Chapter 7
Phytoremediation of Agricultural Pollutants in the Tropics

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Abstract Agricultural pollutants known to have harmful impacts on aquatic species and ecosystems include excess levels of plant nutrients (e.g., ammonium nitrate and phosphate from fertilizers) as well as inorganic (e.g., heavy metals) and organic compounds (e.g., pesticides including insecticides and herbicides) commonly associated with global farming practices. This chapter examines the role of phytoremediation in decontaminating these key pollutants of agricultural origins, with a particular focus on the plant species and environmental dynamics which occur in tropical regions. This chapter also includes strategic applications (e.g., terrestrial barrier plantings around sensitive wetlands), which could provide safe, affordable, and environmentally sustainable solutions for reducing the impacts of agricultural practices on tropical wetlands.

Keywords Farms · Agricultural wastewaters · Wetlands · Decontamination · Barrier plantings · Soils

7.1 Introduction

Agriculture is the practice of farming plants and animals to produce the essential resources required by global communities. Agriculture spans edible crops, timber and fiber, and a range of animals for a variety of products. In modern agricultural practice, crop species are generally grown in uniform monoculture fields or climate-controlled greenhouses supported by highly cultivated soils and water delivered by irrigation systems and occasionally rainfall (Hoffman et al. 1995). Stock animals are conventionally raised in rangelands, typically with barn structures for shelter

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and feedstock and water continually supplied for animals to access. Agricultural productivity varies depending on region and demand, but many crops and animals are widely farmed and have comparable resource requirements, including cleared land and water supply (FAO 2021). Collectively, these industries contributed $3.5 trillion to the global economy in 2018 alone, with farm productivity continually increasing in alignment with human population growth and increasing consumer demand (FAO 2021).

Agricultural practices radically transform natural landscapes through land clearing (i.e., deforestation and shrubland clearing), soil modifications, and altered water regimes (Fig. 7.1). Agriculture is also deemed responsible for ~22% of anthropogenic greenhouse gas emissions and it is acknowledged as a major contributor to global warming (Grosso and Cavigelli 2012). Wastes are continually generated by farmland operations. Waste originating from agricultural activities encompasses diverse pollutant mixtures with varying environmental risks, including animal-origin effluent from farms (e.g., ammonia in soils and as vapor release), plant harvest by-products, nutrient run-off from fertilizer applications, pesticides (including insecticides and herbicides), as well as a wide range of heavy metals and salts (Alengebawy et al. 2021). The composition and concentrations of these chemicals

Fig. 7.1 Aerial image of agricultural plots lining a waterway demonstrating the impacts of land-use change for agriculture (Fisk 2014)

relate to the type and scale of the agricultural practice in operation, but each pollutant creates its own challenges for land and water integrity. In some instances, like plant by-products and manures, wastes may be diverted and recycled for useful purposes (Yang et al. 2021); however, certain pollutants are hazardous in nature and contribute to land degradation. Farmers in developing nations often have little choice but to use polluted landscapes and risk food contamination, given the climatic, spatial, and socio-economic limitations to landscapes where key food crops can be produced (Xiao et al. 2017). Sustainable agriculture, which is focused on long-term crop and livestock production with minimal impacts on the environment, is therefore an immediate global priority in order to ensure a balance between resource production and the preservation of the environment (Hejna et al. 2021).

Developing new methods for remediating environments impacted by agricultural pollutants, including ecologically sensitive wetlands, is an important step in transforming agricultural industries to become safer and more sustainable. This aligns with a growing ambition to improve land management methods and prevent global pollution in general, seeking technologies with higher efficiency, lower costs, and safer implementation which can be tailored to industries and ecosystems of importance, including farmlands of tropical regions (Paz-Ferreiro et al. 2014). Phytoremediation presents an important opportunity for the passive decontamination and management of such pollutants, preventing their spread to vulnerable ecosystems and species. Phytoremediation is a phytotechnology used to clean up contaminated surface waters, soils, air, and groundwater. It is a cost-efficient (Mosa et al. 2016), non-invasive (Dietz and Schnoor 2001), longer-term biotechnology that can be applied in situ to decontaminate sites where contaminants are within reach of plant roots. To date, there has been substantial focus on addressing environmental problems associated with industrial activities and mining operations using applied phytoremediation (Peco et al. 2021), but considerably less attention has been given to the potential for phytoremediation to ameliorate the impacts of the vast range of ubiquitous pollutants associated with agricultural practice as well as protect pollutant-sensitive components of ecosystems.

This chapter examines research progress in the phytoremediation of globally common agricultural pollutants of water and soils, including fertilizers, ammonia discharge, and heavy metals, as well as select insecticides and herbicides. The implementation challenges for phytoremediation associated with decontaminating these pollutants and protecting wetland ecosystems are explored within the context of tropical regions, as well as future opportunities for applied research.

7.2 Fertilizer Pollution

Runoff from agricultural developments often carries excess nutrients from plant fertilizers that are not sufficiently removed by existing control measures (Fig. 7.2). Most elemental nutrients are essential for plant growth, which is the basis for applying supplemental fertilizer to crops, including nitrogen (N), phosphorus (P),

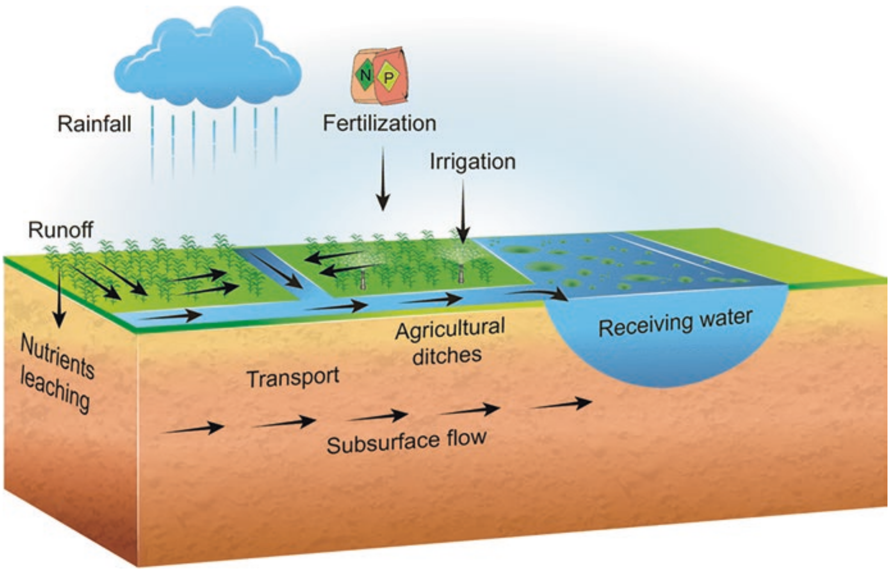

Fig. 7.2 Terrestrial agricultural pollutants and flows into aquatic systems (Xia et al. 2020)

andpotassium (K). However, in excess concentrations, these elements can cause significant stress, degradation, and impairment of ecosystem functions, including eutrophication and catastrophic species declines in freshwater and wetland ecosystems (GES 1997).

Nutrients originating from plant fertilizers have adverse effects on aquatic communities, often acting as a catalyst for eutrophication, triggering rapid growth in aquatic vascular plant and algal biomass and associated declines in water health (Sims et al. 1998). Therefore, although not toxic in trace amounts like certain heavy metals, phytoremediation of excess nutrients, including P, has enormous potential to protect ecologically sensitive areas, including natural water bodies and aquatic communities, from environmental harm.

7.3 Phosphorus

Over the last 50 years, P levels in soils disturbed or modified by human activities have been rising (Coale 2000). Highly elevated soil P levels (i.e., typically defined as 45 mg/kg^{-1}) are frequently recorded in areas of the world where intense animal farming activity occurs, as well as in areas where fertilizers have been applied as supplements for plant crops (Coale 2000). When soil P exceeds the capacity of the substrate to bind P, surface runoff or P transfer to freshwater systems, including wetlands, becomes an environmental concern. The presence of dissolved P, particulate P, and organic P in water may contribute to the eutrophication of rivers and lakes (Sims et al. 1998). Soils with excessive P levels have been identified as an important source of diffuse pollution (Sharpley et al. 1994). Therefore, finding and applying phytoremediator species capable of continually absorbing high levels of P into plant tissues and minimizing the impacts of P pollution is a key objective for protecting sensitive aquatic communities.

In a study by Delorme et al. (2000), phytoremediation of phosphorus-enriched farm soils was trialed using 12 common crop species and grass species, each previously shown to be successful in accumulating heavy metals in non-agricultural contexts. A dual study comprising greenhouse trials and field applications was performed, incorporating farm soils which were artificially enriched with P derived from inorganic fertilizers and manures. While all phytoremediation species were shown to actively remove P from the soil in the two contexts, the P content varied greatly across species. No species demonstrated foliar hyperaccumulation properties of P, but seed-sown corn (*Zea mays*) and Indian mustard (*Brassica juncea*) showed high P removal rates within their root tissues, up to 114 and 108 kg ha^{-1}, respectively (Delorme et al. 2000), which may make them strong candidates for terrestrial buffer plantings on downslope edges of farm sites, thereby preventing excess phosphorus from running off farm sites and entering nearby waterways. A further consideration for these two species is their potential to be further re-used as an animal food supplement or composted into a green fertilizer, given that P enrichment is not noted as harmful to farm animals, unlike heavy metals. One limitation to P being accumulated in below-ground tissues of these two species is that whole-of-plant harvests would therefore be necessary to remove the P-concentrated roots, and fibrous roots typical of these species could lead to the incomplete removal of plants and some P returning to the soil.

7.4 Ammonia

Ammonia nitrogen is a common toxicant derived from animal wastes as well as supplemental fertilizers. Ammonia nitrogen encompasses both the ionized form (i.e., ammonium NH_4^+) and the unionized form (i.e., ammonia NH_3). An increase in environmental pH favors formation of the more environmentally harmful unionized form (NH_3), while pH decreases favor the ionized (NH_4^+) form. NH_3 from poultry production is a major environmental concern for environmental pollution (Fig. 7.3). When birds consume protein, they produce uric acid, which is ultimately converted to NH_3 (Naseem and King 2018). Factors that increase ammonia outputs from poultry farms include soil pH, local climate, litter type, bird age, manure age, and barn ventilation (Naseem and King 2018).

Like P, NH_3 pollution is a common cause of the environmental degradation of wetlands and other water bodies and is attributed to fish kill events (Milne et al. 2000). However, the most common problems associated with NH_3 enrichment often relate to elevated concentrations negatively impacting fish growth and gill condition rather than rapid, mass mortality events (Milne et al. 2000).

Fig. 7.3 Poultry farm operations are a significant source of ammonia for adjacent water systems (Jordan 2011)

Table 7.1 Agricultural-origin NH_3 tolerance in aquatic macrophyte species

Species	Tolerance (mg/L)	Observations	Reference
Eichhornia crassipes	56–136	Survived 4 weeks, degradation of plant health noted in raw sewage (i.e., but not dairy manure)	Ayade (1998)
Hydrocotyle umbellata	136	Wilted on seventh day of test period in dairy manure	Sooknah and Wilkie (2004)
Lemna minor	7	50% growth inhibition reported	Wang (1991)
Pistia stratiotes	136	Wilted on seventh day of test period in dairy manure	Sooknah and Wilkie (2004)

There has been focused research on aquatic plant tolerance responses to NH_3 exposure (i.e., generated by agricultural wastes) which may reveal certain species as ideal candidates for within-wetland phytoremediation applications (Table 7.1). Vascular plants absorb three forms of nitrogen, namely, nitrate ions, urea, and ammonium ions (Kinidi and Salleh 2017). Once NH_3 is absorbed, it is broken down into chemical constituents and incorporated into proteins and other organic combinations through biochemical reactions. However, only the ammonium ions are assimilated into the organic molecules in the plant tissues by means of enzymatic processes (Masclaux-Daubresse et al. 2010). In the previous tolerance studies, plant health and survival were observed and recorded (Table 7.1), but not specifically NH_3 decontamination.

Given that ammonium and nitrate ions are principal sources of nitrogen, which support plant growth, phytoremediation and plant-based technologies are ideal solutions for such agricultural wastes. In a recent 2020 study, water quality improvements including NH_3, total suspended solids (TSS), and chemical oxygen demand (COD) were measured in a before-after experiment of aquatic macrophytes grown in wastewater (Abdul Aziz et al. 2020). It was found that *Lemna minor*, *Salvinia minima*, *Ipomoea aquatica,* and *Centella asiatica* were each able to reduce NH_3 by 80.4%, 89.9%, 97.3%, and 79.1%, respectively; TSS by 50.8%, 77.6%, 85.6%, and 67.6%, respectively; and COD by 75%, 82%, 44.8%, and 36.46%, respectively (Abdul Aziz et al. 2020). The *Ipomoea* species showed the strongest phytoremediation potential for NH_3 decontamination, while the *Salvinia* species was more effective at reducing TSS and COD. This demonstrates that mixed-species macrophyte plantings may provide a good "all around" solution for remediating wetland ecosystems which have water quality issues beyond increased NH_3.

Similarly, in a simulated microcosm study using polluted water sourced from Estero de San Miguel in the Republic of the Philippines, both NH_3 and P decontamination were investigated in a multi-factorial phytoremediation experiment featuring macrophytes transplanted into agricultural wastewaters (Acero 2019). Result revealed that a monoculture plantings of *Azolla pinnata* significantly lowered the NH_3 concentrations in the wastewaters over a 14-day period. Mixed species plantings of both *A. pinnata* and *Eichhornia crassipes* significantly lowered the P level of the wastewaters in the same time frame. Thus, both aquatic macrophyte species were fast acting in reducing both target pollutants and identified as potential phytoremediation options for aquatic environments in this tropical region (Acero 2019). While these results are promising, the tendency for both aquatic species to become invasive and form monocultures in wetland environments is worthy of careful consideration for environmental managers. Rezania et al. (2015) acknowledged this risk and proposed a range of controls that could be used in combination to manage *E. crassipes* in-situ as part of an integrated aquatic phytoremediation strategy, including combination of herbicides, integrated biological controls, and, ideally, watershed management to control nutrient supply (and therefore, restrict plant growth) although some of these environmental controls are more viable at large-scale than others, and the addition of chemicals including herbicides may significantly harm non-target species in sensitive wetland regions. Likewise, each of these control strategies could be evaluated for *A. pinnata,* as well as other aquatic species likely to become overabundant. Introducing any potentially invasive species into sensitive aquatic ecosystems is worthy of deep risk for a wetland system. A rigorous ongoing monitoring should be used.

7.5 Heavy Metals

A wide range of soils used for agricultural activities has been found to be contaminated with certain heavy metals, including Cadmium (Cd), Chromium (Cr), and Lead (Pb) (Nanda Kumar et al. 1995). In France, about 1% of 11,400 agricultural soil samples taken from across the country exceeded the national safe exposure limits for Pb (i.e., 100 mg kg^{-1}) (Mench and Baize 2004). Agricultural contamination of heavy metals, particularly those which bioaccumulate and impact food chains, is a critical risk to food security as well as ecosystem and community safety (Nanda Kumar et al. 1995). The investigation of heavy metal decontamination within the field of phytoremediation has received strong attention, particularly in other contexts, including mining activities and pollution from industrial processes. As of 2020, more than 450 different plant species from at least 45 angiosperm families had been identified as heavy metal hyperaccumulators (Suman et al. 2018). The aquatic macrophyte species *E. crassipes* has been examined in more than ten such phytoremediation studies of heavy-metal polluted water systems, demonstrating strong capacity to extract Cr (i.e., 65% removal) and Cu (i.e., 61–97% removal, depending on initial concentrations) from synthetic wastewaters and simulated wetland environments (Lissy and Madhu 2011; Mokhtar et al. 2011). In one study, which focused on decontaminating heavy metals from agricultural activities, *Zea mays* plantings were shown to be useful in accumulating both Cr and Pb from soils (Braud et al. 2009). Furthermore, bioaugmentation of siderophore-producing bacteria was shown to increase Cr and Pb accumulation in the plants by a factor of 5.4 and 3.8, respectively (Braud et al. 2009). A second field-based study conducted in Zhangshi, China, evaluated the phytoremediation efficiency of *Beta vulgaris* var. *cicla* in agricultural wastewater during a 2-month growing season (Song et al. 2012). These plants were directly exposed to agricultural wastewaters, which had elevated concentrations of Cd. The cultivar was found to accumulate 144.6 mg/ha of Cd over the course of the study. Amending the soil with supplemental organic manure was found to promote biomass increases of the plants, but inhibited Cd phytoremediation efficiency (Song et al. 2012).

These findings suggest that soil amendments aimed at increasing heavy metal uptake into plants should be reviewed on a species-specific basis. A deeper understanding of individual phytoremediator species and their potential interactions with the biotic and abiotic features of sites (e.g., including soil nutrients and rhizosphere activity) is important for achieving optimal outcomes for decontamination.

7.6 Insecticides

Insecticides are broadly defined as chemicals used to protect farmed plants and animals by killing insect species, preventing their reproduction, or deterring herbivory (Fig. 7.4). Insecticides are classified based on their chemical structures and

Fig. 7.4 A farmer manually applying pesticide to an open field (Balazs 2022)

modes of action and ecological research has examined their potential for unintended harm on non-target species, as well as residence time and degradation patterns in soils and water (Hedlund et al. 2019). Many insecticides are designed to act upon insect nervous systems (e.g., cholinesterase inhibition), while others act as growth regulators or endotoxins.

Systemic neonicotinoids are a sub-group of insecticides used to protect a wide variety of crop species. Based on their efficacy to control many insect pests and their systemic activity, they are used extensively in agriculture, so much so that by 2008, neonicotinoids accounted for one quarter of the global insecticide market (Jeschke et al. 2011) and this rate is increasing (Simon-Delso et al. 2014). However, increasing evidence indicates that this large-scale use results in high broad-spectrum insecticidal activity of the neonicotinoids even at very low dosages, and this has led to serious risk of environmental impact (Henry et al. 2012; Goulson 2013). Soil erosion from high-intensity agriculture facilitates the transport of insecticides into waterbodies (Kreuger et al. 1999). Some insecticides are accumulated by aquatic organisms and transferred to their predators, and insecticides by design are lethal to insects, so they pose a particular risk to aquatic insects, but they also affect other aquatic organisms (Goulson 2013). Accordingly, a recent study was designed to assess the neonicotinoid phytoremediation abilities of plant species commonly used in constructed wetland systems: *Acorus calamus*, *Typha orientalis*, *Arundo donax*, *Thalia dealbata*, *Canna indica*, *Iris pseudacorus*, *Cyperus alternifolius*, *Cyperus papyrus*, and *Juncus effusus* (Liu et al. 2021). Compared with the other neonicotinoids in the study, imidacloprid, thiacloprid, and acetamiprid were most readily removed by all plant species. Of note, *C. alternifolius* and *C. papyrus* exhibited the best phytoremediation performance for all six neonicotinoid types; the main phytoremediation mechanisms identified were plant accumulation and biodegradation (Liu et al. 2021).

Alternatives to neonicotinoids include organochlorides and pyrethroid-based insecticides. Pyrethroids can be very toxic to non-target aquatic organisms (i.e., arthropods are particularly sensitive) (Van Wijngaarden et al. 2005; Maund 2009), while several organochlorides are used extensively in agriculture, historically as well as presently (e.g., endosulfan and DDT), have been shown to accumulate in fish species (Darko et al. 2008) and are associated with biomagnification and harm to non-target species, including apex predators (Carson 1962). Using a water-based system, Riaz et al. (2017) evaluated the phytoremediation potential of macrophyte species *Eichhornia crassipes, Pistia stratiotes,* and a mixed algae species treatment (*Chaetomorpha sutoria*, *Sirogonium sticticum,* and *Zygnema sp*.) for removing organochlorine and pyrethroid residues from water. During the experiment, *P. stratiotes, E. crassipes* and all algae species showed insecticide removal efficiency, with 62%, 60%, and 58%, respectively for organochlorines, and 76%, 68%, and 70%, respectively for pyrethroids, with consistently higher concentrations of both pesticides detected in root tissues of the macrophyte species (Riaz et al. 2017). These results indicate aquatic systems for removing insecticides are worth consideration, particularly if farms are near natural water bodies. Insecticides are applied in various formulations and delivery systems (e.g., sprays (Fig. 7.4), slow-release diffusion) that influence their transport and chemical transformation after release. Mobilization of insecticides from farmlands into other ecosystems in the nearby vicinity can occur via runoff (i.e., dissolved or sorbed to soils), atmospheric deposition, or sub-surface flows (Goring and Hamaker 1972; Moore and Ramamoorthy 1984). Considering these scenarios, installations of aquatic macrophyte phytoremediators (e.g., as in-situ floating wetlands or tiered shoreline plantings between the pollutant sources and open waters) may provide low-cost protection from insecticide run-off for rivers, lakes, and wetlands alike.

7.7 Considerations for Tropical Regions

The tropics host one-third of the world's soils, which in turn support more than three-quarters of the world's population (Hartemink 2004; Kummu and Varis 2011). Tropical soils are influenced by highly variable weather patterns, with a predominance of high temperatures and abundant rainfall resulting in the effects of material weathering being more prominent than in other global regions. For example, Cuba tends to contain extensively weathered tropical soils, with 69.6% of soils exhibiting low organic matter and 43.3% with heavy erosion (Olivera Viciedo et al. 2018). As erosion is considerable in the tropics, the inherent deficiencies of weathered soil mean that for agricultural practices, supplementary fertilizers and nutrient enrichment will be necessary to support most food and textile crops in the future.

Considering this, more research on phytoremediation installations designed for P, NH_3, and other nutrient-enriching pollutants is merited, particularly vegetative buffer installations which can be designed to protect waterways and aquatic ecosystems that are sensitive to these chemicals. Further, insecticides are also noted to move off-target due to many factors, including improper application or unpredictable rainfall events, resulting in contamination of areas in the vicinity of agricultural practice and causing adverse effects on inhabiting species (Bish et al. 2020). Through better site management practices, including the implementation of protective vegetative buffer strips, off-target movement of pesticides and other agricultural pollutants can be decreased, while compound degradation and pollutant uptake can be increased via phytoremediation (McKnight et al. 2021). The main types of tropical soils, particularly oxisols and ultisols, differ from most temperate soils in terms of having low organic matter content, low pH values, and high levels of Fe oxides (Guerra Sierra et al. 2021). These soils are found in most of the tropical areas of Africa, the Asia-Pacific region, and Central and South America, coinciding with areas of high agricultural activity (Guerra Sierra et al. 2021; Caritat and Cooper 2011). Rather than a disadvantage, acidic soils can increase the mobility and bioavailability of certain inorganic contaminants (e.g., heavy metals), similar to chelating agents, which may promote the uptake of these pollutants more readily into phytoremediator species (Chen and Huang 2003).

Anthropogenic activities such as deforestation and habitat fragmentation affect the quality of various types of tropical soil, with the biodiversity of tropical forests severely impacted in the last century (Sala et al. 2000; Guerra Sierra et al. 2021). A major benefit of phytoremediation compared to other decontaminating technologies is that it increases site biodiversity both directly, via plant abundance and diversity increases (i.e., the latter for mixed-species plantings), and indirectly, by supporting pollinators and other insect species that use the plants for habitat (Garbisu et al. 2020). Bioprospecting for new, locally endemic tropical phytoremediator species, as opposed to relying on common crop species like *Zea mays* and *Beta vulgaris,* is an important goal for the field of phytoremediation (Prasad and De Oliveira Freitas 2003). Such species are pre-adapted to local soils and climate and are more likely to establish and self-sustain in these dynamic environments, as well as support and protect the biodiversity of tropical ecosystems.

Tropical wetlands also support critical ecosystem services for the planet, including carbon accumulation and storage (Donato et al. 2011), thereby providing resilience against accelerated global warming. These ecosystems are also some of the most biodiverse wetlands in the world for both floral and faunal species (Junk et al. 2006). Mangrove systems in particular are important rearing areas for fish and shellfish species and are responsible for 48% to near 100% of their population reproduction (Rönnbäck 1999). Ensuring these systems are protected from agricultural contaminants, as well as actively remediated when contamination is found to be present, provides more certainty that these critical services can be maintained for future generations. Beyond phytoremediation, there has been much progress in the field of constructed wetland systems for filtrating a wide range of pollutants. A review by Wang et al. (2017) demonstrated that properly designed constructed wetland systems can be a cost-effective strategy for removing a range of agricultural pollutants, including NH_4^+, total N, and total P, but a definitively "one-for-all design" does not exist. The performance of these systems varies with seasonal conditions as well as local operational parameters, including water flow rates. In addition to plant species selection, the optimization of other design criteria, such as pre-treatments, recirculation, forced aeration, and in-series landscape design, can substantially enhance contaminant removal, providing a sustainable and low-energy approach to agricultural wastewater management compared to traditional wastewater treatment facilities (Wang et al. 2017). Applying these engineering principles to planned phytoremediation installations would provide enhanced opportunities for effective aquatic decontamination, which could function in tandem with terrestrial barrier installations, to protect sensitive water systems from the ongoing agricultural processes which generate pollutants.

A further dimension for consideration of phytoremediation is that several secondary products have been proposed as ways to divert the plant material from general landfill and further increase the sustainability of this technology, including animal and fish feed, combustible briquettes for power generation, ethanol, compost, and construction fiber (Rezania et al. 2015). It is important to note that the process of phytoremediation may result in the plant waste becoming saturated with certain pollutants, particularly so in the case of bioaccumulating pollutants like heavy metals, although reducing landfill volume is an important goal for global communities. In the event the plant material has elevated pollutants, construction fiber and ethanol may be safer alternatives for tropical communities compared to using the plant material as stock feed or compost.

Lastly, plant-pollutant interactions should continue to be evaluated in the context of food safety and security in agricultural systems. Rice (*Oryza sativa*) is a wetland cereal crop (Fig. 7.5) belonging to the family *Poaceae* and is a food staple for over half the world's population (Muthayya et al. 2014). It is also noted to accumulate small amounts of As, Cd, Ni, and Pb from polluted agricultural waters (Sridhara Chary et al. 2008; Mao et al. 2019; Song et al. 2021). Of these heavy metals, Ni and Pb were found to exceed the safe limits for cereals and vegetables of the WHO (2010) and FAO (2007). While this species may be absorbing pollutants from agricultural waters, albeit in relatively small concentrations, the application of this species in polluted waters is not recommended if its end-use is intended for human or animal consumption.

7.8 Conclusions

A wide variety of anthropogenic pollutants are generated from animal and plant farming activities, and this is increasing in line with global productivity and population increases. Tropical regions are rich with agricultural activities, and certain pollutants, including animal wastes and other chemicals associated with farming, cause significant environmental degradation in surrounding ecosystems. Certain

Fig. 7.5 Rice produced in a monoculture field in tropical Indonesia (Fisk 2019)

pollutants have more phytoremediation data reported, for example, heavy metals including Cd and Pb. Other more ubiquitous, but less hazardous agricultural pollutants (e.g., P and NH_3) present an important opportunity for future investigation, given their widespread detection and potential impacts. Further in-situ research into phytoremediation systems tailored specifically for agricultural practices in tropical regions is merited, with strength in mixed-species terrestrial phytoremediation plantings as well as water-based systems. In addition, identifying new phytoremediator species that are locally endemic to tropical regions, as opposed to common crop species, can further support, and protect, the local biodiversity of valuable and vulnerable tropical regions.

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