avoiding metal contamination and beneficial approach to overcome health hazards and to ensure many environmental, social, and economic benefits as non-edible products like fuel and timber.

Urban plantations and green areas should be designed on the basis of needs and desires of local populations so that these can serve maximum possible benefits to all residents.

Plantations have potential to improve air, water, and land resource quality, moderate the extreme high and low temperatures, and control floods and erosion with additional advantages creating habitats for wildlife, recreational activities, soothing environment, and above all aesthetic value of the cities.

To make the urban plantations and green park areas a safer and viable alternative for wastewater use, the plantation species should include fast-growing, high transpiration rate multipurpose trees tolerant to salts and waterlogging (e.g., *Eucalyptus*, *Acacia*, *Salix*, etc.) and generate regular income.

To avoid contamination of natural resources, wastewater disposal rate needs to be regulated depending upon the plantation transpiration rate, tolerance to salts, and uptake of toxic substances. *Eucalyptus* hybrid plantations at a stand density of ~550 stems ha^{-1} have the mean daily transpiration rate potential of 6 mm day^{-1} and total annual transpiration rates gradually increasing from 392 to 1417 mm from the third to seventh year of growth. Transpiration rates also increased with plantation density especially during the initial years of growth till canopy closure, as the average annual transpiration at ~2000 stems ha^{-1} varied from 768 to 1628 mm from the third to seventh year of growth. This suggests that plantations should be established at higher stand densities and could be thinned with age as the canopy expands.

As such, the plantation water use is governed by local climatic water requirement; *Eucalyptus* plantation transpiration rates in subtropical conditions were found to vary from 0.56 × OPE (open pan evaporation) during the summer months (April–June) to 1.24 × OPE during maximum growth period of August–October and 1.12 × OPE during winter at canopy closure stage. Under similar climatic conditions in Pakistan, the maximum annual water use potential in *Acacia nilotica* plantations varied from 1248 to 2225 mm depending upon plantation growth conditions. At Wagga Wagga in Australia, *Eucalyptus grandis* closed canopy after 2 years of growth and at this stage have a maximum monthly mean daily water use rate of less than 8 mm day^{-1} and an annual crop factor between 0.84 and 0.93 times pan evaporation. These were not more profligate consumers of water than pines when soil water is not limiting. Plants such as *Eucalyptus*, poplar (*Populus spp.*), pine (*Pinus* spp.), *Melaleuca* spp., bamboo (*Bambusa arundinacea*), acacia (*Acacia mangium*), neem (*Azadirachta indica*), and Indian rosewood (*Dalbergia sissoo*) which have a high transpiration rate system can be effectively utilized as safer alternative for beneficial disposal of wastewater.

Since the plantation transpiration capacity and their water requirement also decrease due to low evaporative demand during winter and rainy seasons, therefore, the provision of storage and soil aquifer treatment needs to be developed in integration with constructed wetland with urban plantations and green area parks.

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