B. B. Jana · R. N. Mandal
P. Jayasankar *Editors*

Wastewater Management Through Aquaculture

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ISBN 978-981-10-7247-5 ISBN 978-981-10-7248-2 (eBook)
https://doi.org/10.1007/978-981-10-7248-2

Library of Congress Control Number: 2017962306

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The efficient use of freshwater is an important concern for the future, because many areas in the world are facing water scarcity on a continual basis or during drought years. The major use of freshwater globally is for food production. Aquaculture is a particularly water-intensive activity, and it competes with traditional agriculture for freshwater in many areas. There is urgent need to improve water use efficiency in all types of agriculture – aquaculture included.

One way of improving water use in aquaculture is by increasing the intensity of production. The largest production sector is pond aquaculture, in which fertilizers are applied to increase the availability of natural feed or manufactured feeds are applied. Fertilized ponds already tend to be managed for the highest level of production possible. The production of aquaculture feed requires a large amount of water for producing plant meals included as ingredients. The water embodied in feed often greatly exceeds the direct water use in ponds. Thus, the opportunities for reducing water use in conventional pond culture through intensification are limited.

Wastewater aquaculture provides a means to lessen water use in ponds. By adding wastewater to ponds, an equal amount of freshwater is conserved. Wastewater also contains nutrients and this lessens fertilizer requirements in ponds. Thus, both water and nutrients are conserved. There is another benefit of wastewater aquaculture; natural processes in ponds remove nutrients, suspended solids, and organic matter from the wastewater. This improves the quality of the wastewater when it is ultimately discharged downstream.

Previous studies have revealed that fish from wastewater aquaculture are safe for human consumption. Nevertheless, there are areas of the world where consumers will not eat fish produced in wastewater. There are other areas where consumers will accept fish grown in wastewater, and wastewater aquaculture has considerable potential in these areas.

Considerable research has been conducted on wastewater aquaculture, but much remains to be done in order to realize the full potential of this resource. This book *Wastewater Management Through Aquaculture* provides a thorough, in-depth assessment of previous findings on the use of wastewater in aquaculture. It covers issues such as integrated planning and design of projects, health risks, production techniques, case studies, results of ongoing projects, and future research needs. The chapters have been prepared by respected scientists who have considerable experience with wastewater aquaculture. The coverage is quite complete, and I believe that this book will be of great interest to all who are involved in wastewater aquaculture or seek information about its potential.

Auburn, Alabama, USA
17 January 2017

Claude E. Boyd

Preface

It is needless to say that the demand for freshwater has been tripled during the last 50 years and is projected to increase by 70% in terms of surface water by 2025. Heavy demand of freshwater results in much depletion of groundwater level accompanied by withdrawal-driven groundwater pollution especially arsenic contamination in drinking water sources in many countries as well as pollution in surface water resources. As a result, concern has been raised about the quality and quantity deterioration of freshwater. Discharge of untreated or partly treated municipal wastewater causes contamination and eutrophication of inland water sources particularly in water-scarce and economically poor countries where facilities for conventional wastewater treatment are inadequate. Climate change has further aggravated the situation with its major implications on ecosystems and human life. It is most urgent to protect and conserve inland water resources to accomplish the ecosystem functionality and sustainable development processes. Hence, the present volume *Wastewater Management Through Aquaculture* has been a noble attempt which is the need of the hour.

In fact, municipal wastewater is the storehouse of fertilizers due to its immense nutrient potentials of phosphorus, nitrogen, and potassium and increasingly high rates of wastewater generation resulting from increased population and urbanization. Hence, wastewater has been rightly called as a resource out of place, and a huge sum of money in the form of chemical fertilizers is not only lost through unmanaged drainage of municipal wastewater every day, but it also causes environmental pollution and eutrophication of water bodies. Municipal wastewater poses a triple-win climate-smart agri-aquaculture strategy toward conservation of water for multiple uses, environmental protection, as well as food and nutritional security by turning wastes into wealth in the form of fish biomass and allied cash crops. Therefore, it is pertinent to respect society's discarded materials as resource. Lack of proper management of wastewater may result in triple losses – environmental degradation, monetary loss from fertilizers, and loss of valuable water source.

As the present and future scenarios of water crisis have been conceived worldwide, the cutting-edge researches and tailor-made solutions are in progress not only to protect and conserve valuable freshwater resources but also to use, reuse, and promote multiple uses of wastewater generated from various anthropogenic activities. Wastewater-fed aquaculture is a unique integrated biosystem in which organic wastes generated by the first system are used by the next subsystem for fish production as means of food and nutritional security mediated through an ecosystem resilient dependent self-purification process and microbial-autotrophic-heterotrophic complex food web mechanism. Though wastewater-fed aquaculture using more than 45 species of indigenous and exotic fishes has been practiced by farmers for a long time in a traditional way as self-wisdom, its scientific exploration and application of proven technologies have been focused in recent years for harnessing the resources in a sustainable way for water conservation and protection of biodiversity in wetlands.

Altogether 16 chapters have been compiled in the present volume, and the contents of this book have been broadly divided into four parts: (a) Understanding the Fundamentals of Soil-Water Interactions and Biogeochemical Nutrient Dynamics, (b) Culture Practices of Wastewater-Fed Aquaculture, (c) Strategies Toward Wastewater Reclamation Using Green and Sustainable Technologies, and (d) Economic Perspectives of Wastewater, Environmental Impact Assessment, and Environmental Law and Regulations.

Healthy soils are of utmost importance to a variety of ecosystem services they provide in aquatic systems. Pond soils act as a source or as a sink of nutrients depending upon the nutrient input and pond metabolism. In view of global cycling of carbon and climate change, the wetland ecosystem has a key role to control the balance of carbon, whether the system becomes a net carbon source or sink. An enhanced, holistic understanding of interactions between soils and overlying water and primary ecosystem drivers in mixed aquatic and soil systems is paramount to developing adaptive strategies to mitigate climate change and strategies for guiding their future construction and management to maximize their beneficial use while minimizing negative environmental impacts. The roles of different biogeochemical cycling bacteria such as heterotrophic, nitrifying and denitrifying, phosphate-solubilizing, and cellulose-decomposing bacteria as well as their activities on degradation and nutrient cycling of carbon, nitrogen, and phosphorus and autotrophic and heterotrophic food chain have been elucidated in a series of sewage-fed ponds placed in a waste stabilization pond system. Dominance of detritus food chain over the grazing food chain in all ponds within a waste stabilization pond system (anaerobic, facultative, and maturation) has been focused. The supremacy of facultative ponds has been reported to be most dynamic than the remaining ponds investigated. The importance of such basic understanding for encouraging healthy conditions and animal associations of the pond bottom particularly in wastewater-fed systems has been highlighted in the first part.

Wastewater-fed-aquaculture-related responses to counteract negative driving forces, pressures, and impacts associated with inadequate sanitation and wastewater treatment and to enhance the state of systems are systematically reviewed with the DPSIR framework. Prospects for a rational design-based approach to safe wastewater reuse using treatment lagoons and cutting-edge biorefinery approaches have been highlighted. Conditions required to support and promote safe wastewater-fed aquaculture are assessed using the STEPS (social, technical, environmental, political/institutional, and sustainability) framework. A SWOT (strengths, weaknesses, opportunities, and threats) assessment is presented concerning the future development of safe wastewater reuse through aquaculture. It is predicted that widespread adoption of wastewater reuse through aquaculture could contribute to achieving targets specified for sanitation and safe wastewater reuse by 2030 in accordance with the United Nations' Sustainable Development Goals. This demands the large-scale and rational uses of municipal wastewater worldwide especially in developing countries with enormous potentials of wastewater.

In developing countries, sewage-fed aquaculture has immense potential to develop into an effective alternate system of fish production in the backdrop of freshwater scarcity and increased farm income. Importance of nutrient harvesting from liquid wastes through aquaculture production in vertically integrated systems has been elucidated along with dominance of heterotrophic microbial pathway. High fish yield to the tune of 5 ton/ha/year at the downstream of the waste stabilization pond system testifies the ecological efficiency of wastewater in the conversion of wastes to wealth through aquaculture. This has been possible by the application of different aspects of management that has been developed through long-term dedicated researches of the country. However, urbanization pressure, improved economic condition, and betterment in the health quality standards warranted imposition of different safety standards in wastewater aquaculture and quality of the produce with respect to microbial load and other pollutants.

The significance of wastewater-fed aquaculture with unique case studies of the East Kolkata Wetlands, an important Ramsar site and one of the largest and oldest wastewater aquaculture systems of the world, has been focused that renders livelihood opportunity to a large section of local people through production of cheap protein food source – fish. However, maintenance of proper ecological conditions is of utmost importance in a wastewater-fed system as enhancement of fish production is often limited by suboptimal water quality and chemical stressors that cause manifestations of different diseases. However, such stress-sensitive manifestation of fish diseases often occurs in farmed ponds under the prevalence of suboptimal ecological conditions.

Sustainable production of fish yield or biomass in a wastewater system contaminated by inorganic and organic pollutants warrants the effective management of wastewater. As a part of enhanced treatment mechanism, application of ecological engineering is highly preferred in developing countries in view of low cost for natural, green, and sustainable technology based on nature's library in the tropical and subtropical zones, where the concept of an engineered resilient ecosystem is being applied to treat partially treated municipal wastewater for beneficial reuse and multiple uses. Macrophytes, microalgae, probiotics, annelids, mollusks, crustaceans, fishes, etc. have been rightly designated as living machines due to their immense beneficial biofilter potentials for remediation/reclamation of eutrophic water bodies, heavy metal-contaminated perturbed aquatic habitats, etc.

Various methods for bioremediation such as biostimulation, bioaugmentation, plant-based assisted bioremediation, phytoremediation, biofilm, periphyton-based bioremediation, biofloc technology, biodegradation, biotransformation, enzymatic bioremediation, recombinant DNA technology, biosorption, and nutriremediation have been presented in the third section. Apart from different basic methods employed for wastewater treatment, recent techniques such as cavitation, high-rate algal pond system, and biotechnology have also been elucidated. Application of nanomaterials such as carbon-based nanoadsorbents, metal-based nanoadsorbents, polymeric nanoadsorbents, nanomaterial-based membranes, and nanofiber membranes for water and wastewater treatment has been elaborated.

Among the technologies available, adsorption has widely been used for the removal of various contaminants from aqueous media, and accordingly different adsorbents have already been prepared over the years. The comprehensive, up-to-date, and critical information on the adsorption of different heavy metal pollutants by various types of biosorbents and polymer-based synthetic adsorbents has been documented. Nevertheless, the waste stabilization pond (WSP) system has gained its importance as an integral tool for treating wastewater as well as for linking with economic-driven activities of fish culture and culture of vegetable crops in aquaponic systems.

Aquaponics is a green and sustainable eco-technological approach integrating aquaculture in a hydroponic system and can play a pivotal role in harnessing nutrients from wastewater resources; it has been focused in the third section of the present volume. Concurrent production of fish crops and green vegetables or other medicinal aquatic plants can also fetch high income from wastewater that will lead to protection and conservation of wastewater by controlling the water loss through surface evaporation and promoting aquatic production through vegetable crops.

The fourth part deals with economic perspectives of water reuse potentials of treated wastewater in different economic-driven activities such as agricultural and landscape irrigation; industrial processes; athletic fields, schoolyards, and playgrounds; edges and central reservations of highways; irrigation of landscaped areas around public, residential, commercial, and industrial buildings; and many others. Partially reclaimed wastewater is used for decorative and ornamental purposes such as fountains, reflecting pools and waterfalls, etc. It is frequently used for fire protection and toilet and urinal flushing in commercial and industrial buildings. In general, low-quality wastewater is widely used for agriculture and aquaculture, whereas treated wastewater is exploited in high-income countries. Industrial water consumption was up to 22% of global water use. Industrial water use in Europe and North America accounted for half of their total water use, whereas in developing countries, it is about 4–12% of national water use. In the process of reusing wastewater in aquaculture, the externality costs are social costs incurred for public health protection as the system is associated with health risk. In order to perform a comprehensive cost-benefit analysis, it is necessary to evaluate all these environmental, social, and ecological impacts by valuing them in monetized way by eliciting people's willingness to pay (WTP), shadow price, and opportunity cost. Recycled water is often more expensive than existing water supply. Efficiency of wastewater recycling in developed countries should be increased to reduce the cost of supply of recycled water so that it can compete efficiently with alternative sources of water. Proper planning, management, and regulation are necessary for effective reuse of municipal wastewater for different activities.

The environmental impact assessment of the East Kolkata Wetlands (EKW) has been discussed using six generic steps. It also focused on the process of "initial environmental examination" (IEE) and "strategic environmental assessment" (SEA) which are recognized as the outcome of Agenda 21. Finally, impact analysis of cultured fishes through histological, histochemical, topological, and enzymological studies has been elucidated.

So far as the environmental law and regulations are concerned within the framework of the United Nations Conference on the Human Environment (1972), it laid emphasis on protection and improvement of environment for inter- and intra-generational equity. India as a participatory nation by 42nd amendment of the constitution incorporated provisions under Art. 48A and Art. 51A (g) for protection and improvement of natural environment. Consequently, by considering alarming effects of solid, liquid, or e-wastes on the environment, various rules are framed by the central government for establishment of regulatory authorities to manage the situation.

It is anticipated that the contents of the book will be useful to students, teachers, researchers, administrators, planners, farmers, and entrepreneurs who make a strong effort on the profitable use of wastewater within the framework of wastes into wealth for the welfare of human society and multiple uses of water in the hour of inevitable freshwater crisis. Further, this would help in achieving targets specified for sanitation and safe wastewater reuse by 2030 in accordance with the United Nations' Sustainable Development Goals.

We urge the readers to consider different innovative technologies and to utilize the low-tech traditional knowledge of the locals to explore the tailor-made appropriate solution to counter the negative impact of environmental pollution caused by discharge of untreated wastewater and promote the safe multiple uses of treated wastewater for societal sustainable development, especially for food and nutritional security and allied economic activities toward conservation of water and protection of our invaluable biodiversity as well as sustaining the clean and green Earth.

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Acknowledgments

The editors would like to thank the director of ICAR-CIFA, Bhubaneswar, for initiating the proposal of the present volume. We thankfully acknowledge the management of Springer Nature, especially their office in Delhi, India, for their helpful cooperation and kindly agreeing to publish the manuscript of the present book. We also record our sincere thanks to all the contributors for their timely submission of the respective manuscripts.

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B. B. Jana a fellow of the National Academy of Agricultural Sciences, New Delhi, as well as some other prestigious academies in India and recipient of the Joy Govinda Memorial Award of the Asiatic Society, is emeritus fellow and academic advisor in the International Centre for Ecological Engineering, University of Kalyani, West Bengal, India. He did his doctorate on aquatic ecology and microbiology and worked as postdoctoral fellow of the then USSR and DAAD visiting fellow in the University of Hamburg, Germany. He has published several monographs, books, and contributed chapters in the UNESCO Encyclopedia and over 235 papers in peer-reviewed journals and supervised 32 Ph.D. students. As a principal investigator, he is the recipient of many national and international projects funded by the European Commission, GTZ and TTZ, ICAR, UGC, CSIR, DST, DBT, DOEn, the government of India, etc. His domain of research includes wastewater aquaculture, ecological sanitation, eco-restoration, ecological engineering, microbial nutrient cycling, integrated organic farming, impact of global warming and climate change in aquaculture, water conservation, etc. A board member of the International Ecological Engineering Society, Switzerland, and editorial board member of several important journals, Professor Jana has extensively traveled abroad and chaired and/or participated and invited speakers in many international conferences held in many countries of the world. At present, his passion is eco-sanitation particularly for the use of human urine as alternative chemical fertilizer. One of his papers published in *Ecological Engineering* has been highlighted in News@Nature.com (doi: https://doi.org/10.1038/news070625-13). His another current publication on human urine has also been highlighted and covered in the *IndUS Business Journal* (http//indusbusinessjournal.com), August 28, 2016, which reads as "Now human urine as an organic alternative to chemical fertilizers" (http//indusbusinessjournal.com/2016/08/now-humanurine-organic-alternative-chemical-fertilizers/). As a secretary, his mission has been focused on outreach programs and extension activities at the grassroots level which are being implemented through his own founded NGO, Kalyani Shine India (www.kalyanishineindia.org), also known as the Centre for Environmental Protection and Human Resource Development, aimed at alleviating rural poverty and ensuring protection and conservation of biodiversity, environment, and water resources.

R. N. Mandal did his M.Sc. and Ph.D. in Botany from the University of Calcutta. Presently, Dr. Mandal has been in the position of principal scientist in the Aquaculture Production and Environment Division (APED), Indian Council of Agricultural Research-Central Institute of Freshwater Aquaculture (ICAR-CIFA), Rahara, Kolkata, West Bengal, India. Dr. Mandal is now working on wastewater-fed aquaculture as the principal investigator in a sewage-fed aquaculture farm in Rahara and deals with different aspects of sewage-fed aquaculture in farmers' field in East Kolkata Wetlands (EKW). He has been working on the management of both aquatic and wetland plants, including utility of beneficial flora and removal of nuisance ones, in the perspective of aquaculture. He has also guided students for their master's dissertation. He has published a number of articles in refereed scientific journals of high repute.

P. Jayasankar has spent 31 years as a researcher in fisheries, including fishery biology and fish stock assessment, phenotypic/genotypic stock structure analysis, evaluation of genetic heterogeneity and molecular taxonomy/DNA barcoding (fish, shellfish, and cetaceans), genetic linkage mapping and QTL, genomic selection, molecular marker-based fish hybrid identification, and transgenics. Recently, Dr. Jayasankar has taken up research on environmental DNA (eDNA). He has published over 150 peer-reviewed papers and books and edited book chapters. He has also guided eight students for their master's and Ph.D. dissertation. As a research and administration manager (ex-director of ICAR-CIFA, Bhubaneswar, India), he contributed toward extension of freshwater aquaculture technology and established linkages among researchers and the industry.

Acronyms

ALPase	Alkaline phosphatase
AB	Ammonifying bacteria
AOB	Ammonia-oxidizing bacteria
EKW	East Kolkata Wetlands
LEISA	Low-external-input sustainable aquaculture
BCR	Benefit-cost ratio
BFT	Biofloc technology
BOD	Biochemical oxygen demand
BMP	Best management practices
CIFA	Central Institute of Freshwater Aquaculture
CPCB	Central Pollution Control Board
CER	Cost-effectiveness ratio
C:N:P	Carbon-nitrogen-phosphorus
COD	Chemical oxygen demand
CREAMS	Chemicals, runoff, and erosion from agricultural management systems
DNB	Denitrifying bacteria
DO	Dissolved oxygen
DPSIR	Driving forces-pressures-state-impacts-responses
DWF	Dry weather flow
EIA	Ecological impact assessment
EIA	Environmental impact assessment
ETA	Ethanolamine
FAO	Food and Agriculture Organization
FACWet	Functional assessment of Colorado Wetlands
FAME	Fatty acid methyl ester
FCR	Food conversion ratio
FQA	Floristic quality assessment
FSH	Follicle-stimulating hormone
EKWL	East Kolkata Wetlands location
GLEAMS	Groundwater loading effects of agricultural management systems
GPP	Gross primary productivity
HB	Heterotrophic bacteria
HRAPs	High-rate algal pond system

HPI	Hypothalamic-pituitary-interrenal
ICAR	Indian Council of Agricultural Research
ICER	Incremental cost-effectiveness ratio
IEE	Initial environmental examination
IMTA	Integrated multi-trophic aquaculture
IRR	Internal rate of return
IUCN	International Union for Conservation of Nature
IWMED	Institute of Wetland Management and Ecological Design
KMWSA	Kolkata Municipal Water Sanitation Authority
LIM	Landscape integrity model
LH	Luteinizing hormone
MFC	Microbial fuel cell
NF	Nanofiltration
NRCP	National River Conservation Plan
NPV	Net present value
NPP	Net primary productivity
NB	Nitrifying bacteria
NFB	Nitrogen-fixing bacteria
NPK	Nitrogen (N)-phosphorus (P)-potash (K)
NFT	Nutrient film technique
NWI	National Wetlands Inventory
OC	Opportunity cost
PCR	Polymerase chain reaction
PEG	Polyethylene glycol
PFC	Proper functioning condition
PPTA	Project preparatory technical assistance
PNCs	Polymer-clay nanocomposites
PMB	Protein-mineralizing bacteria
ROS	Reactive oxygen species
SEM	Scanning electron microscope
SDGs	Sustainable Development Goals
SGOT	Serum glutamate oxaloacetate transaminase
SGPT	Serum glutamate pyruvate transaminase
STP	Sewage treatment plant
SPC	Standard plate counts
SPCB	State Pollution Control Board
STEPS	Social, technical, environmental, political/institutional, and sustainability
EIA	Environmental impact assessment
SWOT	Strengths, weaknesses, opportunities, and threats
TFC	Thin-film composite
TFN	Thin-film nanocomposite
TMDL	Total maximum daily load
TOC	Total organic carbon

TOD	Total organic dissolved
UN	United Nations
USEPA	United States Environmental Protection Agency
VIBI	Vegetation index of biotic integrity
WQI	Water quality index
WSP	Waste stabilization pond
WHO	World Health Organization
WTP	Willingness to pay
ZWEAPS	Zero-water exchange aquaculture production system

Part I
Understanding the Fundamentals of Soil-Water Interactions and Biogeochemical Nutrient Dynamics

Chapter 1
Understanding the Soil-Water Interactions for Sustainable Ecosystem Services in Aquatic Environments

B. B. Jana, S. Lahiri, D. Ghosh, J. N. Bhakta, S. Mandal, and S. K. Bag

Abstract Healthy soils are of the utmost importance to society for the variety of ecosystem services they provide in both terrestrial and aquatic systems. Within aquatic systems, soils play an active role in carbon cycling and interactions between soils and water, and additional components of aquatic ecosystems can control the balance of carbon, whether the system becomes a net carbon source or sink. Understanding the interactions between soils and overlying water is crucial to developing adaptive strategies to mitigate climate change. An enhanced, holistic understanding of primary ecosystem drivers in mixed aquatic and soil systems is paramount for guiding their future construction and management to maximize their beneficial use while minimizing negative environmental impacts. Aeration and water circulation devices can be used to improve dissolved oxygen content of the wastewater pond system. Raking may be practiced to improve the ecological conditions of pond soils for encouraging healthy conditions and animal associations of the pond bottom particularly in wastewater-fed systems. The present chapter provides a review of different aspects of soil-water interactions and strategies to maintain ecosystem health for sustainable development.

Keywords Soil structure · Mud-water exchange · Soil composition · Biological production

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B. B. Jana et al. (eds.), *Wastewater Management Through Aquaculture*,
https://doi.org/10.1007/978-981-10-7248-2_1

1.1 Introduction

Healthy soils are vital for maintaining robust biological production in aquatic ecosystems. The interactions between physical, chemical, and biological properties of soil help regulate aquatic ecosystem function, and soil can play a role in damping or amplifying the effects of environmental perturbations on aquatic systems. In addition to overall health, soil also plays an active role in carbon cycling in aquatic systems. In different cases, soils can act as either a carbon sink (Boyd et al. 2010) or source of carbon emission (Natchimuthu et al. 2014). Hence soils not only play an important role in the nutrient dynamics and productivity of aquatic ecosystems but also, through the carbon cycle, in climate dynamics. Understanding the functional connectivity (e.g., nutrient supply, biogeochemical cycling, etc.) between soils and aquatic ecosystems is crucial to developing a thorough, fundamental understanding of these dynamic systems, as well as being able to predict how the systems will respond to environmental perturbation and what adaptive strategies can be implemented to improve aquatic ecosystem resistance and resilience to this change. The role of soils in aquatic ecosystems is thus pertinent to developing adaptive strategies to mitigate climate change. Wetlands and large-scale aquaculture ponds provide multiple test cases for probing mechanisms of soil-water interactions and their influence on the productivity of aquatic ecosystems. An enhanced, holistic understanding of primary ecosystem drivers in mixed aquatic and soil systems is paramount for guiding their future construction and management to maximize their beneficial use while minimizing negative environmental impacts.

1.2 Ecology and Productivity of Wetlands

An aquatic environment can be conceptualized as an ecosystem containing interacting biotic and abiotic components hosted in a permanent or seasonally water-saturated zone. The biotic component of pond ecosystem consists of autotrophs and a suite of micro- and macroconsumers and saprotrophic organisms. The primary abiotic factors include water, soils, nutrients, and the local climatic regime (Fig. 1.1).

Soils can provide a source of vital nutrient inputs necessary for biological productivity. For instance, decomposable biomass in the water column may accumulate at or within the soil surface where biological activity can remineralize the nutrients to make them available to fuel additional primary productivity or heterotrophic interactions. In this role, soils regulate the biological productivity of the wetland through decomposition and degradation of organic matter through the consumptive actions of a vast array of bacteria, flagellates, fungi, and macro- and microinvertebrates that live at or near the soil-water interface. While aquaculture ponds have some fundamental distinctions from natural systems (e.g., additions of anthropogenic fertilizer to these ponds may shift traditional nutrient limitations),

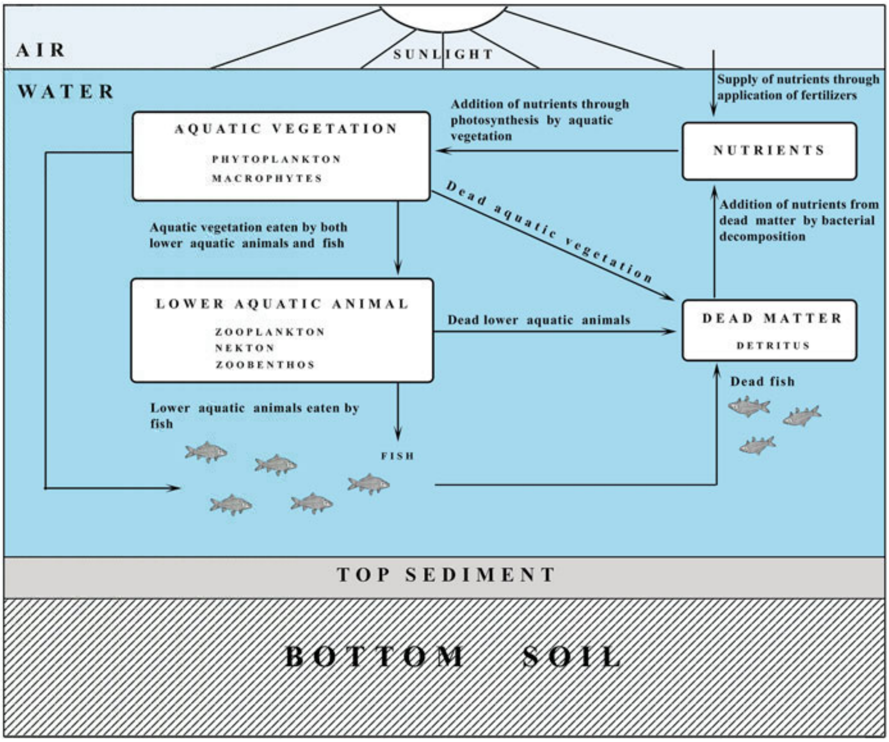

Fig. 1.1 A pond ecosystem showing the interactions of abiotic and biotic factors and food chain dynamics. Top sediment and bottom soil of aquatic system are also shown

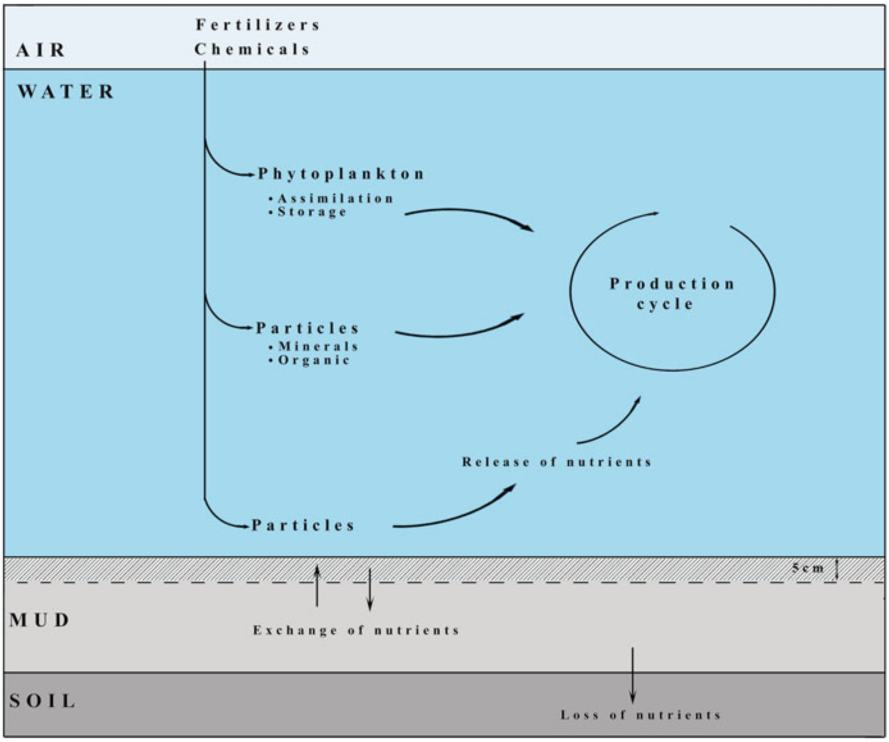

Fig. 1.2 Fate of fertilizers and manure in fish ponds: Most of the particles settle on the top of the mud layer and are released as nutrients for the production cycle in the water column

soils are nonetheless still crucial to overall nutrient cycling. For instance, in organic, manure-fed fish ponds, a large part of fish production can be linked to microbial processes that remineralize the added organics in the soil and make these nutrients available to stimulate fish productivity (Fig. 1.2). This cycling highlights a vulnerability of the aquatic system since decreased soil health can ultimately constrain overall system health and productivity. Further, if soil is unable to actively recycle the added nutrient pool (manure) contained in the municipal wastewater, this could trigger the buildup of the added material and ultimately the transition from the manure being a community resource into an effective waste component.

With a view to enhance reclamation process, more utilization of major food resources, reuse of wastewater for economic-driven activities, and promotion of climate-resilient aquafarming, selection of species of fish in wastewater-fed aquaculture is of major importance. The selected species should be hardy so as to capable of withstanding relatively adverse ecological conditions due to wide diurnal fluctuations of dissolved oxygen and pH of water. In general, cultured fishes of different feeding habits occupy different habitats and ecological niches such as herbivores, detritivores, carnivores, and omnivores. Because of the feeding preference for algae and vegetation, herbivorous fishes such as silver carp and grass carp are well known as low-carbon footprint species, and they are often selected for fish culture. Benthic-oriented species such as common carp, black carp, and tilapia are most suitable species for culture as they consume mostly the benthic invertebrates, decayed vegetation, and detritus available on the pond. Further, bottom-dwelling fishes help reclaim wastewater through physical bioturbation-driven sediment oxidation inducing microbial activities providing congenial environment for nutrient release to the overlying water.

1.3 Structure of Wetland Soils

The soil structure underlying an aquatic system can, at its most fundamental level, be divided into two major divisions: a deeper, bottom soil zone and an upper, top sediment that forms above the bottom soil. Bottom soils themselves can be subdivided to include a more shallow layer which is lighter in color, less compacted, and fairly well aerated and is compositionally a mixture of colloidal mineral and organic matter. The underlying lower layer of the bottom soil, in contrast, is generally anoxic, darker in color (e.g., gray or black) due to the resulting geochemistry (low redox potential, high abundance of ferrous iron and other minerals), and more compacted than the upper layer. The topmost flocculent layer (F) and both oxidized and reduced sediment layers (S) of soil profiles have been emphasized in aquaculture pond because of their roles in nutrient exchange with overlying water and the influence of interaction on water quality (Boyd 2012). Further, the proportions of these two layers are also important in regulating the soil properties and productivity of the ponds. Hence, the top sediment layer of pond is constantly in direct contact with overlying water and performs the exchange mechanism.

At some level, the physical, chemical, and mineralogical features of pond soils are highly similar to those of agricultural soils. Yet, there are specific distinctions between pond and agricultural soils including the following: (1) conglomeration of different soil profiles, which are completely waterlogged, devoid of air-filled spaces, and depleted of oxygen, (2) ponds may have large catchment areas with input of nutrients and soil particles from the neighboring catchment areas and runoff water, (3) sedimentation of organic matter on the pond bottom, and (4) the 10–15 cm surface layer of pond soils tends to have a lower bulk density than found in surface of agricultural soils. Pond soils are also similar to wetland soils, although high-density aquatic vegetation is generally absent in managed aquaculture ponds, despite the fact that nutrient inputs in aquaculture ponds are typically much higher than for pristine wetlands. Wastewater-fed ponds tend to have more sedimentation or accumulation of organic matter contained in the sewage effluents.

Bottom soils influence a variety of water quality conditions in aquaculture ponds including pH, alkalinity, hardness, electrical conductivity, dissolved gases, total nitrogen, organic carbon, available nitrogen, C/N ratio, available phosphorus, and exchangeable calcium. The dynamics of nutrient cycling required for maintenance of these conditions for biological production are controlled through a series of chemical and biochemical reactions that occur at the soil-water interface. These reactions result in the release of essential and beneficial nutrients into the overlying water. The transformation of fertilizers added to aquaculture ponds also influences nutrient cycling. Moreover, bottom soils act as both nutrient sources and sinks depending upon their trophic state, and because the organic matter in pond soils increases over time, the nutrient content is usually higher in older ponds than in newly constructed ponds. For these reasons, bottom soils have been rightly called the chemical laboratory or kitchen of the pond. This is particularly true for wastewater-fed ponds.

Pond soils also impact the bioavailability of heavy metals, toxic elements, and pesticide residues in the water column by adsorption and desorption processes that occur in the bottom sediments. For example, toxic metabolites entering the well-oxygenated ponds may be quickly oxidized and have less toxic effects, but if the amount of toxic elements exceed the oxidation rate of the metabolites, the equilibrium levels of metabolites in the water can have detrimental effects on biotic community (Boyd et al. 2002).

1.3.1 Soil Formation

The formation of soil in aquatic systems is a dynamic process and depends upon a number of typical soil-forming factors including weathering, erosion, leaching, sedimentation, parent material, etc. Erosional processes (e.g., alluvial, fluvial, or resulting from bioperturbation) can introduce particulates into a pond. Two main processes can then aggregate these small particulates into larger structure: (1) electrochemical bonding in which the aggregation of negatively charged colloidal clay and/or humus particles are brought together to bridge water molecules and metallic ions, particularly calcium (Fig. 1.3), and (2) cementing, which involves the action of substances adsorbed on the surface of soil particles that effectively glue them together.

1.3.2 Soil Composition

The composition of soil plays a pivotal role in the biological productivity of aquatic systems. Soil texture is one of the important physical factors, whereas chemical factors such as soil reactivity (i.e., through pH) and nutrient status determine the water holding capacity and productivity of a pond. The elemental composition of various components combined with the organic matter content influences the chemical and biological properties of the soil.

Pond soils grouped as alluvial, black, red, and laterite soils are known to have higher amount of clay, silt, cation-exchange capacity, Ca, Mg, P, N, and organic

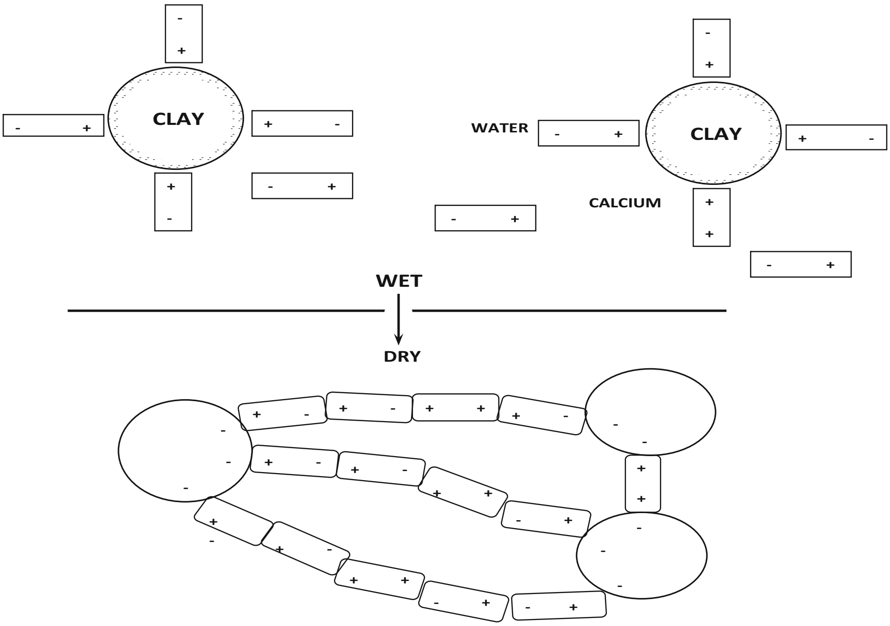

Fig. 1.3 Electrostatic bonding of clay particles in wet and dry conditions (Source: Boyd 2012)

matter with higher resulting water retention capacity than comparable terrestrial soils. Soils dominated by clay and silt tend to have high adsorptive and retention capacities for moisture, gases, and nutrients due to their large surface areas. Sand bottom and high clay bottom soils are not preferred for aquaculture because nutrients are either lost due to heavy leaching (sandy) or because high adsorption capacity removes nutrients from the overlying water (clay), resulting in poor recycling to the water column and reduced productivity. Sand and sandy loam soils are also typically low in colloidal clay and deficient in humus, whereas heavier soils contain more clay and more organic matter. Laterite soils are poor in phosphorus, potassium, calcium, and nitrogen and are usually acidic in reaction.

1.3.3 Clay Particles

Clay particles are generally considered to have a prominent role in maintaining water levels in constructed pond since layers of clay can vastly reduce water permeability, allowing water to be retained in a pond. Clay particles form layered structures typically categorized as a two-layer (e.g., kaolinite) or three-layer structure (e.g., montmorillonite). These structures are malleable and cohesive, capable of being molded into highly plastic forms. Water loss through an underlying soil horizon by seepage is a common phenomenon in pond without clay soil. For