

**Experimental investigations of leaching of sodium,
calcium, potassium, and zinc through refuse soil from
Boragaon Landfill (Guwahati)**

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by
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CERTIFICATE

This is to certify that the thesis entitled “**Experimental investigations of leaching of sodium, calcium, potassium, and zinc through refuse soil from Boragaon Landfill (Guwahati)**”, submitted by ***Pranab Jyoti Barman (Registration No. 07610409)*** is a bonafide research work carried out by him under our supervision. The thesis work, in our opinion has reached the standard for fulfilling the requirement for the award of the Degree of Doctor of Philosophy. This work has not been submitted earlier for the award of any degree to the best of our knowledge and belief.

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ABSTRACT

Landfills are one of the prominent forms of disposal of waste generated from urban areas. The waste dump landfills interact with atmosphere, rainwater, and soil moisture and produce landfill leachates. The leachate may migrate through the vadoze zone and cause pollution of the subsurface aquifer. In recent years, public as well as scientific community have raised intense concerns over pollution of groundwater resources due to spillage of hazardous elements from land surface to the underlying aquifer. This entire environmental phenomenon of landfill leaching is one of the most important issues of concern in urban areas.

Landfill leaching is also an important environmental matter of concern in the city of Guwahati, Assam, India. Unscientific dumping of wastes are observed in many commercial centers, in and around the city. The effort of municipal authority to prevent such dumpings has become unsuccessful due to lack of infrastructure as well as civic sense of the citizens. The Guwahati municipal authorities have earmarked the site at Boragaon, near Deepor Beel, as the location to dispose all the municipality wastes generated from Guwahati. Deepor Beel is a wetland of international importance since it is the only Ramsar site of the North Eastern India. Though scientifically designed landfill waste dumps are planned for the site, the project is not fully functional and the municipal wastes are dumped near Deepor Beel. The landfill was initially designed as a controlled landfill for an estimated capacity of 50 tons per day for an active period of 10 years. However, due to rapid urbanization as well as population growth, the daily waste generation exceeds the holding capacity of the present landfill. Therefore, the wastes are dumped in an unscientific way at Boragaon. These unscientifically dumped wastes consist of many harmful and toxic elements such as zinc (Zn), chromium (Cr), nickel (Ni), lead (Pb), etc. that can cause different types of pollution to the environment. The wastes may also contain nutrients like sodium, calcium, and potassium, etc. that may potentially leach to the surface and subsurface water bodies. Experimental and analytical

investigations of leaching of above components are essential to bring scientific inferences on environmental impacts due to such unscientific waste disposals. Therefore, there is a need for scientific investigation of this acute environmental problem at Boragaon site, to arrive at effective remedial measures to be adopted by the local municipal authority.

Targeting the above needs, the present research study aims to understand the leaching mechanisms of heavy metal and nutrients from the refuse soils of uncontrolled landfills of Boragaon waste dump site. The refuse soil from the landfill site and the locally available normal soil were used in the experimental investigation using column apparatus. The experiments investigated the influence of various factors like the height of the landfill refuse soil, height of base soil layer (or normal soil layer), and inflow filling rate of water, on leaching of a heavy metal, Zn, and some nutrient elements like Na, Ca, and K. For this purpose, three different types of column leach apparatus – viz. short cylindrical column, long rectangular column, and three-dimensional trapezoidal column are fabricated. In the column leach apparatus, landfill refuse soil is stacked over the normal soil. Water is poured from the top, of the column, using a regulatory device in such way that it mimics the rainfall scenario. The effluent liquid coming out from the bottom is collected at various time intervals and using Atomic Absorption Spectrometer (AAS) and flame photometer, the concentration of various elements are determined in the effluents.

The above experiments were categorized into various combinations based on – height of landfill refuse soil; height of base soil layer; water ponding depth; and inflow filling rate. From the above categorized experiments, various inferences as well as the influences of these parameters, on leaching, are drawn from the concentration versus time data of the nutrients and heavy metal. Besides, empirical analysis is also performed to determine the relationship between the leached concentrations of the nutrients, in the effluents, and the aforementioned geometrical and temporal parameters. The regression relations – linear; polynomial;

logarithmic; and exponential equations were tested on the experimental data for empirical model development and the exponential empirical models predicted well the concentrations of nutrients for the independent experiments, which were not part in the model development. The statistical interpretation of Zn leaching through the two-layer soil system indicates the desorption of Zn from the refuse soil into the percolating water.



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NOMENCLATURE

Atomic Absorption Spectrometer	-	AAS
Concentration of nutrient specie	-	C_i
Cation Exchange Capacity	-	CEC
Concentrations of Na (in ppm)	-	C_{Na}
Concentrations of Ca (in ppm)	-	C_{Ca}
Concentrations of K (in ppm)	-	C_K
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Weight of the core cutter (in g)	-	w_2
Water content of soil in percent	-	w
Mass of the container with lid (in g)	-	W_1
Mass of the container with lid along with wet soil (in gm)	-	W_2

Mass of the container with lid along with dry soil (in gm)	-	W_3
X-Ray Diffraction	-	XRD
X-Ray Fluorescence	-	XRF
Bulk density (g/cm^3)	-	γ_1
Dry density (g/cm^3)	-	γ_2
Figures are shown above the caption	-	$\uparrow$
Figures are shown below the caption	-	$\downarrow$



CHAPTER

1

INTRODUCTION

1.1 General

Solid waste disposal has emerged as a major environmental problem for most of the urban centres all over the world. About one- to two-third of the solid wastes that are generated are not collected. The uncollected wastes are dumped in an unscientific manner in the streets and drains, contributing to flooding, breeding of insects and rodent vectors, and spreading of diseases. Sometimes the collected wastes are incinerated in an improper way that may pollute water resources and air. Further, the dumping of electronic wastes enhances the problem as it may release highly toxic carcinogenic agents into the environment. The wastes are produced from various sources and are described as follows (McBean et al., 1995):

Residential waste: The wastes that are discharged from single and multifamily dwellings are defined as residential wastes. The residential wastes include various categories like food waste, garden waste, paper products, metals, glass and ceramics, plastics, rubber and leather, wood and rocks, dirt and ashes, etc.

Industrial waste: Industrial wastes are produced from various industrial operations like processing, manufacturing, and packaging, etc.

Commercial and Institutional waste: Commercial wastes are generated from various activities like retail, wholesale and service establishments. Institutional solid wastes are those produced from hospitals, schools, and municipal or local body offices.

Waste management is a burning problem for most urban centers. In the course of time, various regulations are imposed for environmental safety. The main purpose of these regulations is to take care of human health and environment in the emergence of industrial growth. This objective requires adopting effective remedial measures for existing waste disposal sites and closing them with properly designed features.

1.2 Basic strategies for solid waste management

The basic strategies which are adopted for solid waste management are described as follows (McBean et al., 1995):

- a) Source reduction:** Reducing the quantity of material required for disposal can be achieved in a number of ways, which are furnished below.
 - i) Products should be purchased with minimal packaging.
 - ii) The amount of waste produced may be reduced by designing and manufacturing the product with minimum toxic content and with increased durability.
- b) Reuse:** The principle of reuse is to find out another or similar product from the parent product rather than discarding it. Refurbishing old appliances, reupholstering old furniture, and repairing old automobiles are some examples of reuse.

- c) **Recycling:** Changing of the material into another usable form is the principle of recycling. Composting, use of deinked newsprint for paper manufacturing are some examples of recycling.
- d) **Energy from waste incineration:** Utilisation of heat energy from incineration of waste material is a popular method that is adopted.
- e) **Landfilling:** The waste that cannot be resold and not recyclable are ultimately disposed of in a landfill.

Landfilling is considered as the simplest and, cheapest form of disposal methods. So historically, it has been accepted as a popular method of solid waste disposal in many developing countries. The main aim of landfilling is safe disposal of solid waste, which should be carried out without causing any damage to environment as well as public health. Landfill gas and leachate are the two main emissions from the processes, which should be controlled and treated as far as possible. It was estimated by **Gendebien et al. (1991)** that 10^9 m^3 of landfill gas produced annually from domestic solid waste, which is equivalent to 345 million tonnes of oil. If these landfill gases are allowed to diffuse freely from landfill sites where methane is a dominant greenhouse gas, it may cause substantial damage to the environment (**Doughall et al., 2001**).

Landfilling is also a popular waste disposal method in the sense that it can deal with all materials in the solid waste. There are various other options of waste disposal such as biological or thermal treatment, which again produce waste residues that subsequently need to be landfilled. Therefore, landfilling is inevitable in any solid waste management system. Landfilling may be considered as a waste treatment process instead of a method of final disposal (**Finnveden, 1995**). Landfilling is adopted as waste disposal method in several

European countries as well as in U.S.A. However, selection of suitable site is a difficult task due to rise of land prices.

1.3 Design criteria of landfill sites

Some of the design criteria, which are adopted for location of landfill sites, are briefly presented below (Sharma and Lewis., 1994).

- a) **Location restrictions:** Municipality solid waste landfill should be located at least 10000 feet beyond any airport runway.
- b) **Floodplain:** The location of landfill should be such that it should not restrict the flow of 100-year floodplain.
- c) **Wetland:** Municipality solid waste landfill should not be located near wetland since dumping of waste may damage various flora and fauna.
- d) **Fault areas:** The location of a municipality solid waste landfill should not be within 200 feet of a Holocene fault.
- e) **Seismic impact zones:** Municipality solid waste landfill unit and all its component units including leachate collection system should be designed in such a way that it may resist the maximum horizontal acceleration in event of an earthquake.

1.4 Harmful elemental components in landfill

Disposal of electronic wastes or e-wastes is one of the major issues of environmental safety for the metropolitan cities. Many hazardous elements like lead, chromium, cadmium, etc., which are present in the wastes are highly carcinogenic. Harmfulness of some of the elements is described below (Berkowitz et al., 2014).

Cadmium: Cadmium compounds are classified as human carcinogen by several regulatory agencies. Some studies indicate that occupational cadmium exposure is related to lung cancer.

Chromium: Chromium can attach strongly to soil and only a small amount can move deeper into the underground soil. Skin contact with certain chromium compounds may cause skin ulcers.

Lead: Lead is utilized mainly in the manufacture of acid storage batteries. The adverse effects of lead are indicated by high blood pressure. Lead interferes with the synthesis of red blood cell and causes anaemia.

Nickel: Nickel, which is leached from dumpsites, may contribute to pollution of groundwater. Acid rain mobilizes nickel from soil and enhances leaching into aquifer. Nickel carbonyl is most acutely toxic nickel compound. The effects of acute nickel carbonyl poisoning include frontal headache, nausea, vomiting, insomnia, and irritability.

1.5 Need of the study

Guwahati is the state capital of Assam and is the biggest city in North-East India. In recent years, due to rapid urbanization, there are many unplanned developmental activities taking place along with the planned ones. A major concern in this city is similar to other urban or metro areas facing the problem of solid waste disposal. It has been observed that disposal of waste in most parts of Guwahati city is not appropriate. The wastes are dumped unscientifically that cause un-hygienic scenarios (Fig. 1.1).



Fig. 1.1 Landfill site of Guwahati city



Fig. 1.2 Proposed scientific landfill site of Guwahati city

There is lack of planning for proper disposal of municipality wastes. The landfill site was earlier planned in an open field near the place ‘Six mile’ of Guwahati city. However, due to strong public protests, the landfill site was proposed at Boragaon, which is near Deepor Beel. The location of Deepor Beel is about 10 km southwest of Guwahati city. Deepor Beel

is an important riverine wetland of Assam and is famous for its rich biological diversity. Deepor Beel is also the only major storm water storage basin for Guwahati city. During winter season, large number of migratory birds is seen in Deepor Beel. Birdlife International has selected Deepor Beel as one of the Important Bird Area (IBA) sites. Deepor Beel was recognized as a wetland of international importance and Ramsar Site in November 2002 (Singh, 2011).

The local municipality decided to establish scientific landfill at the proposed site at Boragaon (Fig 1.2). However, the project of scientific waste landfill is not materialised yet and the daily urban wastes are piled around the location of scientific landfill. Disposal of waste in this region pollutes the surface water lake and groundwater resources due to migration of contaminants from the dumpsites to these water bodies. The municipality authority uses dumpers to dispose the waste in Boragaon. The unscientific dumping of wastes nearby the Deepor Beel emerges as a huge potential concern of groundwater and surface water pollution. Therefore, scientific studies are required to investigate the extent of this environmental problem. One simple method to analyse landfill leaching is by recreating the similar scenario in laboratory and then carrying out the measurements to determine the concentration of various elements. The scale models of single-dimension and three-dimensions can be used in the laboratory for simulating the field conditions pertaining to waste dump landfills. Keeping this in view, in the present research work an effort is made to carry out experimental column leach studies in the laboratory under various conditions similar to the field conditions.

1.6 Objectives

The objectives of the present study are formulated as follows.

- a) To perform column-leaching experiment using refuse soil from Boragaon landfill site and locally available normal soils.
- b) To determine the concentrations of nutrient elements like sodium (Na), calcium (Ca), potassium (K), and heavy metals like zinc (Zn) from the effluent leachate obtained from the column leaching experiment.
- c) To develop empirical models to predict the concentrations of these elements in the leachate.
- d) To make statistical interpretations to some of the experimental observations.

1.7 Organization of the thesis

The contents of the thesis have been organized in five chapters:

Chapter 1 is the introductory chapter, which describes the background of the study and the need for seeking new investigation on understanding of the factors affecting landfill leaching in the waste disposal site of Guwahati city at Boragaon near Deepor Beel using column-leaching study.

Chapter 2 reviews the literature on landfill leaching, which includes description of the basic transport processes, various types of column experiments used for investigation on landfill leaching as well as for other purposes like nutrient and fertilizer leaching. Further, a brief literature on microstructural studies of soils is also discussed. Finally, the literature on various developments of empirical approaches is briefly presented.

Chapter 3 provide details of the study area, soil properties, methodology used for collection and analysis of the samples, experimental set-up, different tests conducted and the

procedures followed to obtain the results. In addition, the empirical methodology to predict the concentration of elements in the leachate is also presented in this chapter.

Chapter 4 enumerates the findings of the present investigation in an organized way. The results and detailed discussion on leaching of sodium, calcium, potassium and zinc from leaching experiment using different types of apparatus are systematically presented in this chapter. Further, details about the developed empirical model and its validation for predicting the leached concentrations of nutrients from landfill site are also presented in this chapter.

Chapter 5 provides the summary and conclusions drawn from whole research work of the present study. The scope for further research in this area is also stated in this chapter.

CHAPTER

2

LITERATURE REVIEW

2.1 General

The growth of economy in most countries is deciphered from its spread of urbanization. The rapid planned and non-planned urbanization has often led to problems of disposal of generated wastes. A common method of disposing the wastes is by land filling or dumping them in some remote sub-urban locations. The rapidity in the spread of urbanization often causes these remote regions also to be part of the urban regions within few years. These landfills, as already stated in Chapter-1, may be formed through unscientific dumping and/or developed through proper scientific design. A major environmental concern arising from unscientific landfills is the production and discharge of toxic leachates that are generated by the interaction of rainwater or other liquids with the organic and inorganic pollutants in the landfills. The movement of leachate into the surrounding soil, ground water, and/or surface water could lead to severe pollution problems in and around that landfill locality. Therefore, there is a need to study and investigate the mechanisms of pollution by landfill leachates that will aid in mitigation and prevention of potential

contamination of groundwater resources. In this chapter, a review of numerous research works carried out by different researchers on landfill leaching with a special focus on experimental investigations – including column and batch leach experiments is presented. In addition, the relevant literatures on analytical methods as well as microstructural studies to interpret the leaching behaviour of various elements in the landfills are also presented.

2.2 Theory on landfill leaching

The mechanism of migration of landfill leachates to the subsurface environment has to be studied conceptually as well as experimentally to analyse its effects. Landfills are considered as porous media. The theory of transport of water (or any liquids) and solutes through the porous media are very much applicable to landfill leaching. The movement of contaminants through soil and subsequently into the groundwater involves various processes like advection, diffusion, sorption, and degradation, etc. (Berkowitz et al. 2014). Advection is the process by which solute particles are transported with the bulk movement of water. Diffusion is the process of movement of solute particles from the region of higher concentration to the region of lower concentration by Brownian motion. The rate of diffusion is directly proportional to the concentration gradient normal to the direction of movement.

Sorption is the mechanism by which chemical species are transferred from solid surfaces to liquid or vice versa. Sorption includes adsorption, absorption as well as desorption. Adsorption is the process by which solute particles are adhered into the soil surface. On the other hand, absorption is the phenomenon in which solute particles enter into the soil through pore surface. Desorption is the phenomenon through which chemical species dissolve or transfers from soil to the liquid.

The mechanism of leaching, however, is complex as it involves various chemical and biological processes. Considering the different processes involved in landfill leaching, analytical and experimental approaches are required to analyse the movement of landfill leachates to the subsurface environment. Experimental investigations are popular as they produce realistic results for the given conditions.

Numerous experimental investigations have been carried out all over the world to understand the mechanism of leaching. Column leach and batch experiments are popular methods among the researchers to understand the leaching process.

2.3 Literature review on experimental studies on leaching

2.3.1 Literature review on column leach studies

Column leach experiment is one of the most popular experimental methods to carry out investigations on landfill leaching. Some of the relevant literatures in this regard are described below.

Fortin et al. (1997) have carried out column experiments under saturated conditions to investigate the sorption behaviour of simazine on Tuzunga sandy loam. The authors adopted flow interruption techniques to identify rate-limited processes in leaching. The breakthrough curves of simazine concentrations obtained from column effluents suggested that the simazine sorption was not at equilibrium and involves instantaneous and rate-limited processes.

Poon and Chen (1999) have carried out flow-through and flow-around tests to simulate the leaching behavior and diffusivities of some hazardous wastes consisting of heavy metals like lead, zinc, copper, nickel, and chromium. Their experiments were dynamic leaching tests, in which the flow-through method employs the leachate to be forced to flow

through one-direction in the hazardous waste sample, whereas, in flow-around method, the leachate transport is in all directions through the waste samples. The results demonstrated that the diffusivities of the contaminants continuously increased during the leaching period for the flow-through conditions. However, for flow-around conditions, the variation of diffusivity with time was not regular.

Delgado et al. (2002) have conducted column experiment to determine the capacity of compounds like Horti Anthrosol to attenuate pollution caused by downward leaching from cattle slurry applied at the top surface. The column leaching experiments were compared for cases with and without cattle slurries. Their results proved that the pollution attenuation is more for experiments involving cattle slurries.

Deiss et al. (2004) have conducted a set of peat column experiments to determine the transport potential of Pb and diesel range organics (DRO) in a wetland, which poses threat to fish bearing stream. They extracted three pairs of peat columns from the rifle range for analysis. One pair was along and the other two pairs were across the natural bedding planes of the soil. In each pair, one column was spiked with lead and DRO. They passed water through each column for a certain period and the leachate was collected at regular intervals. It was observed that Pb was mobile both along and across the plane. It may be due to the reason that organic rich environment enhanced lead mobility.

Enell et al. (2004) have performed column-leaching experiments for determining the leaching of hydrophobic organic contaminants from soils. Sterile water was passed through the soil columns with sedimentation chambers at the top and these combinations benefited in measurement of leaching concentrations of various elements from very fine contaminated particles. They successfully applied this method to study the leaching of fluorine, phenanthrene, anthracene, fluoranthene, pyrene, benzo-pyrene, and benzo-

perylene from contaminated aged soil sample. They observed that polycyclic aromatic hydrocarbon in aged contaminated soil are not released to a significant amount only by leaching with water.

Szenknect et al. (2005) have examined the transport of radioactive strontium in eolian sand. They have applied three laboratory techniques to identify and quantify the chemical and hydrodynamic processes involved in strontium transport. The aim of the experiment was to compare the results obtained under static and dynamic conditions and to describe in a deterministic manner the processes involved in radioactive strontium transport using batch experiments, flow-through reactors, and saturated laboratory columns. The experimental data obtained from the flow-through study describes a nonlinear, instantaneous, and reversible sorption process.

Sneddon et al. (2006) carried out column leaching study to test the stabilization of metals in contaminated soils by the formation of low solubility metal phosphates. Bone apatite was used as the phosphate source on a mine waste contaminated with high levels of lead, zinc, and cadmium. The column leaching apparatuses were set in triplicate and filled with bone apatite and soil with ratios of 1:25 and 1:10 by mass. The columns were irrigated daily with synthetic rain solutions of different acidic pH. The concentrations of Pb, Zn, and Cd in the effluent leachate after 100 days were compared for both the cases. It was observed that metal release were more for bone apatite and soil ratio of 1:25.

Juwarkar et al. (2007) have carried out column experiment to determine the usability of environmentally compatible rhamnolipid biosurfactant produced by pseudomonas aeruginosa strain BS2 to remove heavy metals (Cd and Pb) from artificially contaminated soil. The experimental results revealed that di-rhamnolipid removes both the leachable fraction of Cd and Pb and other bound metals, whereas the tap water removed only the

mobile fraction of Cd and Pb. It was observed that washing with tap water removes about 2.7% of Cd and 9.8% of Pb, on the other hand, washing with rhamnolipid removes 92% of Cd and 88% of Pb after 36 hours of leaching. Experimental observations also revealed that pH of the leachate collected from heavy metal contaminated soil treated with di-rhamnolipid solution was low as compared to that of leachate collected from heavy metal contaminated soil treated with tap water. The microbial population of the contaminated soil increased after removal of metals by biosurfactant.

Gwo et al. (2007) have carried out research work to study chemical and physical mass transfer processes of movement of Co (II/III) EDTA (Chelates of cobalt and Ethylene diamine tetra acetic acid) through saprolite bedrocks that are characterized by fracture planes and extensive deposit of Al, Mn, and Fe oxide minerals on the surface. The soil columns used for experiment were extracted by hydraulically pressing an 8.4cm diameter $\times$ 15cm length stainless steel cylinder into an excavation pit. The conservative tracers were injected into the soil column. Physical and chemical mass transfer processes (PMT and CMT) influenced movements of reactive species through the soils. The PMT and CMT processes were inferred from laboratory tests using Br and Co (II) EDTA (chelates of cobalt and EDTA) as tracers in a column leach experiment. It was inferred that physical mass transfer rate of less reactive Co (II/III) EDTA is comparable with chemical mass transfer rate.

Zhang et al. (2007) have carried out experimental column studies on fluorine transport in unsaturated stratified soil. Fluoride contaminants with water were injected at the inlet and the concentrations of fluoride in the effluent were obtained for different times. The experimentally obtained values and numerically modelled solute transport values were compared. They identified that due to the adsorption and desorption effects, the

breakthrough curves of fluorine concentration are not symmetric and subsequently inferred that the process of leaching and purifying requires considerable time for such soils.

Persson et al. (2008) have carried out column leaching test to determine the mobility of chlorinated hydrophobic organic chemicals from contaminated soil. The authors studied the leaching behavior of Chlorophenols (CP), polychlorinateddiphenyl ether (PCDE), polychlorinated dibenzophuran (PCDF), and polychlorinated di bezo-p-dioxin (PCDD) from contaminated soil. The results of the experiment reveals that the leaching of the highly hydrophobic organic compounds and their concentration in the leachate depends upon the particles, which are mobilised in each leaching test. So this experiment reveals that particulate organic matter plays a significant role for the leaching of hydrophobic organic compounds like PCDD.

Dubey et al. (2009) have carried out an experimental investigation to determine the potential impact of municipality solid wastes on loss of arsenic (As), chromium (Cr), copper (Cu), and boron (B) metals from discarded treated wood using TCLP (Toxicity characteristic leaching procedure). From the experimental results, on the test samples that were collected from California, it was observed that the loss of preservative components is influenced by leachate chemistry. Ammonia was observed to be one of the major parameters that determined the leaching of copper from treated wood.

Brown et al. (2010) have investigated the mineralization of uranium and its leach rates in different sediment samples collected from Hanford, USA. The sediment characterizations were done using X-ray diffraction, scanning electron microscopy, and X-ray absorption spectroscopy. Column leach experiments were performed to determine saturation, pore-volumes, and the concentrations of dissolved uranium in leached and residual samples. From the observations of X-ray Absorption spectroscopy it was assumed that uranium in

the sediment is predominantly oxidized. Flow-through column leach test indicated that the uranium release from the contaminated site was non-linear and uranium solutions fail to reach steady state. It was observed that the release of uranium from these sediments is limited by very slow dissolution kinetics of uranium phases.

Comegna et al. (2011) have performed column experiment to study the dispersion process of chloride through undisturbed soil columns. They carried out seventeen sets of experiment through three undisturbed soil column of different texture in both saturated and unsaturated conditions. The experimental data were analysed using the classical convective-dispersive (CD) model. A good agreement was observed between the convective-dispersive fitted curve and the experimentally measured concentrations of chloride.

Naka et al. (2016) studied the feasibility of decreasing testing time of column percolation experiment by increasing flow rate and decreasing equilibration time. They used four types of soils with different characteristics to conduct the experiments; which are referred to as soils A, B, C, and D. Soils A and B were anthropogenically- contaminated soils, soil C was excavated from a depth of about 5–10 m, which contained natural heavy metals and soil D was a naturally-contaminated soil. The total heavy metal contents, the maximum particle size, and the moisture content of the soil samples were determined by different standard methods. The experiments were tested for three equilibration periods (0, 12–16, and 48 h) and two flow rates (12 and 36 mL/h) on four different soils. From the experimental results, the authors concluded that column percolation tests can be shortened from 20 to 30 days to 7–9 days by decreasing the equilibration time to 12–16 h and increasing the flow rate to 36 mL/h for inorganic substances.

2.3.2 Literature review on combined batch and column leach studies

Legret et al. (2005) have conducted batch leach test and column leach test to study the leaching of pollutants from reclaimed asphalt pavement. Some selected heavy metals and polycyclic aromatic hydrocarbons are analysed in the leachate. It was observed that pollutant concentration in the initial stage was high but then reduces rapidly and reaches a value, which is below the detection limit. The factors that influence leaching were observed to be material grain size and percolation water flow rate.

Malkoc et al. (2006) carried out batch as well as column studies on the adsorption of chromium (VI) from the waste pomace of olive oil factory (WPOOF). The effect of various parameters like flow rate and inlet ion concentration on the sorption characteristics of WPOOF was studied by them. They also observed the longest breakthrough time and maximum chromium (VI) adsorption at pH 2. From the results, they concluded that the total amount of sorbed chromium and equilibrium chromium uptake decreases with increasing flow rate and increases with increasing chromium (VI) ion concentration.

Suarez et al. (2007) carried out batch test and miscible displacement column test to determine the transport of simazine in unsaturated soil and then predicted its leaching under hypothetical field conditions. For simulation of the movement of simazine, batch test and miscible column test are performed on sandy loam to quantify the primary parameters and the processes of simazine transport. Chloride was used as non-reactive tracer and simazine was used as reactive tracer. Hydrus 1D model was used to estimate the parameters by inversion from breakthrough curve of the column and thus to determine the potential of groundwater contamination in Chilean valley. It was observed that the chemical non-equilibrium model was in agreement with the miscible displacement experiment in the laboratory.

Wang et al. (2008) carried out a comparative assessment of batch and column experiment on caesium adsorption on granite. From the experimental results, differences in the values of contaminant transport parameters were observed for batch and column tests. They concluded that the solid/liquid ratio is the dominant factor for these types of discrepancies.

Hanna et al. (2010) carried out batch and column tests for adsorption of gentisic acid by haematite nanoparticle under static and dynamic conditions. For simulating natural sediments, iron oxide was deposited on 10-micrometer quartz particles. The adsorption of gentisic acid is described by surface complexation model fitted to a pH adsorption curve. The authors observed that for columns, which are under flow-through conditions, the adsorption of gentisic acid to haematite-coated sand was about 7 times lower than that due to turbulent mixing in batch test. This may be attributed to the reduction in accessibility to the reactive surface site under flow-through conditions.

Komonweeraket et al. (2015) carried out pH-dependent batch-water leach test to investigate the leaching behaviour of Al, Zn, Cr, Cu, Fe and Mn from soil–fly ash mixtures used in highway constructions. The mixtures of soil-fly ash were prepared from six different soils and seven different fly ashes collected from Wisconsin, Minnesota, and Maryland in USA. It was observed that Mn concentrations decreased monotonically as pH increased, whereas Al, Cr, Cu, Fe, and Zn showed amphoteric leaching patterns and concentrations of these metals increased at acidic and alkaline pH. The leached metal and mineral concentrations from soil–fly ash mixtures increased with an increase in fly ash content. Geochemical modelling using MINTEQA2 indicated that the releases of these elements were solubility-controlled.

2.3.3 Literature review on leaching from landfill soil

There are different types of experiments performed to interpret the various processes involved in landfill leaching. Many research works explain the experimental and theoretical advancements on recycling and reusing of municipal solid wastes (MSW) to various forms like organic manure, second grade plastics, electronics, and other products, etc. (e.g., Sharma 1994; Srivastava and Tyagi 1995; Nogueira et al. 2010; Boldrin et al. 2011; Bernstad and Jansen 2011; Jung and Lovitt 2011; Elineema et al. 2013; etc. as referred in Barman et al. 2015). To brief some of them, e.g., **Sharma (1994)** carried out pot experiments to investigate the usage of earthworms as recyclers of organic wastes to produce organic fertilizers for Indian crops; **Boldrin et al. (2011)** evaluated various waste management options using tools like EASEWASTE to assess the garden wastes generated from urban areas; and **Bernstad and Jansen (2011)** used EASEWASTE LCA tool to compare the environmental impacts of waste management techniques like incineration, decentralized composting, etc. of solid wastes; **Jung and Lovitt (2011)** discussed on leaching techniques to remove hazardous metals and nutrients from fish farm effluents and sludges.

Wilson et al. (1982) discussed on leaching of cadmium from pigmented plastics disposed in landfill sites. Their experimental column leaching studies indicated less critical concentrations of cadmium in leachates and, therefore, suggested that landfills are acceptable disposal method for cadmium-pigmented plastics. **Li et al. (2007)** performed batch and column-leaching tests on incinerated MSW ashes to find the leachability of Zn, Cu, and Pb. The incinerated MSW ashes are disposed in controlled landfills in Japan, and the column experiment studies of Li et al. (2007) were useful to estimate the short- and long-term impacts of MSW ash on impermeable liners of landfills. **Miyawaki et al. (2000)**

carried out a similar exercise on Pb leaching from incinerator fly ash in monodisposal landfills. **Yusof et al. (2009)** performed the environmental risk assessment of leachates generated from controlled and uncontrolled MSW wastes in Malaysia. They monitored the concentrations of the organic carbon, nutrients, and heavy metals in the streams at upstream, at par, and downstream of the landfills for different months of a year and informed about the potential risks of contamination in the adjacent water bodies. **Cao et al. (2013)** observed the mobility of hazardous metals like Pb, Cu, and Zn, on different types of phosphorous bearing landfill soils. They found the leachability of Zn as highest, whereas of Pb as lowest in the phosphorous-bearing soil. **Palma and Mecozzi (2010)** inferred the release of more metals in acidic conditions through column and batch experiments on metal mobility from soil samples below municipal waste landfill in Northern Italy. **Schonsky et al. (2013)** conducted column-leaching experiments to analyze sulphate mobilization in the top soil of debris landfill in Berlin, Germany. They used kinetic transport models to describe the sulphate migration in landfills. **Zhao et al. (2014)** performed column-leaching experiments to analyze the effects of dissolved organic matters (DOMs) present in landfill leachate on the transport of heavy metals like lead. They assessed that the DOMs increase the migration of heavy metals in the landfill soils. **Sivakumar (2013)** experimentally investigated the hydraulic properties of solid wastes as well as the total leachate outflow using laboratory-leaching columns to estimate the leachate drainage to the groundwater aquifers.

Barna et al. (1997) carried out experimental investigations to study the pollutant retention in wastes that are solidified with hydraulic binders. These solidifications have long-term influence on leaching behaviour. The wastes used were air pollution control residues from municipal waste incinerators and the binders used were ordinary Portland cement or blast

furnace slag cement. From their results, it is inferred that there are clear distinctions between the species whose solubilities are not sensitive to the chemical context of the pore water, and whose solubilities are sensitive to pore water chemistry such as the amphoteric metals. **Yuen et al. (2001)** performed full-scale experimental water balance studies on MSW landfill in Melbourne, Australia. Their studies were also having two sections for the landfill – one controlled and the other leachate-recirculated zones. These two sections can potentially simulate the pre-capping period and post-capping period of the landfills and evaluate the extent of leachate storage in the landfills after capping. **Thomsen et al. (2012)** used contaminant mass balance and water budget methods to quantify mass discharges of various leachate components to the ground and surface water resources from Risby Landfill, Zealand, Denmark. The authors formulated mass conservation equations from the history, geology, and hydrogeology of the landfill location, and they interpreted the masses of chloride, ammonium, etc.

Ozkaya et al. (2006) monitored, at a site in Turkey, the concentrations of sulphate, chloride, chemical oxygen demand, and biological oxygen demand in the leachates produced from two sanitary landfill cells filled with MSW and through which the drainage of leachates are allowed. The leachates were directly collected in the first cell, whereas in the second cell, the leachates were periodically recirculated back into the cell.

Hyks et al. (2009) performed three percolation column experiments on municipality solid waste incineration bottom ash at Danish Municipality waste incineration plant. Concentrations of metals like Na, Ca, K, Al, Cu, Ni, Mo, Ba, Pb, and Zn, and dissolved oxygen were monitored throughout the entire leaching period. Geochemical modelling were performed to determine the non-equilibrium induced changes in the solubility control of various components. The column leaching experiments also provided information on

readily soluble compounds and solubility controlled elements. Their findings suggested that leaching of Mo was controlled by its availability in the mobile zone, which is again controlled by diffusion from the stagnant zone.

Bi et al. (2010) carried out soil column chromatography for determination of various parameters related to sorption. Standard high performance liquid chromatography systems are used in the soil column chromatography approach with Eurosoil4, quartz, and alumina as packing materials. Heterocyclic aromatic compounds were selected for validation of soil column chromatography. The columns were packed by first grounding the minerals to a designed size, arranging the stainless steel column vertically, and filling it using spatula and pipette. The column was soaked with water using HPLC pump. Dilution materials were used in their experiments to prevent column clogging. Various methods were discussed for the determination of retention time from breakthrough curves. The half-mass method, in which the peak area under the breakthrough curve was divided into equal parts, was recommended by the authors to identify the retention times.

Kiddee et al. (2014) carried out a survey on four selected landfills that receives waste from an arid region in South Australia. The proportions of e-waste in the municipal wastes for all the landfills were determined. Groundwater samples as well as leachate sample in the upgradient and downgradient of the landfills are collected for analysis of certain chemicals and metals. Their results indicated that the selected landfills receive greater than 6% of e-waste in the municipal wastes per year. From their survey results, the authors recommended that there should not be continuous disposal of e-wastes in the old landfills.

2.3.4 Literature review on nutrient and fertilizer leaching

It has been observed that various experiments on leaching are carried out in the area of nutrient and fertilizer leaching. To brief some of them e.g. **Jacobsen et al. (1996)** carried out pot experiment to determine the leaching of nutrients with and without compost. The pots were made of plastic (of size 40 cm × 60 cm × 40cm height) and contained 100 kg of soil on which some crops were planted. The pots were placed outdoors throughout the year without any shelter against the rains. A tube was fitted in the bottom from which it was possible to collect the drain water for chemical analysis. During the growing season, the crops were watered by deionised water. In their pot experiments, 40 pots with compost and eight pots without compost are used. Their experiments also involved partial applications of ammonium nitrate and PK fertiliser to some of the pots. The drain water was collected at the bottom. It was observed that less than 15% of the organically fixed nitrogen are absorbed by the plants and after one month, leaching of nitrogen was very much reduced by the application of the compost. In the winter period, leaching of sodium and chloride were more compared to ammonium and potassium. They concluded that the application of compost improves the soil's physical condition and keeps up the pH and buffering capacity of soil during leaching process.

Moreno et al. (1996) carried out a field experiment in an intensively irrigated agricultural soil in Spain. The objective of the study was to determine the water flow and nitrate leaching below the root zone. The experiment was carried out on a furrow irrigated maize crop at two different nitrogen fertilization rates - the first one being the highest rate traditionally used by the farmers (500 kgN/ha per year); and the second one taken as 170 kg N/ha per year. The main aim of the experiment was to obtain data, which could be used for modifications in nitrogen fertilization rates and prevent degradation of the environment.

Nitrogen uptake by the plant and the root and nitrate produced by mineralization was also determined. From the experimental results, it was observed that crop evapo-transpiration was similar at both nitrogen fertilization rates. However, differences in nitrate leaching for the above two fertilisation rates were observed for the situation having higher drainage.

Litkas et al. (2014) developed a simple procedure to evaluate the mass balance of calcium, magnesium, potassium and sodium in lowland agricultural region. They used statistical method of cluster analysis to determine the effect of crop distribution on the quality of drainage water. They observed that cation concentration in irrigation and drainage water followed the trend $\text{Na}^+ > \text{Ca}^+ > \text{Mg}^{2+} > \text{K}^+$. Their analysis showed that rice irrigation practice and salinity or sodicity of some soil influences the quality of drainage water.

Ghiberto et al. (2015) carried out an experiment to quantify nutrient leaching losses at 0.9 m depth in Ultisol, which was cultivated with sugarcane. They evaluated the leaching of nitrite, nitrate, ammonium, sulphate, phosphate, calcium, magnesium and potassium. They carried out the experimental design in four random blocks and three different methods of treatment – viz. without fertiliser; 100 kg ha⁻¹ of N and 114 kg ha⁻¹ of S; and 150 kg ha⁻¹ of N and 172 kg ha⁻¹ of S. From the investigations on the fate of N-fertiliser and S-fertiliser, the authors observed that the leaching of N was between 3.9 and 34.9 kg ha⁻¹ and that of S was between 4.6 and 8.4 kg ha⁻¹. Similarly, the maximum amount of leaching of P, K, Ca and Mg were 1.2, 53.6, 135.7 and 39.8 kg ha⁻¹, respectively. Therefore, from the overall results the authors could not conclude whether there is risk of contamination of groundwater from fertiliser application.

2.4 Brief literature review on spectroscopic analysis like XRD, XRF, and SEM on landfill soil

Spectroscopic studies are useful to gain information on micro-structural changes of soil due to leaching. Some of these studies using spectroscopic analysis like X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), and Scanning Electron Microscopy (SEM) are described below.

Lee and Touray (1998) studied the leaching behaviour of an artificial polluted soil by leaching experiment. XRD analysis of the soil showed four main types of components e.g. quartz, feldspar, carbonate, and mica. It was observed that after the leaching experiment, carbonate disappeared from the XRD pattern.

Kahle et al. (2002) discussed various methods of quantification of soil minerals using XRD. The method of known additions, absorption-diffraction method, and full Pattern methods, etc. were discussed in this paper and were compared. **Ouhadi et al. (2003)** discussed various methods for quantitative mineral identification of soil. From their experimental results, it was observed that quantitative XRD analysis based on peak intensity of areas might cause overestimation or underestimation of the quantity of clay minerals.

Halim et al. (2005) studied the utility of leaching test for assessment of hazards of lead contaminated soil. XRD analyses were conducted on urban and industrial soil samples that were subjected to leaching. The XRD analysis of urban soil indicated the presence of calcite, quartz, kaolinite, and dolomite, whereas, the industrial soil was comprised of quartz, feldspar, kaolinite, and haematite. **Moon and Dermatas (2006)** studied the leachability of lead under semi-dynamic leaching condition. They investigated the immobilization mechanism of lead using XRD analysis. **Yang et al. (2007)** carried out an

experimental study on in-situ chemical fixation of arsenic contaminated soil. XRD technique was used to investigate the mineralogical composition of soil. **Zanelli et al. (2007)** studied the vegetation effect on pedogenic forms of Fe, Al and Si on clay minerals in soil in southern Switzerland and northern Italy. They studied the XRD diagram of Na citrate treated sample and compared those with the corresponding untreated samples.

Cappuyns and Swennen (2008) carried out an experimental and mathematical investigation to assess the pH dependent release of trace metals from soils, sediments and waste materials. They performed pH_{stat} leaching tests to determine the mobility of heavy metals and subsequently developed mathematical fitting for leaching behaviour with respect to time. To aid and compare the chemical analysis, XRD analysis of the samples before and after the leaching tests were also carried out and the combined inferences from all the tests provided information on solid-phase speciation and reactivity of heavy metals in the samples.

Chiang et al. (2010) studied Arsenic and Pb contamination in Guandu plain in northern Taiwan. XRD analysis was performed to study the mineralogical phase of Pb. **Yao et al. (2010)** studied the effect of weathering on leaching behavior of copper from municipality waste residue. XRD tests were used to study the mineralogical changes during the weathering process. The principal minerals identified were quartz, calcite, magnetite, and bauxite. It was observed that the content of silica decreased during the weathering process, which indicates that SiO_2 has transformed into other minerals. **Nunez et al. (2012)** carried out leaching tests to evaluate the efficiency of materials in the remediation of metal contaminated soil. They carried out pH dependent leaching test and XRD analysis was carried out to determine the material, which can be efficiently used for the remediation of soil contaminated with heavy metal and Arsenic. **Singh and Agarwal (2012)** carried out

XRD, EDXRF, and AAS techniques to identify minerals of major elements. They also used principal component analysis (PCA) to get an idea of the minerals present in a qualitative manner, since PCA is a multivariate statistical method that utilizes extraction of useful information from the elemental concentration data. This information on elemental concentration data was used by the authors in predicting the presence of crystalline phases containing the detected elements.

2.5 Literature review on development of empirical models

Empirical formulations and experimental investigations are becoming increasingly popular among scientific communities since theoretical analysis becomes very complicated for some situations. On the other hand, use of statistical analysis after extensive experimentations or field study provides useful insights about the various bio-physico-chemical processes. Some of the relevant literatures in this regard are furnished below.

Simmelsgaard and Djurhuus (1998) developed an empirical model to estimate the annual average nitrate leaching due to variation in nitrogen fertilisation rate and crop type in Denmark. The authors came up with this empirical model using the various field observations of nitrate leaching, obtained from the drainage, for different nitrogen fertilisation rates over a period of 17 years. Their nitrate leaching empirical model consists of sub-models on nitrogen fertilisation as well as on combinations of crop, soil and drainage. The developed model was observed to be suitable for predicting the nitrate leaching in sandy to loamy soils.

Magnuson et al. (2002) investigated the effects of particle size on the leaching behaviour of metallic pollutants in settling ponds. For this, they used acid rain simulated conditions to observe the leaching from water-borne soil particles in the settling pond. The authors

utilised different empirical models to interpret the metal-loading curves as a function of particle size. They concluded that the particle settling rate decreases with the square of its size and therefore, the size of the particle to be received plays an important role for design and management of settling ponds.

Singh et al. (2007) described empirical models for predicting trace metals like Mn, Cu, Fe, Zn and Pb in the leachates from the ash ponds of thermal power plants. Their logarithmic empirical models for individual trace metals, based on lab-scale data, correlated well with the field data with high regression fitting. The variations in the predicted concentrations with the observed ones of the trace metals, in the leachates, were very less for the thermal power plants addressed in their study. Further, the authors recommended the use of their developed empirical models for prediction of trace metals in leachates from similar thermal power plants.

Obersteiner et al. (2007) utilised data of four different landfill types (open dump, sanitary landfill, mechanical biological treatment landfill, and municipal solid waste incineration landfill) for three different time periods (0-5 years, 6-30 years, and 31-100 years) to develop an empirical model to estimate the leachate emission of different elements for first 100 years of landfilling. Their study was part of life cycle assessment of landfills in central Europe. Their empirical model was formulated using average annual rainfall, percentage of rainfall that comes out as leachate, and the concentration of individual element in the leachates, for the three different time periods. In their studies, the authors had assumed that the leachates are collected and treated almost full for the first thirty years that is till the end of active aftercare period of the landfill. However, beyond 30 years there may be no aftercare treatment on the leachates, which may potentially contaminate the subsurface groundwater. Their empirical model results for the period beyond the active care (i.e. from

31-100 years) indicated the presence of pollutants in the landfill leachates even after 25 years of stopping the active operation of landfills.

Manfredi et al. (2010) developed an empirical model to estimate the emissions from landfilling of various waste fractions in their life-cycle assessment (LCA) studies. The empirical model estimated the gaseous and liquid emissions pertaining to the anaerobic degradation of individual waste fractions. Utilising the LCA-model EASEWASTE, the authors estimated the impact potentials for 1 tonne of mixed waste disposed in a conventional landfill consisting of bottom liner, leachate collection and treatment unit, as well as gas collection and utilization for electricity generation. The authors have incorporated various environmental impact categories such as standard categories, toxicity-related categories and groundwater contamination, which were accounted for 100 years after disposal. The authors observed that the environmental impacts are mostly due to the liquid and gaseous emissions of heavy metals and other toxic chemicals from such MSW landfills.

Moghaddam et al. (2015) developed empirical models to predict the copper extraction from low-grade ores through bio-leaching. The predicted values were optimised using response surface methodology. The effect of leaching time on copper extraction at different time periods was modelled. Under the optimal conditions, the total copper extraction predicted were significantly close to that obtained from the experiments. Their results showed that response surface methodology could be useful to predict the maximum copper extraction from a low-grade ore.

Shackelford and Glade (1997) used non-linear least square regressive techniques for the development of empirical equations on leaching mass ratio (LMR), in their study on mass leaching from contaminated soils and soil stabilised wastes. The results of the analyses on

leaching of cadmium, lead, and zinc from sand – fly ash mixture as well as sand-fly ash-bentonite mixture indicated that the bentonite added soil delayed the leaching of the above heavy metals.

2.6 Summary of the literature review

The major environmental concern of waste dumping due to rapid urbanisation was discussed in this chapter. The problems of development of toxic leachates, from unscientific landfills, and its subsequent spreading in the environment pose huge pollution threat to the fauna and flora of urban locations. Therefore, this chapter highlights the need to study the pollution mechanisms that can help in mitigation and management of dumped landfills. The chapter conceptualises the theory on landfill leaching by discussing various transport processes like - advection, diffusion, dispersion, and sorption. As experimental studies are important to understand various phenomena involved in leaching processes of contaminants and nutrients, the importance of batch and column studies are narrated through various literatures in this chapter. The experimental studies involved both the laboratory exercises as well as field studies. In addition, the micro-structural studies like XRF, XRD, SEM, etc. on soil samples from leaching sites as well as laboratory columns are also briefly presented. The need of empirical analysis from various experimental observations is highlighted in one section of this chapter, wherein the relevant literatures on empiricism are reported. From the review of literature presented in this chapter, it is observed that numerous research works are carried out in the area of leaching of contaminants as well as nutrients from the land surface to the underlying aquifer. Further, it is observed that batch test and column leach test are most popular methods for experimental investigation of migration of contaminants and nutrients. However, there are very few studies, reported in the literature here, on correlation among field parameters like

intensity of rainfall, heights of refuse soil and local soils etc. with the leaching behaviour. Therefore, an effort is made in this research work to perform experimental investigations on leaching of nutrients like sodium (Na), calcium (Ca), potassium (K) and contaminants like zinc (Zn), etc. for various combinations of landfill refuse soil height, subsurface base layer soil depth, and the intensity of precipitation. Subsequently, empirical relations are also developed to interpret the effect of these parameters on leaching of nutrients.



CHAPTER

3

EXPERIMENTAL PROGRAM AND DEVELOPMENT OF EMPIRICAL METHODOLOGY

3.1 General

In this chapter, an experimental methodology for determining concentrations of various elements in the effluent leachates from soils composed of waste refuses from landfills and locally available normal soils is presented. Further, an empirical approach to predict the leached concentrations of various elements is also enumerated. Adhering with the research objectives, the experimental work was carried out in three types of column apparatus. These column apparatus, which are fabricated at IIT Guwahati, are used to perform column leaching experiments to measure the concentrations of nutrient elements namely Na (sodium), Ca (calcium), K (potassium) and heavy metal like Zn (zinc) in the effluent leachates. The three different types of column apparatus used in this research investigation include – a long rectangular column apparatus to observe the variation in leaching of Zn, a small cylindrical apparatus and a three-dimensional heap shaped apparatus both for

evaluating leached concentrations of Na, Ca, and K. All the column apparatus are filled with locally available normal soil at the bottom and the landfill refuse soil at the top. Several sets of experiments are performed in the column apparatus by changing the heights of landfill refuse soil layer and base normal soil layer, water ponding depth, and filling rate (Fig. 3.1). The leached effluent, which comes out from the bottom of the apparatus was collected at various time intervals. The concentration of Zn in leached effluent from long rectangular column apparatus is determined using AAS (Atomic Absorption Spectrometer), whereas the concentrations of Na, Ca, and K in the leached effluent obtained from small cylindrical apparatus and three dimensional heap shaped apparatus are determined using flame photometer. Further, an attempt is made to develop an empirical model from large number of experimental results to predict leached concentrations of nutrients with respect to landfill refuse soil height, base soil height, water ponding depth, and filling rate.

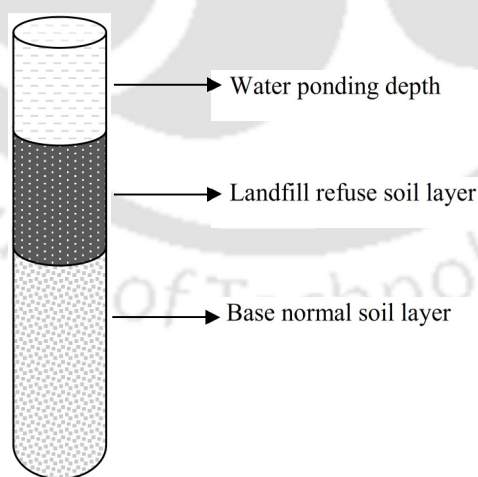


Fig. 3.1 Schematic representation of filled column apparatus with different soils

3.2 Study area

The waste disposal site of Guwahati city is located at a place called Boragaon, near Deepor Beel (Fig. 3.2). The coordinates of the site are; latitude: $26^{\circ}06.872$ N, longitude: $91^{\circ}40.896$ E; and site elevation is 46.9 m above MSL (Singh, 2011).

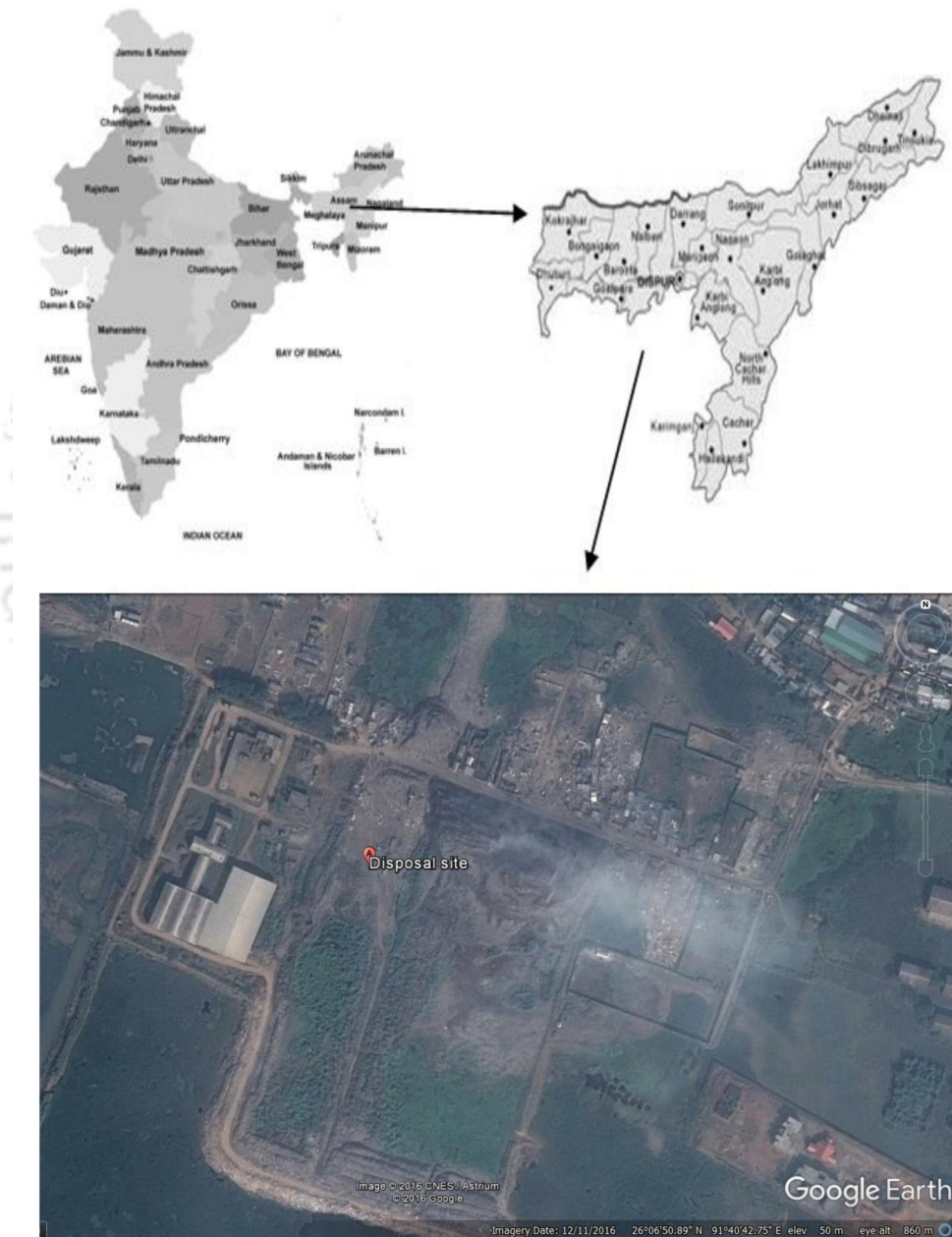


Fig. 3.2 Google Earth image of landfill site at Boragaon, Guwahati



Fig. 3.3 Waste landfill site of Guwahati city

The site is dumped with all types of wastes collected from the main city and nearby places (Fig. 3.3). There are huge quantities of waste hauling through dump trucks and many other types of carriage vehicles and the area is filled with heaps of wastes at various locations. After dumping of wastes from the vehicles, the stockpiles are spread by earth moving equipment like dozers on the heaps. This spreading equipment also does intermittent covering of the wastes with daily cover soil. For the experimental investigation, landfill refuse soil samples were collected from Boragaon landfill site, whereas the normal soil samples were collected from IIT Guwahati campus.

3.3 Characterization of soil samples

Various physical and chemical properties of landfill refuse soil and locally available normal soils were measured in the Geotechnical Engineering and the Environmental Engineering laboratories of IIT Guwahati. The procedures as stated in different relevant standards were followed to determine the physical and chemical characteristics of the soils.

3.3.1 Physical characteristics

There are various physical characteristics of a soil. Some of the relevant physical properties determined in this study are described below and are tabulated (Table 3.1).

Specific gravity:

Specific gravity, which is the ratio of average unit weight of solids to the unit weight of water at 20° C (Fratta et al., 2007), is determined using IS 2720 (Part III/Sec I) – 1980.

The specific gravity of the soil particles G was measured at room temperature by density-bottle method. The following relation was used to calculate G :

$$G = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \quad (3.1)$$

Where, m_1 = mass of density bottle (g); m_2 = mass of bottle and dry soil (g); m_3 = total mass of bottle, soil, and filled water (g); and m_4 = mass of bottle filled with water (g)

Bulk density and dry density:

Bulk density and dry density of soil samples are calculated as per IS: 2720 (Part XXIX) – 1975 by Core Cutter method. The bulk density (g/cm^3) is:

$$\gamma_1 = \frac{w_1 - w_2}{V} \quad (3.2)$$

where, w_1 = weight of soil and core cutter in g; w_2 = weight of the core cutter in g; and V = volume of the core cutter in cm^3 .

The dry density, γ_2 (g/cm^3) of the soil sample is:

$$\gamma_2 = \frac{100\gamma_1}{100 + w} \quad (3.3)$$

where, w = water content of soil in percent. The moisture content “ w ” was taken in accordance with IS: 2720 (Part II)-1973.

Gravimetric Moisture content:

Moisture content is determined using the method given in IS: 2720 (Part II)-1973.

Moisture content ' W ' is:

$$W = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \quad (3.4)$$

where, W_1 = mass of the container with lid (in g); W_2 = mass of the container with lid along with wet soil (in g); and W_3 = mass of the container with lid along with dry soil (in g).

Particle size distribution of soil samples:

Particle size distribution of soil samples is done using IS: 2720 (Part 4)-1985.

Table 3.1 Physical properties of landfill refuse soil and campus normal soil

Description	Normal Soil	Landfill Soil
Specific gravity	2.38	2.35
Dry Density (kg/m ³)	1313	1454
Bulk density for the sample collected (kg/m ³)	1458	1500
Gravimetric water content (%)	11.04	31.77
Percentage silt	67	Mostly silty clay
Percentage fine sand	21	
Percentage clay	7	
Percentage medium sand	4	

3.3.2 Chemical characteristics

Chemical characteristics are determined to find out the chemical compositions like nutrient concentrations, heavy metal concentrations, and compound compositions in the soil. The concentrations of nutrients like Na, Ca, and K are determined using flame photometry. Similarly, the concentration of heavy metal like Zn is measured using AAS.

Digestion process:

Digestion of the soil sample was carried out as per the guidelines stated in ASTM D3974-81) to determine the initial concentrations of elements i.e. zinc, sodium, calcium, and potassium in both landfill refuse soil and normal soil. The soil sample was crushed if any

hard mass was formed during drying, and then 0.4 g of the dried soil sample was taken into a 250 ml beaker. An empty beaker was also included in the analysis. Afterwards, 100 ml of water was added to the sample and in the blank beaker. Concentrated nitric acid of 1 ml was added to the soil sample to observe the presence of carbonates. A foaming reaction indicates the presence of carbonates in the soil samples. In that case, the nitric acid was added slowly to the sample. Thereafter, 10 ml of concentrated HCl was added. The beakers were covered with ribbed watch glasses and were then heated on a hot plate at a temperature of about 95°C. Each beaker was heated on the hot plate until the solution remaining in it is 10-15 ml. The solution in the beaker was then allowed to cool to room temperature. Subsequently, this solution was filtered and diluted up to 100 ml. This diluted solution was then analysed using flame photometry to determine the concentration of nutrients i.e. Na, K, and Ca and Atomic Absorption Spectrometry to determine the concentration of Zn in landfill refuse soil and normal soil before using in the column experiment.

Flame photometry:

Flame photometry is an analytical technique used for elemental analysis, which uses flame as an excitation source. In the flame photometer, the sample in solution is aspirated through an aspirator or nebulizer into the flame, which is usually propane, or air fuel. In the process, sample evaporates and hence atomization of the sample takes place. Due to absorption of energy from the flame, atoms present in the high temperature zone of the flame are excited to higher energy levels. When these excited atoms come back to the ground state they emit radiation in definite wavelength that depends upon the energy level from which the atom drop. In this way, a line spectrum is generated. In flame photometry, the intensity of the emission line is practically measured and is related to the original

concentration of the sample in solution. The detector is usually photomultiplier tube depending on the quality of the instrument (Kennedy, 1990).

Atomic Absorption Spectrometry:

Atomic absorption spectrometry (AAS) is a popular analytical technique used for measurement of concentrations of elements. This method is sensitive enough to measure up to parts per billion. Different elements absorb wavelengths, which is characteristic to that element. In atomic absorption spectrometry, the sample is first converted from ground state to free atom in the vapour state. Then a beam of electromagnetic radiation containing excited Zn atom is passed through the sample. This electromagnetic beam is produced by a lamp containing Zn, which produces a mix of wavelengths that can be absorbed by any Zn atom in the sample. When this beam is passed through the vaporised sample, Zn atoms in the sample absorb some of the radiation. The amount of absorption is proportional to the concentration of the element. By this principle, the concentration of Zn present in the soil samples are measured (Kennedy, 1990).

Cation Exchange Capacity (CEC):

Cation-exchange capacity (CEC) is the parameter used for measuring nutrient retention capacity of soil. CEC may be defined as the number of exchangeable cations per dry weight of a soil at a given pH value, which is available for exchange with the soil water solution. CEC is usually expressed as milli-equivalents of hydrogen per 100 g of dry soil ($\text{meq}^+/\text{100g}$), or the SI unit is centi-mol per kg (cmol^+/kg) (Tan, 2011).

The amount of exchangeable bases and the cation exchange capacity (CEC) are important properties of soils and sediments. They relate information on a soil's ability to sequester

toxic heavy metals. Sorption capability of the soils increases with the increase in specific surface area (SSA) and CEC (Tindall and Kunkel, 1999).

CEC is estimated by summation of exchangeable bases (Ca, Mg, Na, and K). The most common method of CEC estimation by using 1.00 M ammonium acetate extraction at pH 7.0 (Hendershot et al., 2008) is employed in this experimental investigation. The soil sample is extracted with 1.00 M ammonium acetate extraction at pH 7.0. The soil-solution (2g: 20 ml) slurry is shaken for 2 hours, and the solution is separated from the solid by centrifuge at 9000 rpm for 5 minutes. Samples are then collected from the clear supernatant for further analysis. The addition of excess NH_4^+ to the soil displaces the rapid exchangeable alkali cations from the exchange sites of the soil particles. The concentrations of Na^+ , K^+ , Mg^{2+} , and Ca^{2+} are subsequently estimated by flame photometry.

The CEC and initial concentrations of nutrients and Zn in the landfill soil and normal soil are presented in Table 3.2.

Table 3.2 Chemical properties of landfill refuse and normal soil

Description	Normal Soil	Landfill Soil
CEC (meq/100 g)	48.14	54.27
Initial concentrations of Na in soil (ppm) (Through digestion process)*	9.231	5.715
Initial concentrations of Ca in soil (ppm)	21.321	30.875
Initial concentrations of K in soil (ppm)	24.432	16.085
Initial concentration of Zn in soil (ppm)	0.227	1.01

* Initial concentrations of Ca, K, and Zn were also determined through digestion process.

X-Ray Fluorescence (XRF) Analysis:

X-ray fluorescence (XRF) is an analytical technique used for determination of chemical composition of materials. X-Ray fluorescence is the phenomenon, which occurs when primary X-ray excites a material causing emission of secondary X-ray or fluorescence. The

fluorescence emitted is characteristic to the element. Therefore, XRF analysis is used extensively for detection of elements and for research in geochemistry, forensic science, and archaeology (Kennedy, 1990). The landfill refuse soils may consist of several elements and the X-ray fluorescence (XRF) can be a useful to quantitatively determine the elemental composition of the soils. In the XRF analysis, the test sample is exposed to short-wavelength X-rays that causes the ionisation of component atoms. As the electrons are removed due to ionisation, the atom becomes unstable and the electrons from higher orbital falls to the lower orbital. This movement of electrons results in release of energy that is equivalent to the energy difference of the two orbitals. The energy emitted or radiated has the characteristics of the component atoms (Jenkins, 1999).

The X-ray fluorescence analysis was conducted on the landfill soil samples and the oxides of sodium, potassium, and calcium were detected in them. The average weight percentage of the oxides – Na_2O , CaO , and K_2O were 2.31 %, 1.61 %, and 2.9 %, respectively.

3.4 Column experiment

For the experimental investigation, different types of column apparatus were fabricated. In the column experiment, refuse soil samples collected from Boragaon landfill site, and normal soil samples collected from IIT Guwahati campus were used without any prior aggregate sieving and chemical treatment in all the column apparatus. Tap water from the regular water supply system in the laboratory was used in the column leaching experiment. The experimental set up is designed in such a way that it may simulate realistic field scenario of landfill site. In the unscientific landfills, there is refuse soil layer over base soil. Rainwater percolates through the refuse soil and base soil and ultimately reaches the groundwater aquifer. Three types experimental set up are designed to study the leaching

behaviour of Na, Ca, K and Zn for different field scenarios. The short cylindrical column represents a scenario where the depth of landfill soil and the base soil are not very large. On the other hand, the long rectangular apparatus represents a condition where the depth of the base layer is large although the height of the refuse layer is much smaller. Similarly, the heap shaped apparatus represents a situation where the waste is piled like a heap.

3.4.1 Long column leach apparatus

The first type of apparatus comprises of a rectangular hollow chamber made of Perspex sheet that is placed on an iron stand (Fig. 3.4). The chamber was filled with locally available normal soil at the bottom and the landfill refuse soil on top. The schematic diagram of the long column leach apparatus depicting the height of landfill refuse soil (H_1), height of normal soil (H_2) i.e. base soil layer and water ponding depth (H_3) are shown in Fig. 3.5. Raw tap water was poured through a pipe at the top of the soil at the selected filling rates. This rate of pouring or filling rate of water was measured, initially before applying to the soil column, using a flask and a stop-clock.



Fig. 3.4 Photograph of long rectangular column leach apparatus

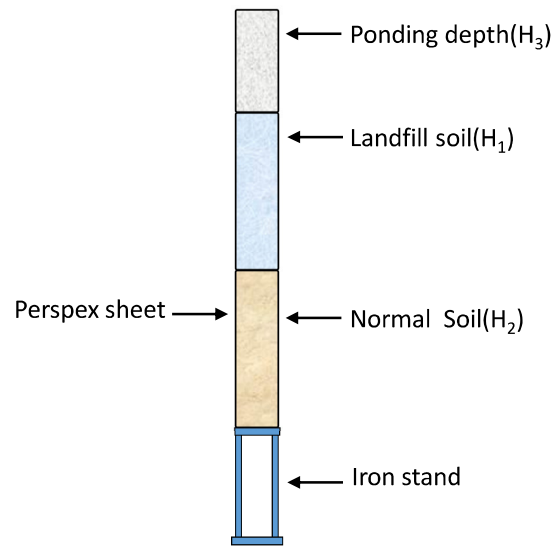


Fig. 3.5 Schematic diagram of long rectangular column leach apparatus

3.4.2 Cylindrical column leach apparatus

The second type of apparatus comprises of different sizes of cylindrical columns of hollow chamber made up of Perspex sheet. The column leach apparatus with base plate was placed on an iron stand and was filled up with landfill refuse soil at the top and locally available normal soil at the bottom (Fig. 3.6).



Fig. 3.6 Photograph of cylindrical column leach apparatus

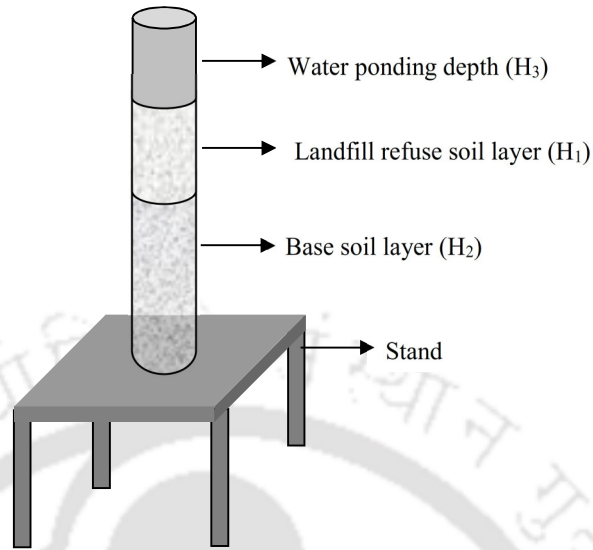


Fig. 3.7 Schematic diagram of cylindrical column leach apparatus

The inflow tap water was poured on top of landfill refuse soil through a pipe at the required filling rate (F) with a regulatory mechanism till the ponding depth ' H_3 ' is attained at the top. The height of different soil layers and water ponding depth is shown in Fig. 3.7.

3.4.3 Heap shaped column leach apparatus

The third type of apparatus for column leach experiment comprises of a three dimensional trapezoid made up of Perspex sheet and having bottom width of 90 cm, top width of 55 cm and slanted height of 60 cm (Figs. 3.8 and 3.9). The apparatus was placed on an iron stand of height 70 cm. A perforated net was fitted at the bottom of the apparatus, through which the leachate may come out and accumulate in a container placed just at the bottom of the net. A rainfall simulator was fitted at the top to spray tap water over the refuse soil layer to simulate a scenario of rainfall on the actual landfill site. The rainfall simulator was supplied with tap water through a pipe at different filling rates (F) with the help of a regulatory mechanism.

The leachate was collected in the measuring beaker placed at bottom of each column apparatus at different time intervals and was then transferred to reagent bottles for determining the concentration of various elements in the effluent leachate. The concentration of Zn in the effluent leachate was obtained from long rectangular column apparatus was determined using AAS. The concentrations of nutrients i.e. Na, Ca, and K in the effluent leachate obtained from small cylindrical column apparatus and three dimensional heap shaped column apparatus were determined using Flame photometer. It may be noted that the initial concentration of these elements in the tap water was also measured before the column leaching experiment.



Fig. 3.8 Photograph of heap shaped column leach apparatus

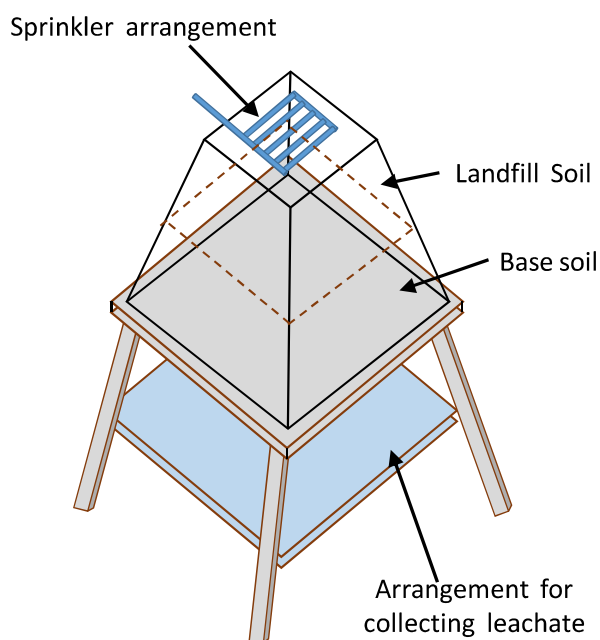


Fig. 3.9 Schematic diagram of heap shaped column leach apparatus

The experimental plan with the range of geometrical and flow parameters for the three-types of experiments are presented in Table 3.3.

Table 3.3 Geometrical dimensions and flow parameters for the column experiments

Column Apparatus	Geometrical and flow parameters			
	H ₁ (cm)	H ₂ (cm)	H ₃ (cm)	F (ml/s)
Rectangular Long Column	5, 10	55, 60, 65	8, 15	100, 110, 120, 130, 140
Short Cylindrical Column	5, 10, 15, 20	15, 20, 25, 30	8, 10	50, 70, 80, 100
Heap Shaped Column	6, 8	6, 8, 10	-	50, 60, 80, 100, 125, 150, 200

3.5 Empirical methodology

Empirical methods for analysis of experimental results as well as for development of predictive models have become an area of extensive research since theoretical analysis for some situations are complex that needs many assumptions. Many popular formulas like

Manning's formula, in open channel hydraulics, are empirical in nature. Analytical modelling in some areas requires many assumptions and involves rigorous mathematical practice. Therefore, use of statistical analysis along with experimental investigation may produce useful results. In this research, empirical models are developed to predict the leached concentration of Na, Ca, and K from landfill soils using large set of the experimental results.

The mathematical (or empirical) forms of predicting the nutrient concentrations in effluent landfill leachates, using the information from column experiments, can be a useful tool for preliminary design of landfills. The objective of these empirical formulations, in this research, is to develop independent functional relations between concentrations of Na, Ca, and K with H_1 , H_2 , H_3 , F , and time t . The functional form is as follows (Barman et al. 2015):

$$C_i = f(H_1, H_2, H_3, F, t) \quad (3.5)$$

where, C_i is the concentration of nutrient specie $i = \text{Na, Ca, or K}$, in dissolved state in the leachate, and ' f ' is the function. The present study is intended to find the impact of leaching from uncontrolled landfills and therefore, the objective here is to identify a suitable function to relate C_i with H_1 , H_2 , H_3 , F and t using least squares method from the experimental observations. The primary reason for selecting H_1 , H_2 , H_3 , F and t as independent variables in this regressive empirical analysis is attributed to the fact that H_1 resembles the tentative height of the refuse or landfill soil above the ground level; H_2 resembles the height of ground below the landfill soil and above water table; H_3 resembles the height of water ponding over the landfill soil due to precipitation; and F mimics the rainfall intensity. In addition to the above geometric variables, the physical and chemical properties of the soils and the initial moisture contents in the soils may also play significant

role in leaching. However, those soil parameters are not considered, in the laboratory experimental study here, and the effluent leachate concentrations are empirically related only with respect to the geometrical parameters. Levenberg-Marquardt algorithm is used in this research here for the nonlinear least squares method to formulate the empirical equations for C_i (GRETl 2014). The equations tried for the empirical model development are first-degree (linear) polynomial, higher-degree polynomial, logarithmic function, and exponential function, etc. The Lavenberg Marquardt algorithm is an iterative method used for calculation of the minimum of a function. The algorithm is usually applied to solve non-linear least square problems.

3.6 Summary

This chapter describes the experimental methodologies that were carried out to observe the leaching of nutrients (Na, Ca, and K) and heavy metals (Zn) from landfill refuse soils and normal soils using laboratory columns. The column experiments were carried out in three different types of apparatus for various combinations of H_1 , H_2 , H_3 , F , and t . The methodology of using the experimental observations to develop empirical formulations for predicting concentrations of nutrients from the column effluents is also described in this chapter. The results of this research are presented and discussed in the next chapter.

CHAPTER

4

RESULTS AND DISCUSSIONS

4.1 General

The experimental program consisting of the column apparatus and the test procedure for determining leached concentration of various elements is already presented in Chapter 3. The leaching experiments were carried out in three different types of column apparatus as described in the previous chapter. The local normal soil and the Boragaon landfill refuse soil are filled at the bottom and top, respectively in these column apparatus. These two soil samples are used without any prior aggregate sieving and chemical treatment. The heights of landfill refuse soil and base layer soil, from the schematic representation of column apparatus (Figs. 3.5 and 3.7) are H_1 and H_2 , respectively. The inflow raw tap water is poured on the top of the landfill refuse soil, at a requisite filling rate (F), until the ponding depth on the top reaches H_3 (Figs. 3.5 and 3.7). In the heap shaped column leach apparatus (Fig 3.9), raw water was sprayed through a rainfall simulator over the refuse soil to simulate a similar rainfall scenario on actual landfills. The experiments are conducted for different combinations of H_1 , H_2 , and H_3 and at different values of filling rates (F). The ponded water percolates through the soil layers in the column and in the process leaches the nutrients like

Na, Ca, and K, and heavy metals like Zn from these soils into it. After a certain period, the leached liquor accumulates at the bottom and is collected in measuring beakers at different time intervals. There are several sets of experiments for various combinations of H_1 , H_2 , H_3 and F used in these studies to interpret the leaching of above elements. The procedure for determining the leached concentrations of the elements in the effluents is already presented in Chapter 3.

4.2 Results for leaching of sodium, calcium, and potassium

The experimental study on leaching of nutrients (sodium, calcium, potassium) was performed using the small cylindrical column apparatus (Fig 3.6). The several sets of experiments with different combinations of H_1 , H_2 , H_3 , and F are performed to evaluate the leaching mechanisms of Na, Ca, and K (Table 4.1). The soil layers are packed with similar degrees of compactions in these set of experiments. The outflow from the column appears within the first ten minutes of the experiment. The leachate samples are then collected at every 10 minutes interval from the outflow section of the vertical column and the concentrations of the nutrients in these samples are measured using flame photometer apparatus. The initial concentrations of Na, Ca, and K present in the inflow raw tap water used in the experimental investigations were 4.39 mg/l, 12.41 mg/l, and 2.08 mg/l, respectively (Barman et al., 2015). As already reported through CEC (Table 3.2) and XRF analysis in Chapter-3 (Section 3.3.2), the nutrients (Na, Ca, and K) are also present in the soils used in the experiments.

The figures on variations of concentrations of nutrients with respect to time are grouped in terms of H_1 that mimics, albeit scaled down, the height of landfill refuse soil. There are

four groups with $H_1 = 5, 10, 15,$ and 20 cm, respectively (Figs. 4.1-4.5) and in each group, the height H_1 is kept constant and the other parameters are varied.

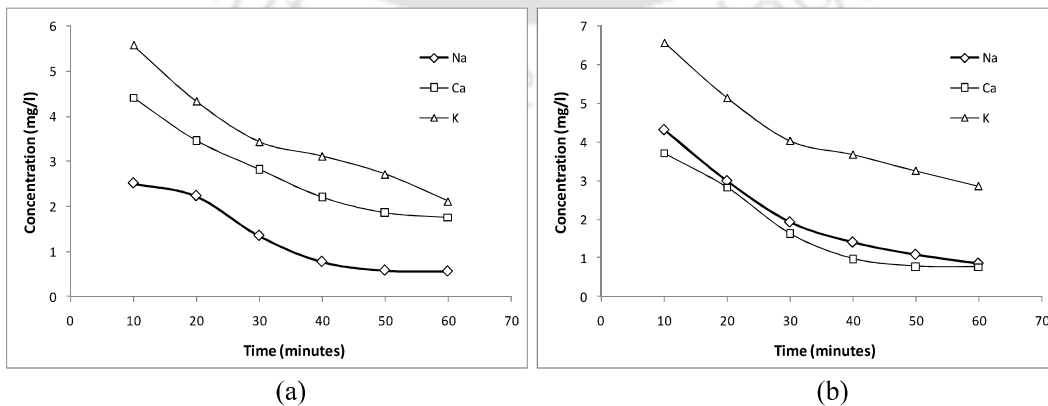
Table 4.1 Combinations of H_1, H_2, H_3 and F in the short column experimental program

Sl. No.	H_1 (cm)	H_2 (cm)	H_3 (cm)	F (ml/sec)
1	5	15	8	50
2	5	15	8	80
3	5	25	8	50
4	5	25	8	80
5	10	15	8	50
6	10	15	8	80
7	10	15	10	50
8	10	15	10	80
9	10	25	8	50
10	10	25	8	80
11	10	25	10	50
12	10	25	10	80
13	15	20	10	50
14	15	30	10	50
15	15	30	10	70
16	15	30	10	100
17	20	20	10	50
18	20	30	10	50
19	20	30	10	70

Most of the experiments were over within 60 to 70 minutes beyond which there were no significant or measurable outflows from the column. As expected, the concentrations of the nutrients in the leachate outflows are high in the first ten minutes interval and reduce gradually in the next fifty minutes (Figs. 4.1a-d). For the first case (Fig. 4.1a), where $H_1 = 5$ cm, $H_2 = 15$ cm, $H_3 = 8$ cm, and the filling rate $F = 50$ ml/s, the concentrations of Na and Ca at ten minutes are observed as 2.512 and 4.41 mg/l, respectively. The concentrations of these nutrients subsequently reduce in the next fifty minutes. The concentrations of Na and Ca in the leachate obtained for this case is less than their concentrations in the raw tap water. These reductions in concentrations imply that some nutrients in the tap water are adsorbed in the landfill refuse soil and/or the bottom layer soil. However, the concentration

of K in the leachate is higher than that of raw water that implies the leaching of K from the refuse layer and/or base layer soil into the water.

As observed from Fig 4.1b, the concentrations of Na (C_{Na}) in the leachate at different time intervals for the case of $H_2 = 15$ cm and $F = 50$ ml/s, were less than that of raw water and implies net absorption of Na into the soil layers. The concentrations of Na in the leachates are, however, higher during the initial periods for the same group (Figs. 4.1c, d), with higher H_2 , which implies that the leaching of Na occurs from the base soil. The concentrations of Ca (C_{Ca}) in the leachates for all the cases in group-1 (Figs. 4.1a-d) are lesser than the concentration of Ca in raw water. This suggests that more Ca gets absorbed or trapped into the base and/or landfill refuse soils. Concentrations of K (C_K) in the outflow leachates in all the cases (Figs. 4.1a-d) are higher than that in the raw water and this shows significant leaching of K from the soils. Moreover, C_K in the leachates were more for higher heights of base soil. This again implies that the base soil leaches more K into the water compared to the landfill soils. In the group-1 experiments, the specified ponding depth (H_3) of water is kept constant at 8 cm for all the cases. The effects of filling rate from the group-1 experiments are non-interpretable as there are no systematic variations, in the concentrations of nutrients in the outflow leachates.



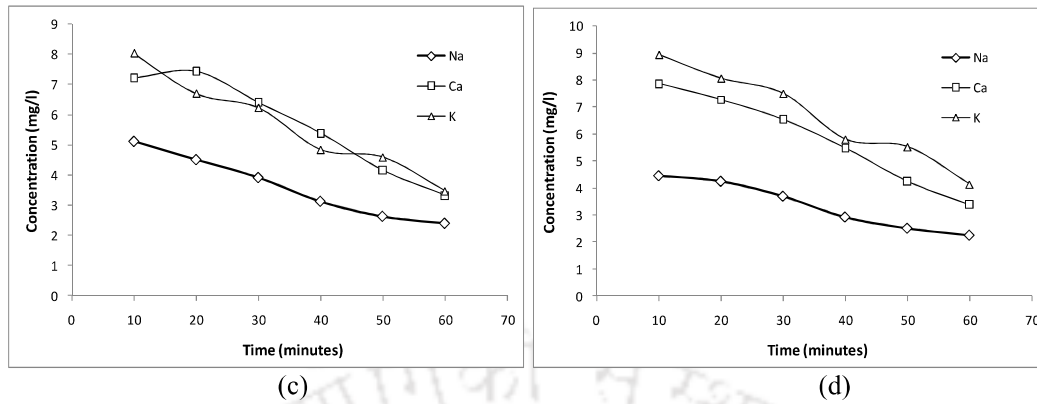
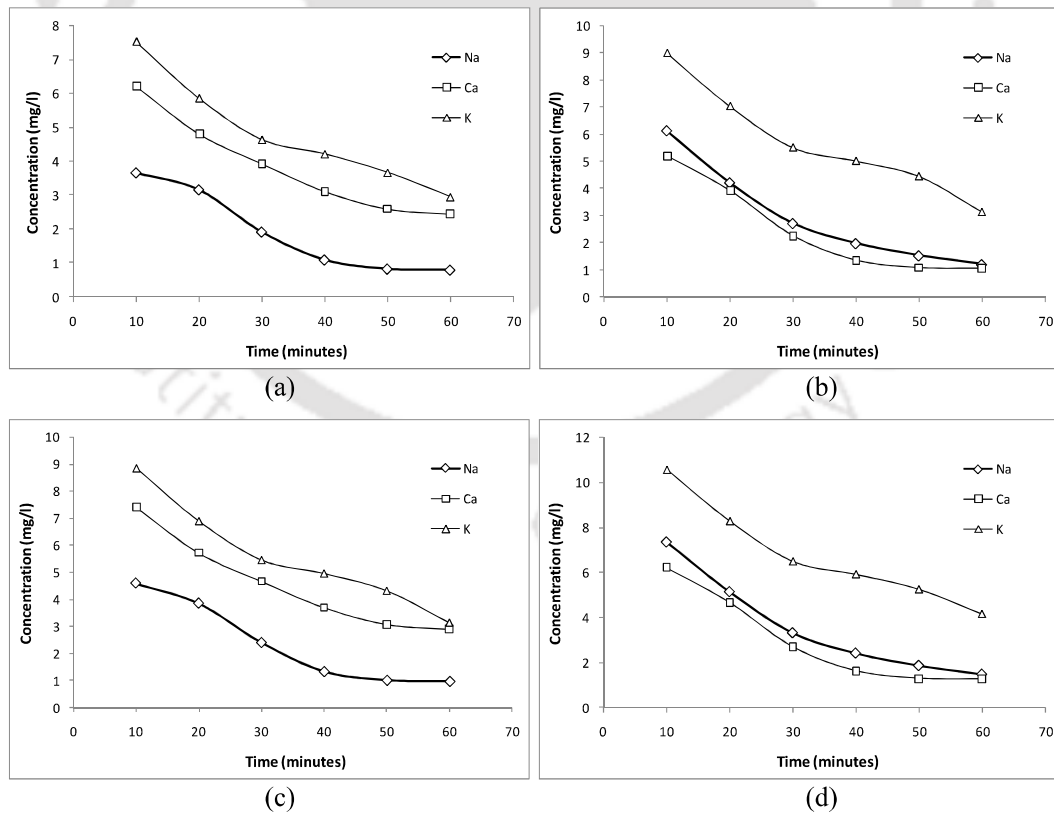


Fig. 4.1 Concentrations of nutrients in leachates for landfill soil height $H_1 = 5$ cm: a) $H_2 = 15$ cm, $H_3 = 8$ cm, and $F = 50$ ml/s; b) $H_2 = 15$ cm, $H_3 = 8$ cm, and $F = 80$ ml/s; c) $H_2 = 25$ cm, $H_3 = 8$ cm, and $F = 50$ ml/s; d) $H_2 = 25$ cm, $H_3 = 8$ cm, and $F = 80$ ml/s

The group-2 experiments were by increasing the height of landfill refuse soil from 5 cm to 10 cm and systematically varying the other quantities viz. H_2 , H_3 , and F . In this case as well, the calcium concentrations observed in the leachates were less than that in raw water and this implies the loss of Ca from raw water into the soils (Figs. 4.2a-h). In Group-1 experiments, C_{Na} was mostly less than C_{Ca} in the leachate outflows for all cases. However, in Group-2 experiments, C_{Na} is more than C_{Ca} for certain cases (Figs. 4.2b,d). Unlike in Group-1 experiments, where the height of refuse landfill soil (H_1) was considerably less than that of base soil (H_2) and the ratio H_1/H_2 was in the range from 0.2 to 0.333, in Group-2 experiments the ratio H_1/H_2 was in the range from 0.4 to 0.67. These increase in C_{Na} over C_{Ca} are observed for cases having higher filling rates (F) i.e. 80 ml/s and relatively higher H_1/H_2 ratio i.e. 0.67. The variations in the ponding depths and filling rates that impact the percolation of raw water and leachates through the landfill refuse soils and normal base soils can be modelled using extensive continuum mechanics principles of unsaturated flow and reactive solute transport through porous media (Karthi and Srivastava, 2012). However, the analysis based on continuum mechanics and mathematical differential equations are beyond the scope of this experimental investigation.

The flow in the vertical column increases due to increased ponding depths and/or filling rates, and consequently more sodium leaches from the landfill soils. These dissolved Na nutrients from landfill refuse soils have fewer interactions with the base soils of H_2 for higher H_1/H_2 ratios (i.e. $H_2 \leq 15$ cm), thereby increasing the Na concentration in the outflow leachate. However, for cases having lower H_1/H_2 ratios, to a certain extent as compared to Ca, the leached Na from landfill soils may get trapped in base soil. These experiments also emphasize the importance of the filling rate, which may mimic the rainfall intensity, to attain the ponded depth of water. Further, it is observed that similar to Group-1 combinations, the concentrations of Na in the outflow leachates were higher than that in raw water during the initial times for the cases having higher value of H_2 i.e. 25 cm (Figs. 4.2 e-h).



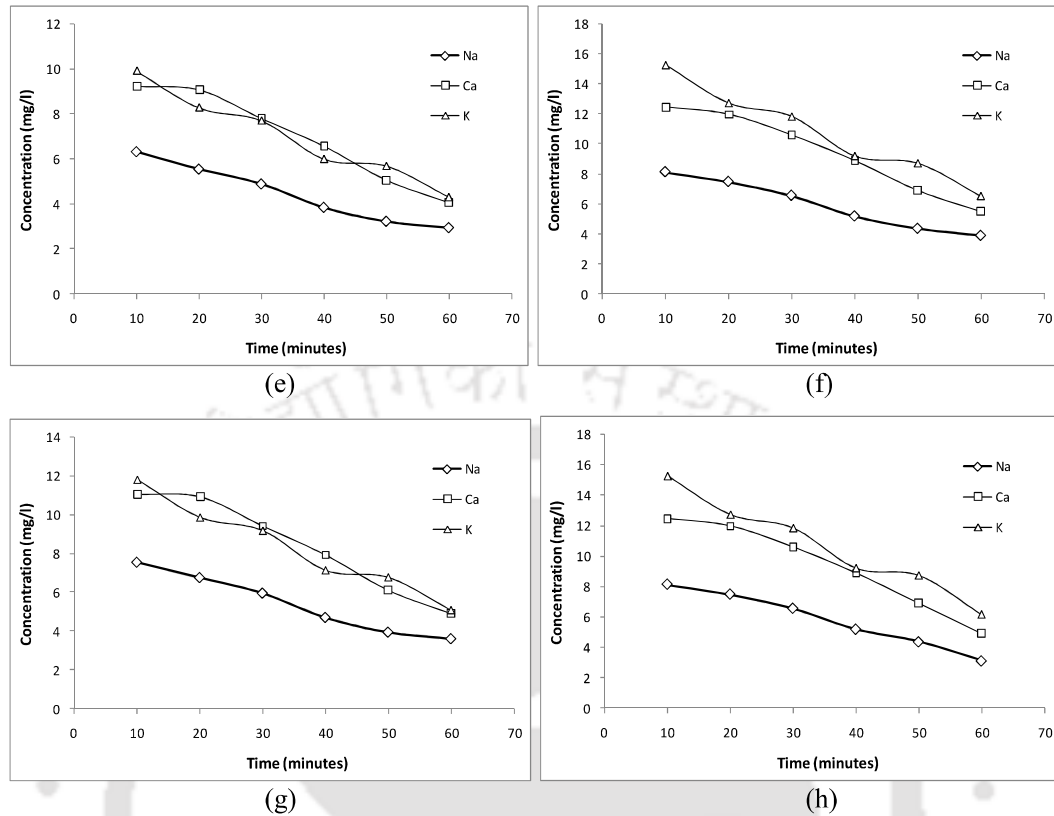


Fig. 4.2 Concentrations of nutrients in leachates for landfill soil height $H_1 = 10$ cm: a) $H_2 = 15$ cm, $H_3 = 8$ cm, $F = 50$ ml/s; b) $H_2 = 15$ cm, $H_3 = 8$ cm, $F = 80$ ml/s; c) $H_2 = 15$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; d) $H_2 = 15$ cm, $H_3 = 10$ cm, $F = 80$ ml/s; e) $H_2 = 25$ cm, $H_3 = 8$ cm, $F = 50$ ml/s; f) $H_2 = 25$ cm, $H_3 = 8$ cm, $F = 80$ ml/s; g) $H_2 = 25$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; h) $H_2 = 25$ cm, $H_3 = 10$ cm, $F = 80$ ml/s

The results shown in Figs. 4.2 a-h depict the leaching of potassium (K) from the soil layers as its concentration in the leachates are higher than that in the raw water in all the cases. In addition, the concentrations of K (C_K) in the outflow leachates were more for higher heights of base soil.

The Group-3 experiments describe about the nutrient concentrations in the leachates when the height of landfill refuse soil (H_1) is 15 cm. The magnitudes of C_{Na} in the leachates during initial periods are higher than that of raw water followed by lower concentrations in the later periods (Figs. 4.3a-c). This shows Na leaches from soil layers during initial periods and absorbs into the soil layers during later periods. However, for the case $H_2 = 30$ cm, H_3

= 10 cm, $F = 100$ ml/s (Fig 4.3d), the concentrations of Na in the leachates are higher than that of raw water at all periods. This higher concentration is because of continuous leaching of Na from soil into the water due to higher filling rate. Similar to sodium, the concentrations of calcium (Ca) in the leachates during initial periods are higher as compared to that of raw water followed by lower concentrations in the later periods (Figs. 4.3b-d). In spite of that, for the case $H_2 = 20$ cm, $H_3 = 10$ cm, $F = 50$ ml/s (Fig 4.3a), the concentration of Ca in the leachates is less than that of raw water at all periods. This reduction in Ca concentration implies the absorption of calcium into the soil layers. For potassium (K), in all the cases (Figs. 4.3a-d), its concentration in the leachates is higher than that in the raw water. The higher potassium concentrations indicate significant leaching of K from soil into the water.

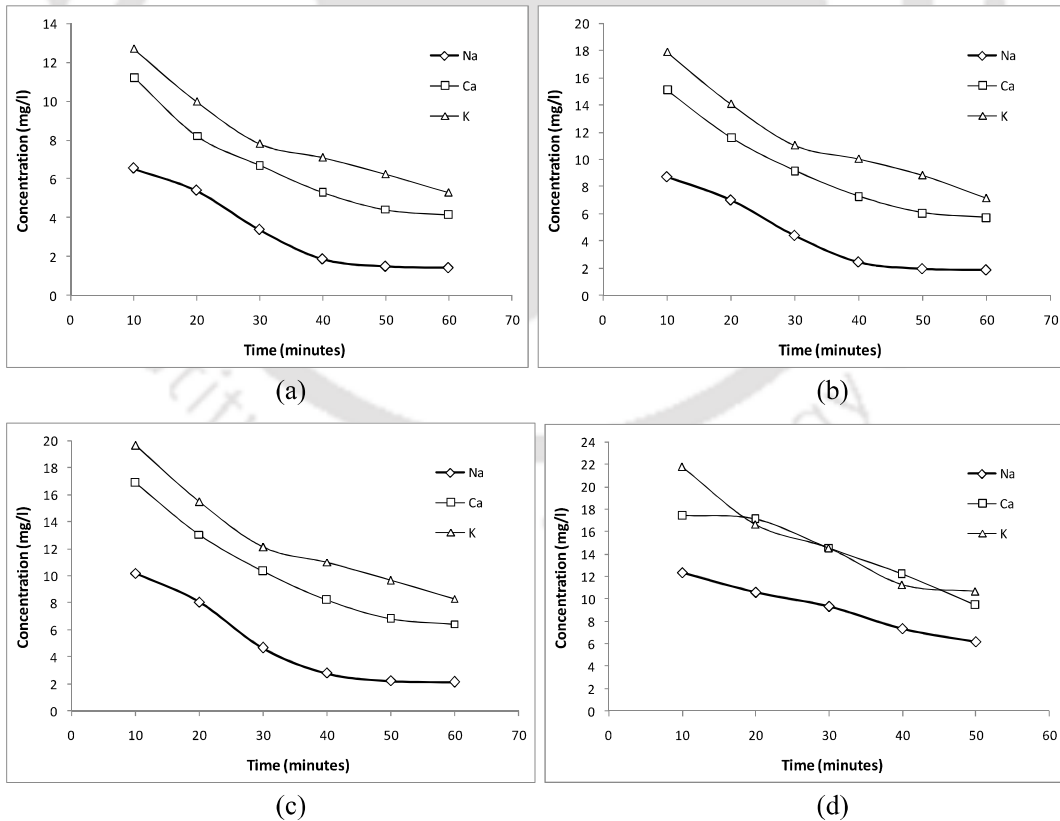


Fig. 4.3 Concentrations of nutrients in leachates for landfill soil height $H_1 = 15$ cm: a) $H_2 = 20$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; b) $H_2 = 30$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; c) $H_2 = 30$ cm, $H_3 = 10$ cm, $F = 70$ ml/s; d) $H_2 = 30$ cm, $H_3 = 10$ cm, $F = 100$ ml/s

The group-4 experiments involve increase of H_1 to 20 cm, and varying H_2 , H_3 , and F (Table-4.1). From the magnitudes of C_{Na} , C_{Ca} , and C_K in the leachates observed (Figs. 4.4a-c), except for the first case (Fig 4.4 a) where the heights of base soil and landfill refuse soil are same, the magnitude of C_{Na} is less than that of C_{Ca} at all intervals. The results of the first case of this group are for the reason that the height of base soil is not sufficient to trap the leached Na from the landfill refuse soil compared to leached calcium. From all the group experiments described, we conclude that the calcium and potassium nutrients leach more from the base soil. In the case of sodium, it is uncertain whether it leaches more from landfill refuse soil or base soil.

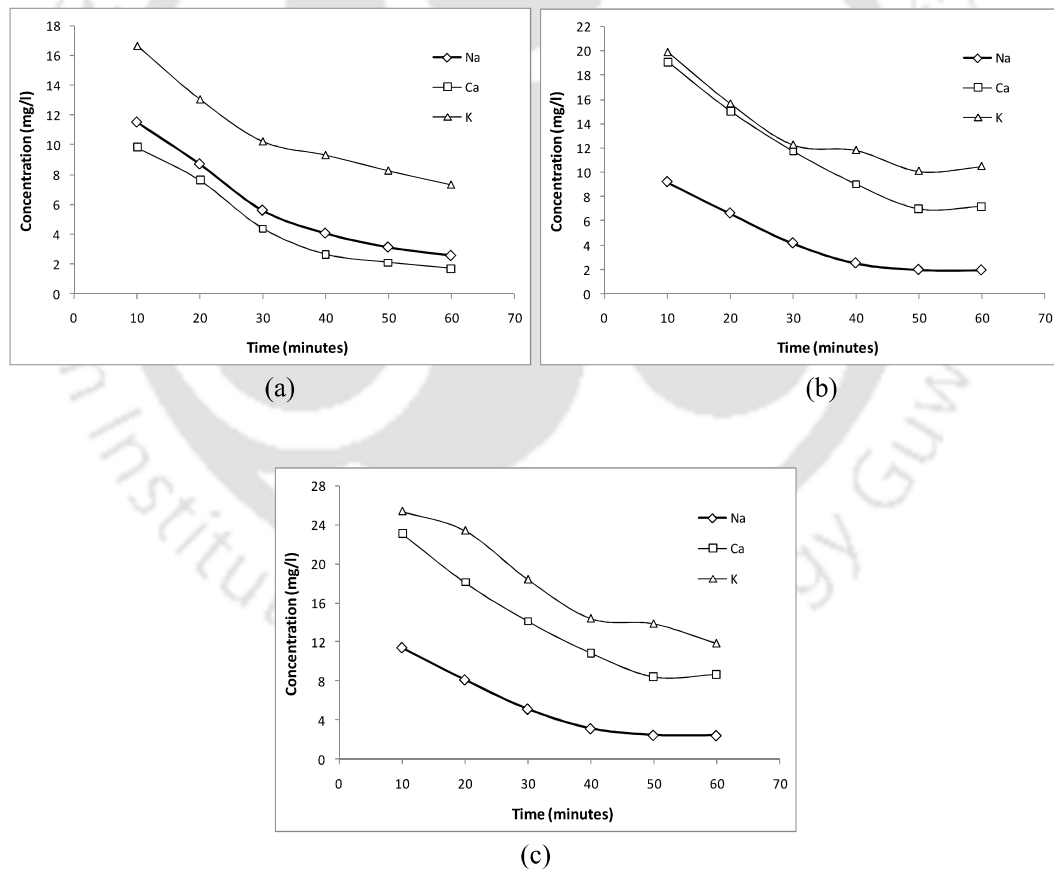


Fig. 4.4 Concentrations of nutrients in leachates for landfill soil height $H_1 = 20$ cm: a) $H_2 = 20$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; b) $H_2 = 30$ cm, $H_3 = 10$ cm, $F = 50$ ml/s; c) $H_2 = 30$ cm, $H_3 = 10$ cm, $F = 70$ ml/s

Effect of ponding depth on nutrient leaching

From the experimental studies (Table-4.1), an attempt to compare and infer the effects of ponding depth on the nutrient leaching is made. The magnitudes of C_{Na} , C_{Ca} , and C_K in the outflow leachates are compared, for a typical case where $H_1 = 15$ cm, $H_2 = 20$ cm, and filling rate $F = 50$ ml/s, for varying the ponding depths of 8 and 10 cm (Figs. 4.5a, b). The plots clearly demonstrate that the nutrient leaching is more for cases involving higher ponding depths. This implies that chances of leaching are more for situations of larger ponding conditions, which may arise due to insufficient drainage at the terrain surface. The larger ponding conditions cause higher energy heads that may enhance the flow of liquids and subsequent reaction in the column.

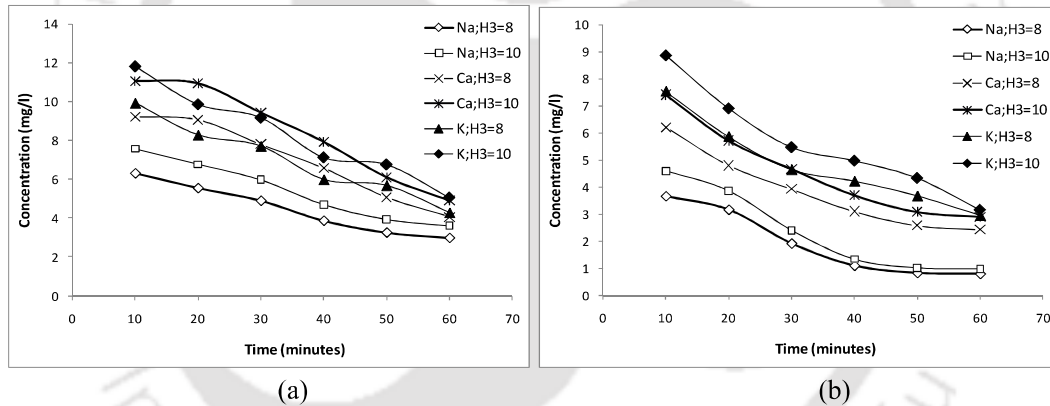


Fig. 4.5 Comparison of concentrations of nutrients in leachates for ponding conditions $H_3 = 8$ and 10 cm for input parameters: a) $H_1 = 10$ cm, $H_2 = 15$ cm, $F = 50$ ml/s; and b) $H_1 = 10$ cm, $H_2 = 25$ cm, $F = 50$ ml/s

4.3. Results for Zinc leaching

The zinc leaching studies were performed in the long rectangular vertical column apparatus (Fig 3.4). For the purpose of evaluating the effect of geometrical parameters (H_1 , H_2 , and H_3) and the water filling rate (F) on the leaching of zinc at different time intervals, the experimental investigation was conducted for various combinations of these parameters.

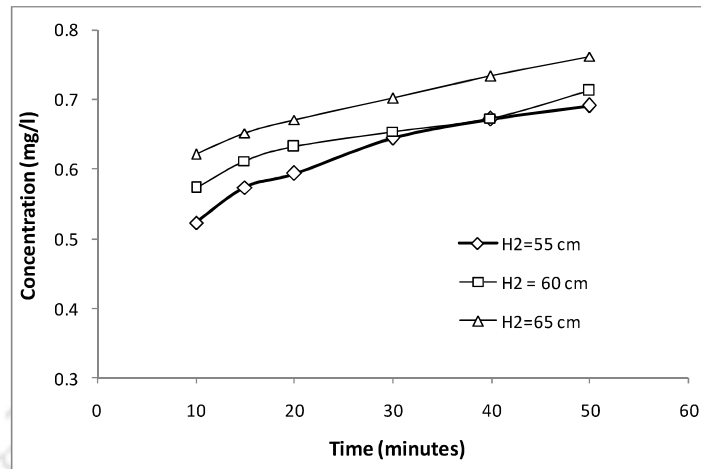
The water poured from the top percolates through the landfill refuse and the base layer soils

and leaches zinc from them. The average initial concentration of zinc (as determined through digestion) in landfill soil and base soil are 1.01 ppm and 0.227 ppm, respectively. Similarly, the measured initial concentration of Zn in the raw water used for experiments was zero. Therefore, there is a possibility of leaching of Zn from the two soils during the passage of raw water through them. The experiments for zinc were grouped into five different sets based on filling rates such as 100 ml/sec, 110 ml/sec, 120 ml/sec, 130 ml/sec, and 140 ml/sec. In each group, the heights of landfill refuse soil (H_1), height of base layer soil (H_2) and ponding depth (H_3) taken are – 5 cm and 10 cm; 55 cm, 60 cm and 65 cm; and 8 cm and 15 cm, respectively. The different combinations of H_1 , H_2 and H_3 at various filling rates are presented in Table 4.2. The outflow from the column appears within the first ten minutes of the experiment and leachate samples were then collected at every 10 minutes interval from bottom of the vertical column. The concentrations of Zn in leached effluent samples were determined using AAS (Atomic Absorption Spectrometer). These concentrations of zinc at different time intervals were plotted for all the experimental combinations of H_1 , H_2 , and H_3 (Figs 4.6 – 4.10), for the five different sets based on filling rates of 100 ml/s, 110 ml/s, 120 ml/s, 130 ml/s, and 140 ml/s, respectively.

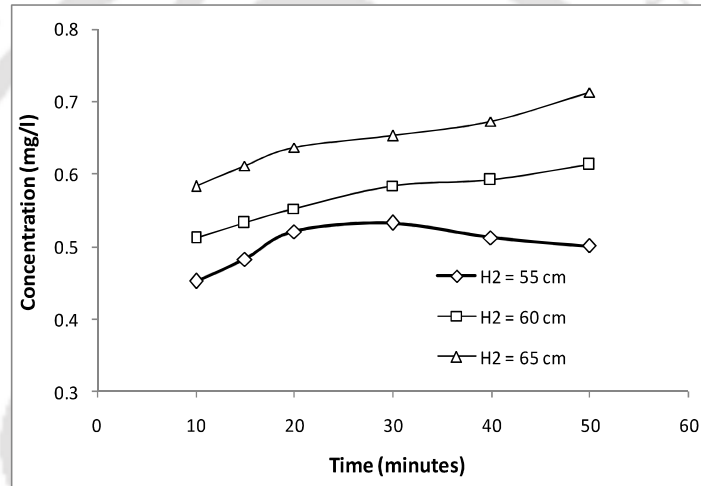
For the first case (Fig. 4.6 a), where the filling rate $F = 100$ ml/s, $H_1 = 5$ cm, and $H_3 = 8$ cm, for $H_2 = 55, 60, 65$ cm, the concentrations of Zn in the effluents after 10 minutes were observed as 0.3821, 0.4311, and 0.4921 mg/l, respectively. This increase in Zn concentrations shows that more Zn is leached when the base layer height is increased. In addition, the magnitude of Zn concentrations in the column effluents continuously increase in the next fifty minutes (within the short time scale used in the experimental studies here), unlike the decreasing trends witnessed in the case of nutrient leaching.

Table 4.2 Combinations of H_1 , H_2 , H_3 , and F for leaching study on zinc (Zn)

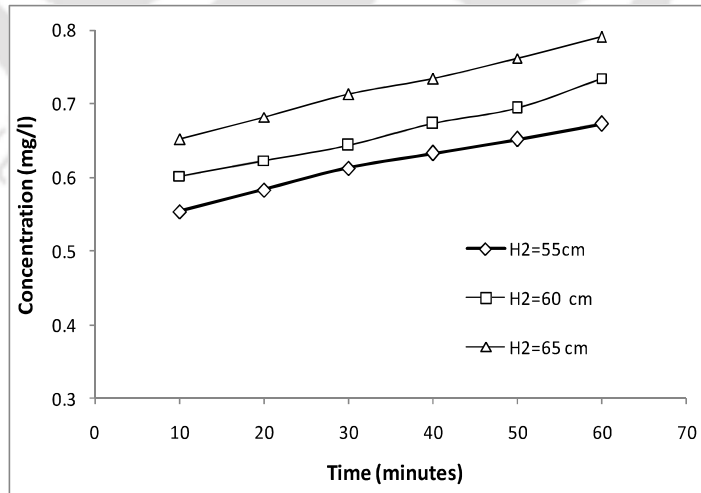
Sl.No.	H_1 (cm)	H_2 (cm)	H_3 (cm)	F (ml/s)
1	5	55	8	100
2	5	60	8	100
3	5	65	8	100
4	10	55	8	100
5	10	60	8	100
6	10	65	8	100
7	10	55	15	100
8	10	60	15	100
9	10	65	15	100
10	5	55	8	110
11	5	60	8	110
12	5	65	8	110
13	10	55	8	110
14	10	60	8	110
15	10	65	8	110
16	10	55	15	110
17	10	60	15	110
18	10	65	15	110
19	5	55	8	120
20	5	60	8	120
21	5	65	8	120
22	10	55	8	120
23	10	60	8	120
24	10	65	8	120
25	10	55	15	120
26	10	60	15	120
27	10	65	15	120
28	5	55	8	130
29	5	60	8	130
30	5	65	8	130
31	10	55	8	130
32	10	60	8	130
33	10	65	8	130
34	10	55	15	130
35	10	60	15	130
36	10	65	15	130
37	5	55	8	140
38	5	60	8	140
39	5	65	8	140
40	10	55	8	140
41	10	60	8	140
42	10	65	8	140
43	10	55	15	140
44	10	60	15	140
45	10	65	15	140



(a)



(b)



(c)

Fig. 4.6 Concentrations of Zn in effluent leachates for filling rate, $F = 100$ ml/s for different soil heights: a) $H_1 = 5$ cm, $H_2 = 55$ cm, 60 cm and 65 cm and $H_3 = 8$ cm, b) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm, and 65 cm, $H_3 = 8$ cm, c) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 15$ cm

At 50 minutes, the Zn concentrations for the above three H_2 values were 0.5433, 0.5541, and 0.6123 mg/l, respectively. As the raw tap water had zero concentration of Zn, the presence of Zn in the effluents implies the occurrence of Zn leaching from the soils in the column. The leaching processes here may be through dissolution and desorption. As the height of base soil increases from 55 to 60 cm, the increase in Zn concentrations in the effluents at 10, 20, 30, 40, and 50 minutes, were evaluated as 12.8 %, 9.5%, 9.1%, 3.7%, and 2%, respectively. This decrease in percentage increase of Zn concentration with respect to time suggests that the rate of leaching decreases with time (over a duration of 50 minutes here) despite the increase in height of base soil layer.

On changing the depth of landfill refuse from 5 cm to 10 cm (Fig 4.6 b), while keeping the other parameters same as in Fig 4.6 a, the effluent Zn concentrations at 10 minutes were 0.4322, 0.4933, and 0.5422 mg/l, respectively for $H_2 = 55, 60$, and 65 cm. Here again, the increase in Zn concentrations in the effluents with increase in H_2 is witnessed that substantiates the claim that Zn is leached more when the base layer soil height is more. In addition, the Zn concentrations in the effluent leachate increase with time. Similarly, in Fig 4.6c, where the ponding depth (H_3) is increased from 8 cm to 15 cm, the same above philosophies of – more leaching of Zn for cases involving larger heights of base layer; as well as increase in Zn concentration in the effluents with respect to time; are depicted. Figs 4.6a-c apparently suggests that the effluent Zn concentrations increase with the increase in base layer height. Following analysis determines the effect of increase in base layer height on the leaching mechanisms, by computing the difference in effluent Zn concentrations at any instant. With the increase in height of base layer soil (H_2) from 55 cm to 60 cm, 60 cm to 65 cm, and 55 cm to 65 cm, for the experimental case described in Fig 4.6 a, where $H_1 = 5$ cm, $H_3 = 8$ cm, and filling rate $F = 100$ ml/s, the average percentage change of Zn

concentration along with its standard deviation, irrespective of time, is 7.80 ± 4.10 %, 14.43 ± 2.89 %, and 23.43 ± 7.28 %, respectively (Table 4.3). Similarly, from Fig 4.6b, where H_l is changed from 5 cm to 10 cm, and the rest of the parameters remaining same, the average and standard deviation of percentage change of effluent Zn concentration, at any instant, for the increase in base layer soil height from 55 cm to 60 cm, 60 cm to 65 cm, and 55 cm to 65 cm, is 13.13 ± 1.64 %, 6.70 ± 2.16 %, and 20.72 ± 3.46 %, respectively (Table 4.3). In a similar way, from Fig 4.6 c, where $H_l = 10$ cm and $H_3 = 15$ cm for $F = 100$ ml/s, the corresponding average and standard deviation of percentage change, when the base layer soil height increases from 55 cm to 60 cm, 60 cm to 65 cm, and 55 cm to 65 cm, is 10.95 ± 1.26 %, 7.46 ± 2.79 %, and 19.21 ± 2.86 %, respectively (Table 4.3). The positive values for average percentage change imply that there is increase in effluent Zn concentrations due to more leaching of Zn from base soil layer, when its height is increased.

This research also analyse the effect of increase in landfill refuse layer height (H_l) on the effluent Zn concentrations. For example, for the first set of experiment, where the filling rate (F) is 100 ml/s, the effect of H_l is analysed by again determining the average percentage change at any instant. While comparing the cases shown in Figs 4.6a and 4.6b, when the landfill refuse layer height is increased from 5 cm to 10 cm, the average and standard deviation of change in Zn concentration at any instant for $H_2 = 55$, 60, and 65 cm, is 9.94 ± 3.69 %, 15.40 ± 1.56 %, and 7.62 ± 1.94 %, respectively (Table – 4.4).

This research observes that the ponding depth (H_3) also influences the quantity of contaminant leaching into the water. There are increases in Zn concentrations in the effluent leachates, due to increase in ponding depth that may be attributed to more advective transport. As described in Section 4.2, the thesis emphasizes on the experimental works and the mathematical and conceptual models describing the advective transport

through soils are beyond the scope of this research. Comparing Figs 4.6 b and 4.6 c, for the experiments where the ponding depth (H_3) is increased from 8 cm to 15 cm, the average and standard deviation of change in effluent Zn concentration at any instant for $H_2 = 55$, 60, and 65 cm, are $10.62 \pm 2.06 \%$, $8.48 \pm 1.17 \%$, and $9.24 \pm 1.63 \%$, respectively (Table 4.4). From these percentage increase values described above, for the experimental cases involving filling rate of 100 ml/s, it is inferred that the height of landfill refuse soil (H_1) as well as ponding depth (H_3) have significant effects on leaching of Zn. In some cases, the changes are more prominent as is for the case when H_1 is increased from 5 cm to 10 cm at $H_2=60$ cm ($15.40 \pm 1.56 \%$) for ponding depth $H_3 = 8$ cm. Coincidentally, the standard deviations of effluent Zn concentration change are observed minimum for $H_2 = 60$ cm for both the scenarios – i.e. increase of H_1 from 5 to 10 cm (1.56 %) and increase of H_3 from 8 to 15 cm (1.17 %) for the filling rate of $F = 100$ ml/s.

Similar analysis are performed for the experimental groups having the filling rates $F = 110$, 120, 130, and 140 ml/s. The time versus effluent Zn concentrations, for $F = 110$, 120, 130, and 140 ml/s, are given in Figs 4.7-4.10, respectively.

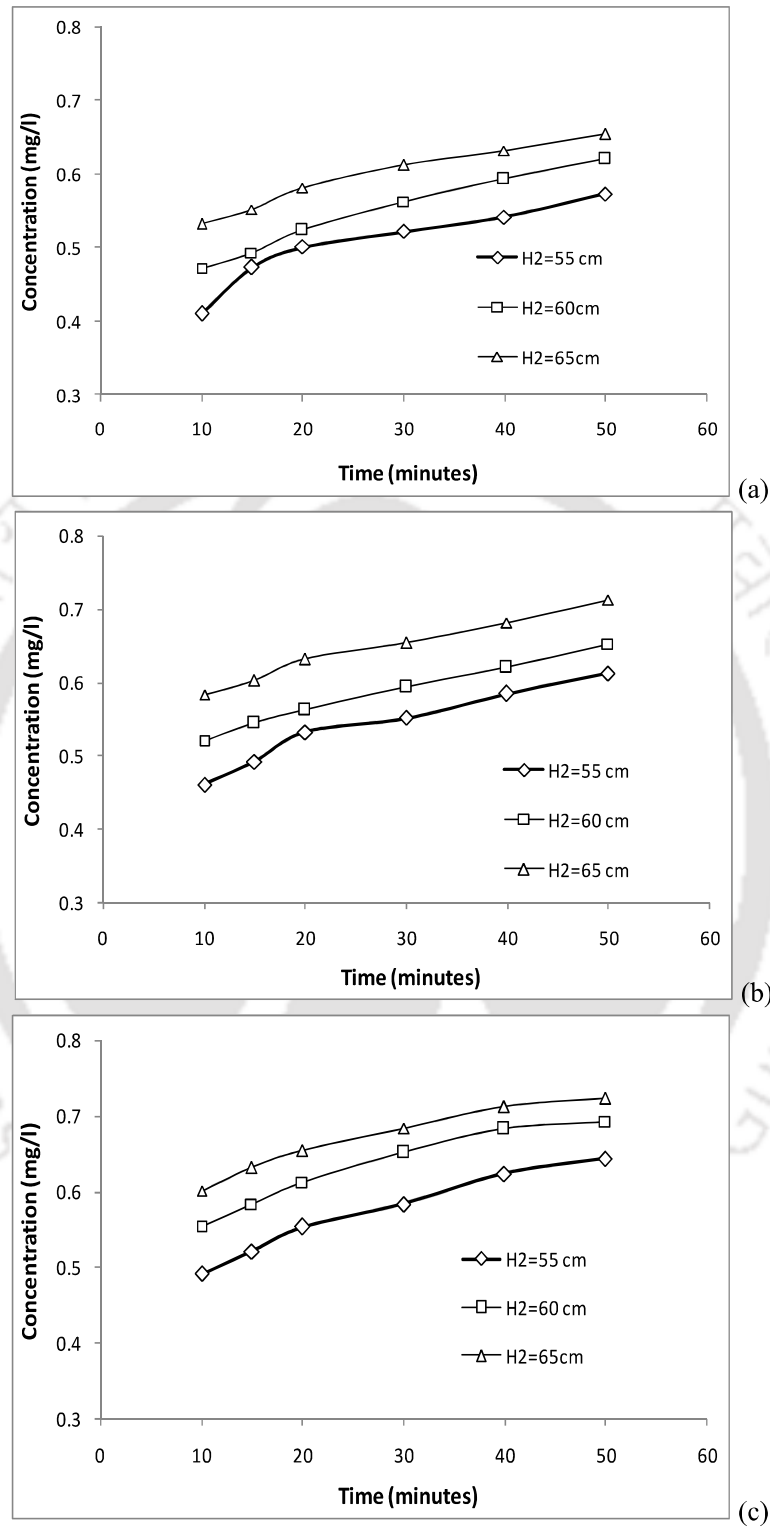


Fig. 4.7 Concentrations of Zn in effluent leachates for filling rate, $F = 110$ ml/s for different soil heights a) $H_1 = 5$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 8$ cm, b) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm, and 65 cm $H_3 = 8$ cm, c) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 15$ cm

From Fig 4.7 a, where the landfill refuse soil height is 5 cm, $H_3 = 8$ cm, and the filling rate is 110 ml/s, the average change in effluent Zn concentrations, at any instant, when the base layer height is changed from 55 to 60 cm, 60 to 65 cm, and 55 to 65 cm, is 5.85 ± 3.78 %, 14.24 ± 2.57 %, and 20.88 ± 3.79 %, respectively (Table 4.3). Similarly, the percentage change in effluent zinc concentrations, when the base layer height changes from 55 to 60 cm, 60 to 65 cm, and 55 to 65 cm, for the cases described in Figs 4.7 b-c are also noted in Table 4.3. The effect of change in landfill refuse soil height H_1 , on average change in effluent zinc concentrations (ΔC_{Zn}), at any instant, for the filling rate $F = 110$ ml/s (Figs 4.7a-b) can be interpreted from Table 4.4. Similarly, for the same F , the average change in effluent concentration, for different values of H_3 is also depicted in Table 4.4. As obvious from the experiments, the average percentage increase in effluent Zn concentrations (ΔC_{Zn}) is more when the height of base layer soil is increased from 55 cm to 65 cm (refer percentage changes in column 4 of Table 4.3).

As the experiments involved here were for short durations (50 minutes), the effluent Zn concentrations were still increasing gradually suggesting that there may be further significant amounts of Zn in solid form present in the soils that are leachable. Due to the fact that the effluent volume after 50 minutes was almost negligible, prompted the experimental observations to conclude at 50 minutes. Obviously, the duration of the experiments can be further increased for hypothetical situations, where the ponding depth of the water can be raised considerably from 15 cm to a large value. However, to attain such large ponding depths, almost instantaneously, with the above filling rates are impossible and therefore, persuaded the researchers here to conduct short duration experiments.

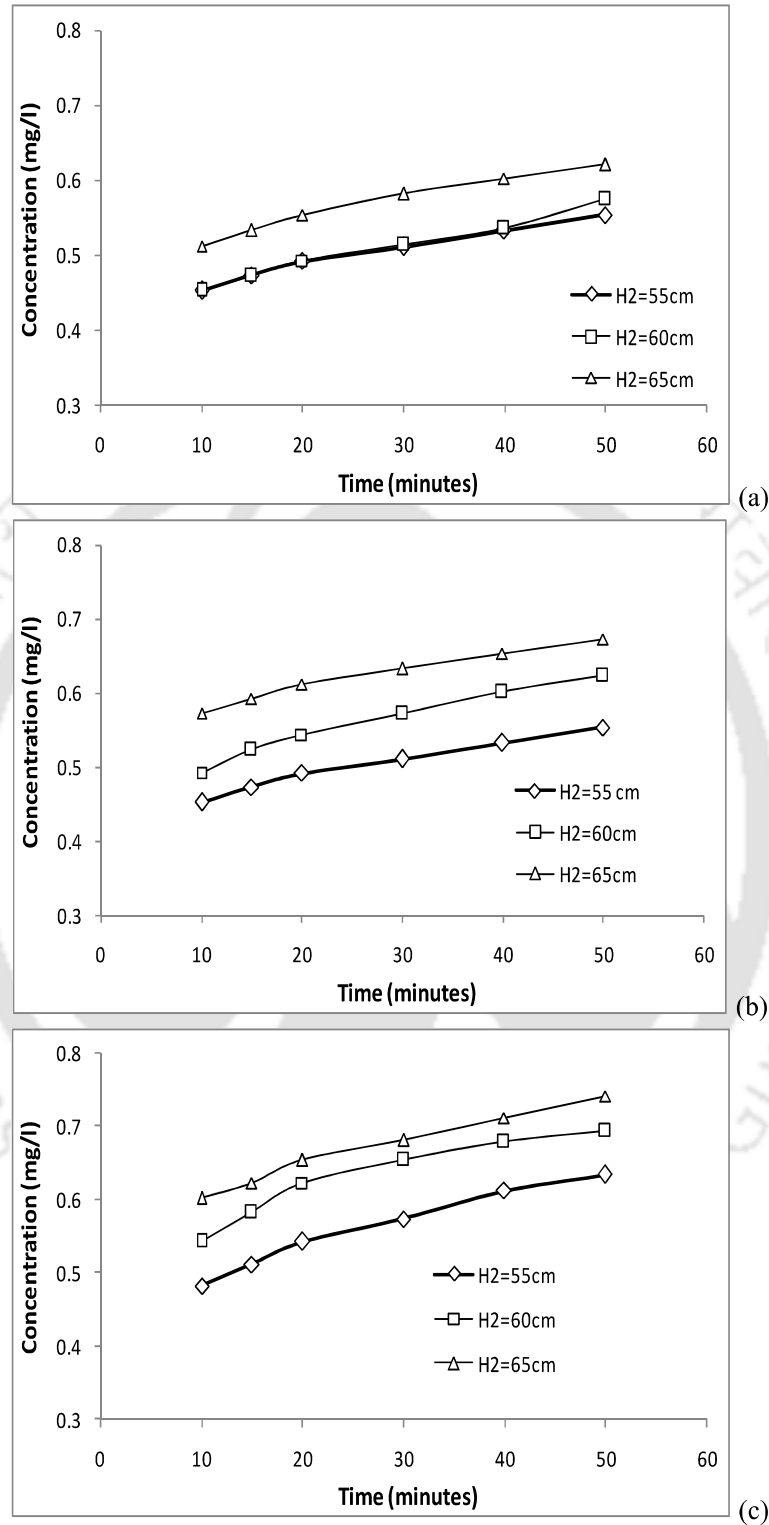


Fig. 4.8 Concentrations of Zn in effluent leachates for filling rate $F = 120$ ml/s for different soil heights a) $H_1 = 5$ cm, $H_2 = 55$ cm, 60 cm and 65 cm and $H_3 = 8$ cm b) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm, and 65 cm $H_3 = 8$ cm c) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 15$ cm

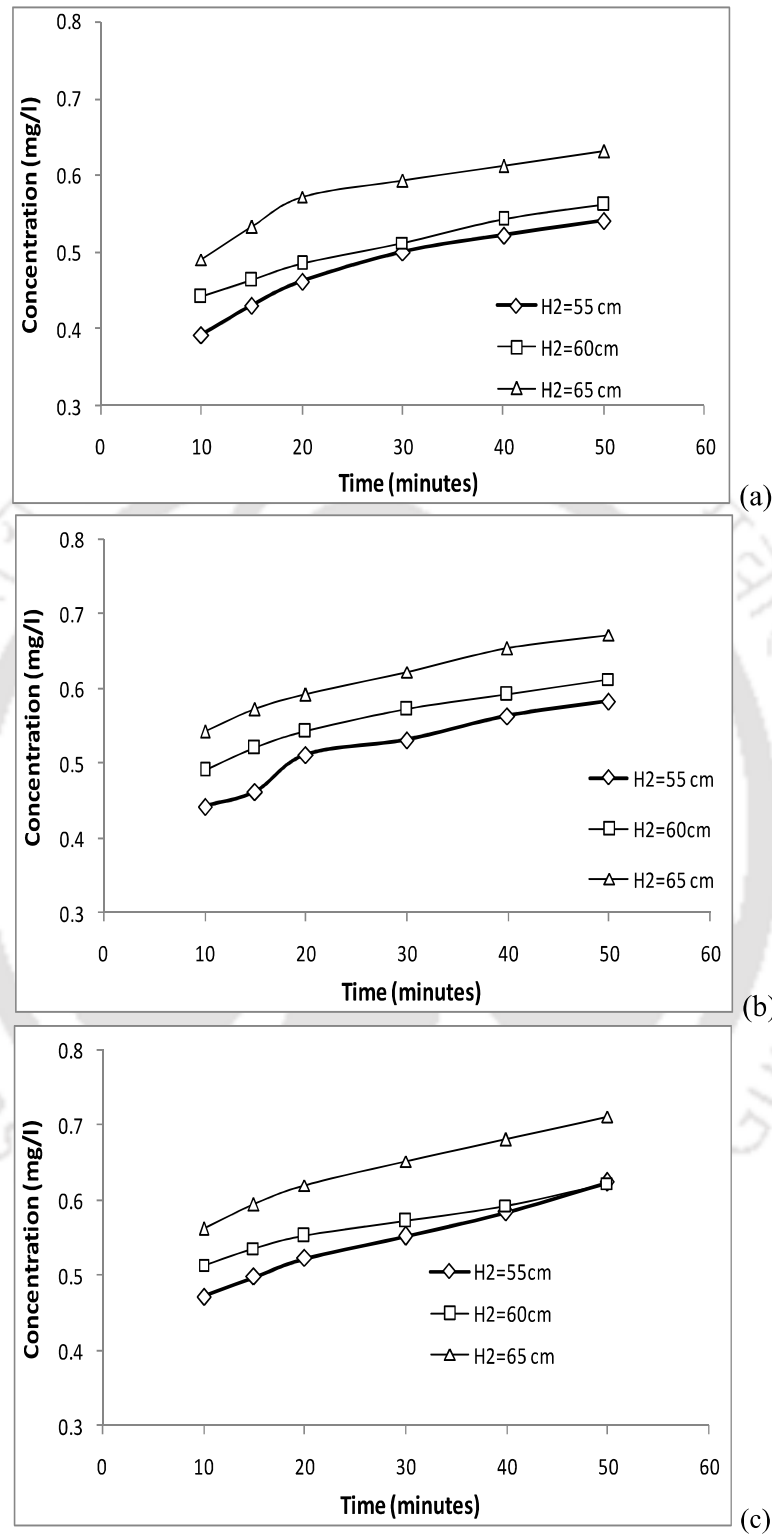


Fig. 4.9 Concentrations of Zn in effluent leachates for filling rate $F = 130$ ml/s for different soil heights a) $H_1 = 5$ cm, $H_2 = 55$ cm, 60 cm and 65 cm and $H_3 = 8$ cm b) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm, and 65 cm $H_3 = 8$ cm c) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 15$ cm

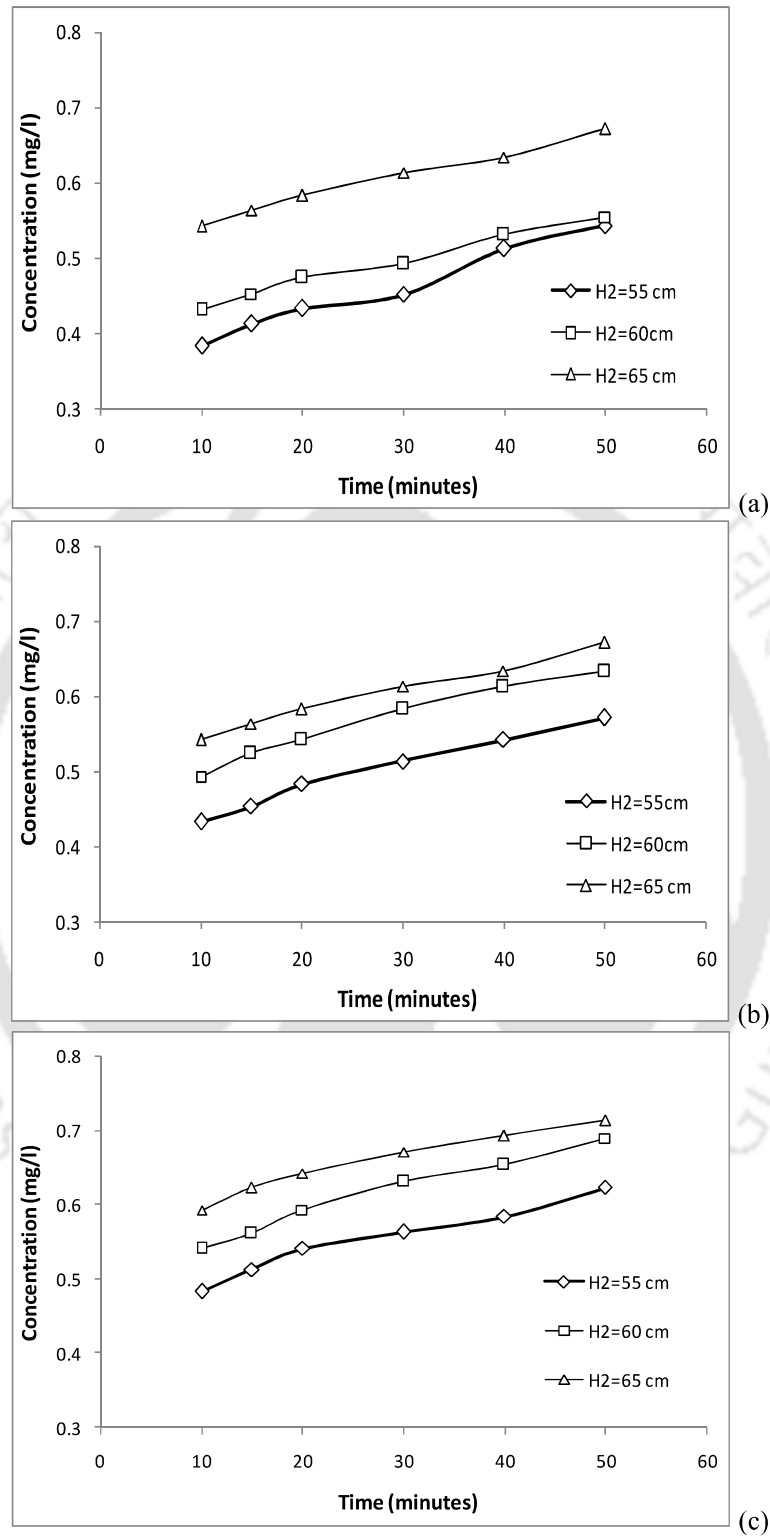


Fig. 4.10 Concentrations of Zn in effluent leachates for filling rate $F = 140$ ml/s for different soil heights a) $H_1 = 5$ cm, $H_2 = 55$ cm, 60 cm and 65 cm and $H_3 = 8$ cm b) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm, and 65 cm, and $H_3 = 8$ cm c) $H_1 = 10$ cm, $H_2 = 55$ cm, 60 cm and 65 cm, and $H_3 = 15$ cm

Table 4.3 Average and standard deviation of percentage change of effluent Zn concentrations, at any instant, for cases involving change in H_2

Case	Average percentage increase in effluent Zn concentration (ΔC_{Zn})		
	H_2 changes from 55 to 60 cm	H_2 changes from 60 to 65 cm	H_2 changes from 55 to 65 cm
$H_1 = 5$ cm, $H_3 = 8$ cm, $F = 100$ ml/s (Fig 4.6a)	7.80 ± 4.10	14.43 ± 2.89	23.43 ± 7.28
$H_1 = 10$ cm, $H_3 = 8$ cm, $F = 100$ ml/s (Fig 4.6b)	13.13 ± 1.64	6.70 ± 2.16	20.72 ± 3.46
$H_1 = 10$ cm, $H_3 = 15$ cm, $F = 100$ ml/s (Fig 4.6c)	10.95 ± 1.26	7.46 ± 2.79	19.21 ± 2.86
$H_1 = 5$ cm, $H_3 = 8$ cm, $F = 110$ ml/s (Fig 4.7a)	5.85 ± 3.78	14.24 ± 2.57	20.88 ± 3.79
$H_1 = 10$ cm, $H_3 = 8$ cm, $F = 110$ ml/s (Fig 4.7b)	8.01 ± 3.20	9.72 ± 0.64	18.51 ± 3.77
$H_1 = 10$ cm, $H_3 = 15$ cm, $F = 110$ ml/s (Fig 4.7c)	4.58 ± 3.48	12.61 ± 2.14	17.70 ± 1.99
$H_1 = 5$ cm, $H_3 = 8$ cm, $F = 120$ ml/s (Fig 4.8a)	0.20 ± 7.34	12.16 ± 2.00	12.43 ± 9.36
$H_1 = 10$ cm, $H_3 = 8$ cm, $F = 120$ ml/s (Fig 4.8b)	11.32 ± 1.53	11.61 ± 3.14	24.20 ± 1.83
$H_1 = 10$ cm, $H_3 = 15$ cm, $F = 120$ ml/s (Fig 4.8c)	12.66 ± 2.09	6.44 ± 2.41	19.91 ± 3.16
$H_1 = 5$ cm, $H_3 = 8$ cm, $F = 130$ ml/s (Fig 4.9a)	8.32 ± 4.01	9.38 ± 3.04	18.48 ± 5.64
$H_1 = 10$ cm, $H_3 = 8$ cm, $F = 130$ ml/s (Fig 4.9b)	8.33 ± 2.89	10.71 ± 1.24	19.94 ± 3.84
$H_1 = 10$ cm, $H_3 = 15$ cm, $F = 130$ ml/s (Fig 4.9c)	10.79 ± 1.84	6.16 ± 1.93	17.64 ± 3.84
$H_1 = 5$ cm, $H_3 = 8$ cm, $F = 140$ ml/s (Fig 4.10a)	12.86 ± 5.61	14.35 ± 1.63	29.08 ± 7.41
$H_1 = 10$ cm, $H_3 = 8$ cm, $F = 140$ ml/s (Fig 4.10b)	4.59 ± 3.59	7.39 ± 1.07	12.31 ± 3.72
$H_1 = 10$ cm, $H_3 = 15$ cm, $F = 140$ ml/s (Fig 4.10c)	7.19 ± 1.58	9.15 ± 1.11	16.99 ± 0.65

Table 4.4 Average and standard deviation of percentage change of effluent Zn concentrations, at any instant, for cases involving change in H_1 and change in H_3

Filling Rate (ml/s)	Case	Average percentage increase in effluent Zn concentration (ΔC_{Zn})		
		$H_2 = 55$ cm	$H_2 = 60$ cm	$H_2 = 65$ cm
100	H_1 increases from 5 to 10 cm; $H_3 = 8$ cm	9.94 ± 3.69	15.40 ± 1.56	7.62 ± 1.94
	$H_1 = 10$ cm; H_3 increases from 8 to 15 cm;	10.62 ± 2.07	8.48 ± 1.17	9.24 ± 1.63
110	H_1 increases from 5 to 10 cm; $H_3 = 8$ cm	8.85 ± 2.50	11.08 ± 1.42	6.72 ± 2.29
	$H_1 = 10$ cm; H_3 increases from 8 to 15 cm;	5.24 ± 2.32	1.87 ± 1.79	4.53 ± 0.76
120	H_1 increases from 5 to 10 cm; $H_3 = 8$ cm	-0.54 ± 8.17	10.44 ± 1.54	9.88 ± 1.59
	$H_1 = 10$ cm; H_3 increases from 8 to 15 cm;	11.28 ± 3.37	12.59 ± 1.78	7.39 ± 2.09
130	H_1 increases from 5 to 10 cm; $H_3 = 8$ cm	7.16 ± 2.91	7.19 ± 2.63	8.50 ± 0.98
	$H_1 = 10$ cm; H_3 increases from 8 to 15 cm;	5.66 ± 0.99	8.08 ± 1.76	3.63 ± 1.23
140	H_1 increases from 5 to 10 cm; $H_3 = 8$ cm	23.09 ± 9.47	13.87 ± 1.74	6.94 ± 1.22
	$H_1 = 10$ cm; H_3 increases from 8 to 15 cm;	0.47 ± 3.61	2.96 ± 1.20	4.64 ± 0.83

In all the above five experimental groups (Figs 4.6 – 4.10), the effluent concentrations were mostly increasing on increase of landfill refuse layer (H_1), base layer soil (H_2), and ponding depth (H_3). The influence of increase in height of landfill refuse layer (H_1) on change in effluent Zn concentrations (ΔC_{Zn}) was briefly described earlier for the experimental set-I, where $F = 100$ ml/s. Continuing the same analyses for other experimental sets, the influence of H_1 was observed by comparing the average percentage change as well as its standard deviation, at any instant, for different depths of $H_2 = 55$, 60, and 65 cm (Table 4.4). The percentage change in Zn concentrations (ΔC_{Zn}), as a result of increase in H_1 from 5 cm to 8 cm, is found maximum at 23.09 ± 9.47 % for the experimental case having $H_2 = 55$ cm,

$H_3 = 8$ cm, and $F = 140$ ml/s. The minimum percentage change was -0.54 ± 8.17 %, observed for the experimental case having $H_2 = 55$ cm, $H_3 = 8$ cm, and $F = 120$ ml/s. The negative value indicates that there may be reduction in average Zn concentration in the latter case, despite the increase in refuse layer height.

Describing the experimental observations further, for the above scenario where $H_2 = 55$ cm, as H_1 increases from 5 cm to 10 cm (Table 4.4), the average increase in effluent Zn concentrations, at any time instant, for filling rates $F = 100, 110, 120, 130$, and 140 ml/s is 9.94 ± 3.69 %, 8.85 ± 2.50 %, -0.54 ± 8.17 %, 7.16 ± 2.91 %, and 23.09 ± 9.47 %, respectively. The average percentage increase is highest for the filling rate 140 ml/s. However, this research cannot conclude that the average percentage increase will increase with the speed in filling the water up to ponding depth on the top of the column. This is evident from these average percentage increase values, which ranges from -0.54 to 23.09 , without following any pattern with the increase in filling rates. Similarly for the scenario, where $H_2 = 60$ cm, as H_1 increases from 5 cm to 10 cm (Table 4.4), the average increase in effluent Zn concentrations, at any time instant, for filling rates $F = 100, 110, 120, 130$, and 140 ml/s is 15.4 ± 1.6 %, 11.08 ± 1.42 %, 10.44 ± 1.54 %, 7.19 ± 2.63 %, and 13.87 ± 1.74 %, respectively. Here, the highest percentage increase is observed when the filling rate is 100 ml/s, which is exactly contrasting from that for $H_2 = 55$ cm. Likewise for the scenario, where $H_2 = 65$ cm, as H_1 increases from 5 cm to 10 cm (Table 4.4), the average increase in effluent Zn concentrations, at any time instant, for filling rates $F = 100, 110, 120, 130$, and 140 ml/s is 7.62 ± 1.94 %, 6.72 ± 2.29 %, 9.88 ± 1.59 %, 8.50 ± 0.98 %, and 6.94 ± 1.22 %, respectively. Here also, there is no systematic pattern in percentage increase with respect to the filling rates. Among the various observations available for the cases involving

increase of H_1 from 5 to 10 cm, the standard deviation was found to be minimum for the case having $H_2 = 65$ cm, $H_3 = 8$ cm, and $F = 130$ ml/s.

The effect of height (or depth) of ponding water at the top of surface, on the leaching of Zn into the column effluents from the soils is also witnessed in the results in Table 4.4. The effluent Zn concentrations increase with increase in ponding depths, as is evident from positive percentage change (ΔC_{Zn}) values (Table 4.4). For example, for the experimental set-I having filling rate $F = 100$ ml/s and $H_1 = 10$ cm, the average percentage change in Zn concentrations for $H_2 = 55, 60$, and 65 cm, respectively are 10.62 ± 2.07 %, 8.48 ± 1.17 %, and 9.24 ± 1.63 %, respectively. Similarly, for $F = 110$ ml/s, the average percentage change in Zn concentrations for $H_2 = 55, 60$, and 65 cm, respectively are 5.24 ± 2.32 %, 1.87 ± 1.79 %, and 4.53 ± 0.76 %, respectively. Table 4.4, further describes the average percentage change and standard deviations for other filling rates as well (viz $F = 120, 130$, and 140 ml/s). Here again, the observations do not reveal any strict pattern in average percentage change of Zn concentrations in the effluents. In addition, the average percentage change in Zn concentrations are observed lower for higher filling rates for $H_2 = 55, 60$, and 65 cm, as is seen for $F = 140$ ml/s (Table 4.4). The average percentage increases were 0.47 %, 2.96 % and 4.64 %, respectively. These low values of average percentage change, for higher values of F , may be attributed to higher advective transport and lower sorption in the base layer in the column. From Table 4.4, it is visible that the standard deviations for percentage change in Zn concentrations were $1.56, 1.17, 1.42, 1.79, 1.54, 1.78, 2.63, 1.76, 1.74$, and 1.20 for $H_2 = 60$ cm, experimental cases. These standard deviations are more or less consistent with just one outlier of 2.63 . Therefore, the consistent standard deviations imply that the experiments in which the base layer soil height is kept as 60 cm may be used as representative columns.

Some typical observations for certain instants, like time $t = 10$ min and 30 min are presented in Tables 4.5 and 4.6. These observations reveal an interesting fact that for the same geometrical dimensions (like H_1 , H_2 , and H_3) for the experiments, the Zn concentration in the effluent is more for cases having higher filling rates. As stated earlier, the increase in Zn concentration may be attributed to more convective transport in the soil column.

Table 4.5 Comparison of Zn concentration in the effluent at time $t = 10$ min and 30 min for $H_1=5$ cm and 10 cm, and $H_3=8$ cm at various filling rates (F)

Time	F (ml/sec)	Concentration of Zn in ppm at different values of H_2 (in cm)					
		55		60		65	
		$H_1 = 5$	$H_1 = 10$	$H_1 = 5$	$H_1 = 10$	$H_1 = 5$	$H_1 = 10$
$t = 10$ min	100	0.3821	0.4322	0.4311	0.4933	0.4921	0.5422
	110	0.3921	0.4423	0.4421	0.4912	0.4912	0.5422
	120	0.4001	0.4521	0.4522	0.4922	0.5122	0.5732
	130	0.4101	0.4611	0.4723	0.5211	0.5322	0.5833
	140	0.4521	0.5231	0.5122	0.5733	0.5832	0.6212
$t = 30$ min	100	0.4511	0.5133	0.4921	0.5823	0.5723	0.6133
	110	0.5001	0.5321	0.5122	0.5733	0.5933	0.6233
	120	0.5321	0.5101	0.5131	0.5712	0.5822	0.6321
	130	0.5221	0.5513	0.5632	0.5932	0.6123	0.6543
	140	0.5321	0.6443	0.5843	0.6541	0.6531	0.7023

Table 4.6 Comparison of Zn concentration in the effluent at time $t = 10$ min and 30 min for $H_1=10$ cm and $H_3=15$ cm at various filling rates (F)

Time	F (ml/sec)	Concentration of Zn in ppm at different values of H_2 (in cm)		
		$H_2 = 55$ cm	$H_2 = 60$ cm	$H_2 = 65$ cm
$t = 10$ min	100	0.4833	0.5412	0.5933
	110	0.4724	0.5144	0.5633
	120	0.4823	0.5433	0.6021
	130	0.4911	0.5543	0.6012
	140	0.5531	0.6021	0.6511
$t = 30$ min	100	0.5633	0.6312	0.6712
	110	0.5522	0.5731	0.6533
	120	0.5732	0.6544	0.6822
	130	0.5833	0.6521	0.6842
	140	0.6122	0.6431	0.7122

4.4 Experimentation with three-dimensional apparatus

The experimental set up for the three dimensional column leach experiment comprises of a trapezoidal apparatus having bottom width of 90 cm, top width of 55 cm, and slanted height of 60 cm. The apparatus was made up of perspex sheet. Soils are filled inside the apparatus. A rainfall simulator is fitted at the top to spray water over the soil layers to simulate rainfall. The apparatus is placed on an iron stand of height 70 cm (Fig 3.9). The bottom of the apparatus contains a perforated net through which the leachates percolate down and accumulate in a collector device fitted just at the bottom of the net. The leachate subsequently flows from the collector to a container, placed at the bottom. This leachate is further transferred and stored in closed bottles.

The refuse soil samples and the normal base layer soil samples used are the same that were collected from the landfill site of Guwahati city and IIT Guwahati campus, respectively. Water is poured over the refuse soil layer using the rainfall simulator device at predetermined inflow intensity. Here, in the three dimensional experiment, the inflow intensity is different from the filling rates for ponding used in one-dimensional experiments. The inflow intensity (F) is the rate at which the water is supplied to the rainfall simulator, from which the water is sprayed or irrigated over the top of the soil surface in the heap for certain duration without ponding. The inflow rate is measured using stop clock and a measuring bottle. Water is sprinkled over the refuse soil layer for 100 seconds. After a certain time, the leachate comes out from the mesh at the bottom of the device, which is collected in a collector arrangement comprising of tin sheet with a slope, fitted below the cylindrical portion of the apparatus. Experiments were conducted for various combinations of heights of refuse soil and base soil with the refuse soil layer ranging from 6 cm and 8

cm and base layer ranging from 6-cm to 10 cm. The inflow intensity is varied from 50 ml/sec to 200 ml/sec.

4.4.1 Results for leaching of sodium, calcium, and potassium in heap shaped column apparatus

The details about heap shaped column leach apparatus and the experimental methodology were presented in Chapter 3. A total of 10 experiments were conducted on the three-dimensional apparatus (Table 4.7). The height of landfill refuse soil (H_1) is varied from 6 cm to 8 cm, whereas that of normal soil is varied as 6 cm, 8 cm and 10 cm. The inflow intensity is varied as 50 ml/s, 60 ml/s, 80 ml/s, 100 ml/s, 125 ml/s, 150 ml/s and 200 ml/s. The concentrations of sodium (Na), calcium (Ca), and potassium (K) in the effluent leachates collected at different time intervals through the perforated net fitted at bottom of the apparatus were determined using Flame photometer.

Table 4.7 Total experiments based on various values of H_1 , H_2 and F in heap shaped column apparatus

Sl. No.	H_1 (cm)	H_2 (cm)	F (ml/sec)
1	6	6	50
2	6	8	50
3	6	8	60
4	6	8	80
5	6	8	100
6	6	10	100
7	6	10	125
8	8	10	125
9	8	10	150
10	8	10	200

In the experiments, the time intervals of sample collections increased from 1 minute in the initial periods to 10 minutes in the later periods. This increase in time interval was for the reason that the volume of effluent collected from the apparatus decreased significantly in

the later periods and, therefore, the interval between sample collections was raised. A typical plot showing the variations in concentrations of nutrients (Na, Ca and K) in the effluent leachates with time is shown in Fig 4.11, where $H_1 = 6$ cm, $H_2 = 6$ cm and $F = 50$ ml/s.

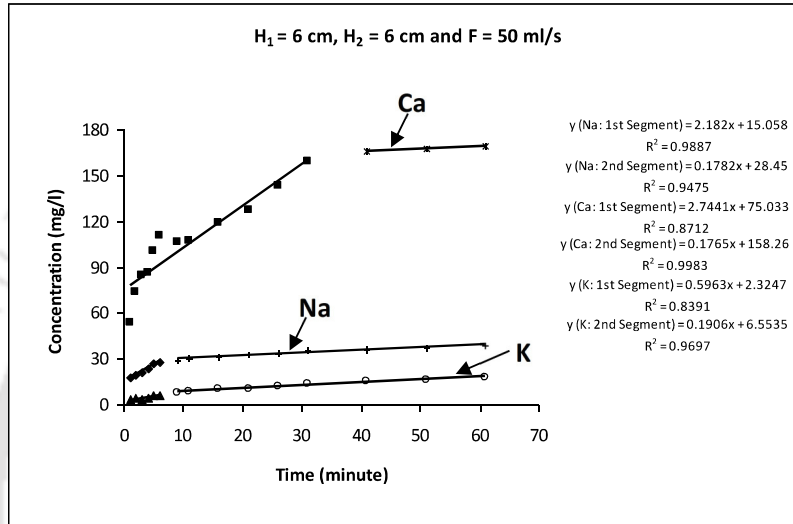


Fig. 4.11 Concentrations of Na, Ca, and K in leachates for $H_1 = 6$ cm, $H_2 = 6$ cm, $F = 50$ ml/s

From Fig 4.11, it is observed that the concentrations of Na, Ca, and K in the effluent leachate increased with time. The rate of increase in concentration of the nutrients was higher during initial period as compared to that during later periods as observed from the slope of the lines plotted on the obtained results. The concentration rate of increase for Na and K in the effluents was higher till about 6 minutes, whereas, the rate for Ca was higher till about 31 minutes (Fig 4.11). The rate of increase of Ca concentration during the initial periods was higher compared to the concentrations of Na and K. In addition, the leached concentration of Ca was significantly higher as compared to Na and K at all intervals. It may be noted that the initial concentrations of Na, Ca, and K in the inflow tap water used in the experimental investigation were 4.39 mg/l, 12.41 mg/l, and 2.08 mg/l, respectively. The concentrations of Na, Ca, and K in the effluent leachate at different time intervals are

higher than that in the inflow tap water as observed from Fig 4.11. These higher concentrations indicate leaching of nutrients from landfill refuse soil and/or normal soil into the percolating water. Similar behaviour is observed in other nine experiments given in Table 4.7.

In order to evaluate the effect of variations in H_1 (height of landfill refuse soil), H_2 (height of normal soil), and F (inflow intensity) on leaching of nutrients, the leaching experiment was categorised as different combinations based on these parameters (Table 4.8).

Table 4.8 Combinations of experiments based on differences in H_1 , H_2 , and F

Combination	H_1 (cm)	H_2 (cm)	F (ml/sec)
I	6	6	50
	6	8	50
II	6	8	100
	6	10	100
III	6	10	125
	8	10	125
IV	6	8	50
	6	8	60
	6	8	80
	6	8	100
V	6	10	100
	6	10	125
VI	8	10	125
	8	10	150
	8	10	200

4.4.2 Effect of normal soil height (H_2) on leaching of sodium, calcium, and potassium

Combinations I and II (in Table 4.8) address the effects of variations in normal soil height on leaching of nutrients. The concentration of nutrients in the effluent leachates, with respect to time, for the experimental combination-I (Table 4.9) increased with increase in height of normal soil layer. As a result, the normal soil can be inferred to contribute to the leaching of these nutrients into the inflow water.

Table 4.9 Concentrations of Na, Ca, and K in the effluent for Combination-I ($H_1 = 6$ cm, $F = 50$ ml/s)

Time (min)	Concentration of nutrients (mg/l)					
	Na		Ca		K	
	$H_2 = 6$ cm	$H_2 = 8$ cm	$H_2 = 6$ cm	$H_2 = 8$ cm	$H_2 = 6$ cm	$H_2 = 8$ cm
1	17.23	19.01	53.22	54.62	3.01	4.41
2	19.44	20.54	73.7	75.1	4.12	5.52
3	21.34	23.11	84.93	86.33	3.44	4.84
4	23.78	25.33	85.92	87.32	4.22	5.62
5	26.75	28.15	100.27	101.67	5.45	6.85
6	27.63	29.03	110.39	111.79	6.23	7.63
9	28.75	30.15	106.43	107.83	7.66	9.06
11	30.53	31.93	107.41	108.81	8.22	9.62
16	31.11	31.92	118.93	120.33	9.87	11.27
21	32.74	34.15	126.87	128.27	10.34	11.74
26	33.41	34.81	143.45	144.85	11.71	13.11
31	35.41	36.81	159.33	160.73	13.36	14.76
41	35.71	37.11	165.45	166.85	15.23	16.63
51	37.05	38.45	167.34	168.74	16.13	17.53
61	38.93	40.33	168.98	170.38	17.35	18.75

Table 4.10 Percentage increase (change) in concentration of nutrients in leachates from the experimental Combination-I for normal soil height H_2 increasing from 6 cm to 8 cm, $H_1 = 6$ cm and $F = 50$ ml/s

Time interval (min)	% increase in concentration		
	Na	Ca	K
1	9.36	2.56	31.75
2	5.36	1.86	25.36
3	7.66	1.62	28.93
4	6.12	1.60	24.91
5	4.97	1.38	20.44
6	4.82	1.25	18.35
9	4.64	1.30	15.45
11	4.38	1.29	14.55
16	2.54	1.16	12.42
21	4.13	1.09	11.93
26	4.02	0.97	10.68
31	3.80	0.87	9.49
41	3.77	0.84	8.42
51	3.64	0.83	7.99
61	3.47	0.82	7.47
Minimum	2.54	0.82	7.47
Maximum	9.36	2.56	31.75
Average	4.85	1.30	16.54
Standard deviation	1.74	0.47	8.02

The average percentage increase (or change) in the leached concentrations of sodium, calcium, and potassium over all time intervals (Table 4.9) are 4.85% (Min: 2.54%; Max: 9.36%), 1.30% (Min: 0.82%; Max: 2.56%) and 16.54% (Min: 7.47%; Max: 31.75%) respectively as the normal soil height increased from 6 cm to 8 cm (Table 4.10).

The percentage change in concentration of the nutrients in leachates at different time intervals, when the normal soil height H_2 increased from 6 cm to 8 cm is calculated using the following expression.

$$P_c = \frac{(C_2 - C_1)}{(C_2)} \times 100 \quad (4.1)$$

Where,

P_c = Percentage change in concentration of nutrient; C_2 = concentration of nutrient in the leachate at a given time interval for higher H_2 (i.e. 8 cm); and C_1 = concentration of nutrient in the leachate at a given time interval for lower H_2 (i.e. 6 cm).

A more or less similar inference can also be made for the experiments in Combination-II, with $H_1 = 6$ cm and $F = 100$ ml/s and H_2 varying from 8 cm to 10 cm (Table 4.11). For the experimental Combination-II (Table 4.11), it is observed that the concentration of sodium and calcium in the leachates mostly increased with increase in the height of normal soil. The average percentage increase (or change) in the leached concentrations of sodium and calcium, over all time intervals are 2.74% (Min: -1.27%; Max: 6.34%) and 2.72% (Min: 1.08%; Max: 4.54%), respectively. However, for potassium, the opposite behaviour was observed. That is, the concentration in the leachates mostly decreased with increase in the height of normal soil. This may be attributed to trapping of potassium in the normal soil to a greater extent for higher heights, after leaching from the landfill soil. The average percentage change in the leached concentrations of potassium is 22.93% (Min: 39.17%; Max: 17.73%).

Table 4.11 Concentrations of Na, Ca, and K in the effluent for Combination-II ($H_1 = 6$ cm, $F = 100$ ml/s)

Time (min)	Concentration of nutrients (mg/l)					
	Na		Ca		K	
	$H_2 = 8$ cm	$H_2 = 10$ cm	$H_2 = 8$ cm	$H_2 = 10$ cm	$H_2 = 8$ cm	$H_2 = 10$ cm
1	23.23	24.11	58	59	7.33	8.91
2	25.44	25.12	79.23	80.33	9.23	10.01
3	27.89	28.33	86.33	90.44	11.23	9.12
4	29.45	30.35	89.21	92.45	12.11	10.44
5	31.33	33.45	103.23	106.39	13.95	11.12
6	32.44	34.45	112.45	116.39	15.01	12.45
9	33.15	35.33	107.99	112.23	16.45	13.33
11	34.89	36.85	109.45	113.23	18.11	14.12
16	36.13	37.24	120.35	124.49	19.23	15.55
21	37.45	39.33	128.39	132.34	22.11	16.23
26	39.33	40.13	145.88	149.39	24.23	17.41
31	41.44	41.35	160.33	164.85	26.11	19.33
41	42.33	42.33	168.22	171.45	28.33	21.12
51	44.55	44.45	170.34	173.45	29.39	22.13
61	45.29	45.83	172.33	174.21	30.85	23.45

The percentage change in concentrations of the nutrients in the effluents, in experimental Combinations I and II, can be speculated to mostly decrease with passage of time. However, this inference may not be satisfactory in some of the cases.

4.4.3 Effect of landfill refuse soil height (H_1) on leaching of sodium, calcium, and potassium

In order to demonstrate the effect of height of landfill refuse soil (H_1) on leaching of the nutrients in the heap shaped column apparatus, a comparative analysis (Table 4.12) showing the variations in concentrations of the nutrients in leachates between two cases i.e. $H_1 = 6$ cm and $H_1 = 8$ cm for $H_2 = 10$ cm and $F = 125$ ml/s (Experimental Combination III) is presented.

Table 4.12 Concentrations of Na, Ca, and K in the effluent for Combination-III ($H_2 = 10$ cm, $F = 125$ ml/s)

Time (min)	Concentration of nutrients					
	Na		Ca		K	
	$H_1 = 6$ cm	$H_1 = 8$ cm	$H_1 = 6$ cm	$H_1 = 8$ cm	$H_1 = 6$ cm	$H_1 = 8$ cm
1	25.12	27.1	60.12	60.11	10.11	11.52
2	26.23	28.2	81.33	81.23	11.21	12.44
3	29.33	29.1	91.35	91.25	10.45	12.12
4	31.34	31.2	93.34	93.22	11.23	13.23
5	33.44	33.1	107.33	107.32	11.45	13.11
6	35.22	35.1	117.87	117.85	13.33	15.11
9	36.32	36.22	113.52	113.55	14.32	16.23
11	37.34	37.01	114.25	114.23	15.45	17.11
16	38.23	38.22	126.11	126.25	17.43	18.45
21	40.32	40.22	132.43	132.45	18.23	19.23
26	41.22	41.34	150.32	150.21	19.45	20.23
31	42.45	42.21	166.11	158.34	20.31	21.22
41	43.43	43.71	172.43	166.24	22.23	22.34
51	45.33	45.1	174.35	172.45	23.44	23.59
61	46.91	46.23	175.12	173.88	25.12	25.12

The concentration of potassium in the leachates increased with increase in height of landfill refuse soil, whereas for sodium and calcium, mostly there were slight decrease in concentration with increase in landfill refuse soil height (Table 4.12). This indicates that for potassium, the increase in the height of landfill soil resulted in an increase in its leaching from landfill refuse soil into the inflow water. However, for Na and Ca, the decrease in their concentrations in the leachates with increase in landfill refuse soil height may be attributed to relatively more trapping of these nutrients from the flowing water into the lower portions of the refuse soil. The substantiation of this trapping phenomenon of nutrients, in the lower portions of refuse soil, using mechanics of flow and transport through porous media are, however, beyond the scope of this research. The percentage increase in the leached concentration of potassium with increase in landfill soil height (i.e. H_1 from 6 cm to 8 cm) over all time intervals varied from 0.0% to 15.12% with an average value of 7.80%. For sodium and calcium, the percentage change in the leached

concentration varied from -1.47% to 7.31% (average: 0.57%) and from -4.91% to 0.11% (average: -0.72%), respectively.

4.4.4 Effect of inflow intensity (F) on leaching of sodium, calcium, and potassium

The inflow intensity (F) or inflow filling rate in the heap shaped column experiments used may simulate the rainfall of different intensities on the landfill sites. Comparative plots showing the variations in concentrations of nutrients among different inflow filling rates i.e. 50 ml/s, 60 ml/s, 80 ml/s and 100ml/s for the case of $H_1 = 6$ cm and $H_2 = 8$ cm (Combination-IV) are shown in Figs 4.12, 4.13, and 4.14 for sodium (Na), calcium (Ca), and potassium (K), respectively. From these figures, it is observed that the concentrations of all the nutrients in the outflow leachate mostly increased with increase in inflow filling rate. This increase indicates that an increment in inflow filling rate increases the spraying over the landfill refuse soil that results in increased leaching of these nutrients from soil into the inflow water. By simulating this scenario at landfill site, the variations in the amount of leaching of nutrients with different rainfall intensities may be construed.

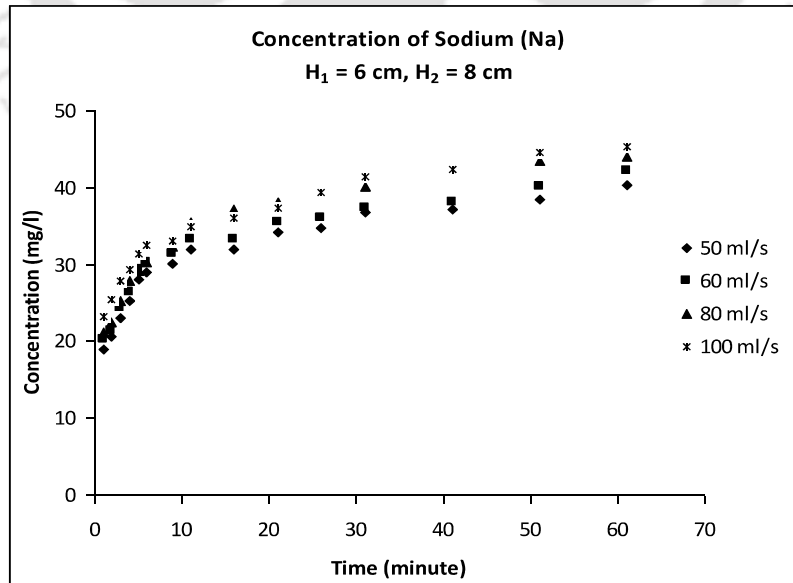


Fig. 4.12 Variation in concentrations of sodium (Na) in leachates among different inflow filling rates for $H_1 = 6$ cm and $H_2 = 8$ cm

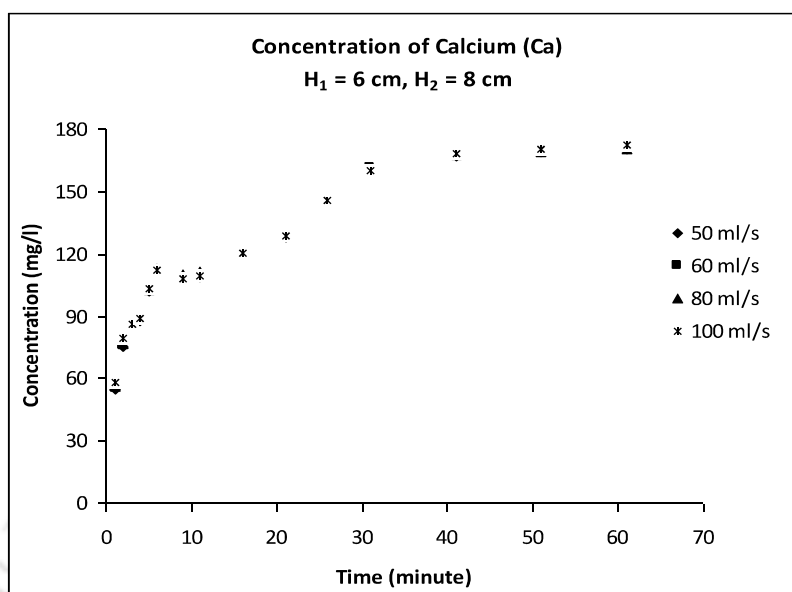


Fig. 4.13 Variation in concentrations of calcium (Ca) in leachates among different inflow filling rates for $H_1 = 6$ cm and $H_2 = 8$ cm

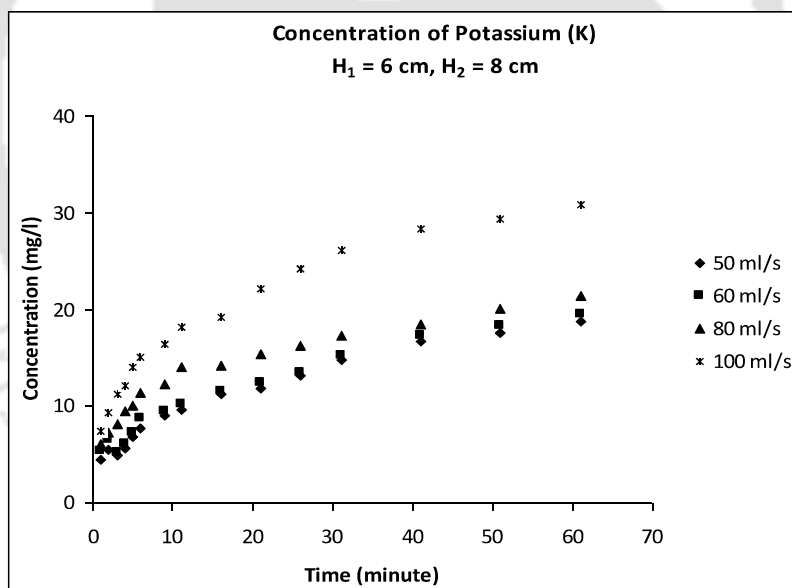


Fig. 4.14 Variation in concentrations of potassium (K) in leachates among different inflow filling rates for $H_1 = 6$ cm and $H_2 = 8$ cm

For quantifying the increase in the extent of leaching of the nutrients with increase in inflow filling rate, the percentage increase values are calculated. The average percentage increase in the leached concentrations of sodium, calcium and potassium over all the time periods

are 3.98% (Min: 1.42%; Max: 6.49%), 0.51% (Min: 0.12% ; Max: 1.33%), and 6.57% (Min: 2.42%; Max: 17.26%), respectively as the inflow filling rate increases from 50 ml/s to 60 ml/s. Similarly, the average percentage increase in the leached concentrations of Na, Ca, and K are 5.39% (Min: -1.17%; Max: 10.75%), 0.44% (Min: -0.62%; Max: 2.17%), and 19.23% (Min: 6.57%; Max: 35.51%), respectively for increase in inflow intensity from 60 ml/s to 80 ml/s and 3.54% (Min:-3.02%; Max: 11.75%), 0.35% (Min:1.85%; Max: 3.51%), and 27.25% (Min: 16.64%; Max: 34.95%), respectively as the inflow filling rate increases from 80 ml/s to 100 ml/s. From these values it is observed that, the increase in leaching of calcium with increase in inflow filling rate is very less as compared to sodium and potassium, although the magnitude of leached concentrations of calcium in the outflow leachate are significantly higher as compared to sodium and potassium. This indicates that an increase in amount of spraying has less effect on leaching of calcium from the soil as compared to sodium and potassium. For other experimental combinations, i.e. combinations with $H_1 = 6$ cm, and $H_2 = 10$ cm for inflow filling rates of 100 ml/s, and 125 ml/s (Combination-V) and combinations with $H_1 = 8$ cm, and $H_2 = 10$ cm for inflow filling rates of 125 ml/s, 150 ml/s and 200 ml/s (Combination-VI), the concentrations of nutrients with respect to time are presented in Tables 4.13 and 4.14, respectively. As observed from these tables, the nutrient concentration in the outflow leachate increased with increase in inflow filling rate. However, a decrease in concentration of Na and Ca was observed in some cases with the increase in inflow filling rate for the above experimental combinations.

Table 4.13 Comparison of concentrations of nutrients in leachates for different inflow intensities (Combination-V: $H_1 = 6$ cm, and $H_2 = 10$ cm)

Time interval (min)	Concentration of Na (mg/l)		Concentration of Ca (mg/l)		Concentration of K (mg/l)	
	F= 100 ml/s	F= 125 ml/s	F= 100 ml/s	F= 125 ml/s	F= 100 ml/s	F= 125 ml/s
1	24.11	25.12	59	60.12	8.91	10.11
2	25.12	26.23	80.33	81.33	10.01	11.21
3	28.33	29.33	90.44	91.35	9.12	10.45
4	30.35	31.34	92.45	93.34	10.44	11.23
5	33.45	33.44	106.39	107.33	11.12	11.45
6	34.45	35.22	116.39	117.87	12.45	13.33
9	35.33	36.32	112.23	113.52	13.33	14.32
11	36.85	37.34	113.23	114.25	14.12	15.45
16	37.24	38.23	124.49	126.11	15.55	17.43
21	39.33	40.32	132.34	132.43	16.23	18.23
26	40.13	41.22	149.39	150.32	17.41	19.45
31	41.35	42.45	164.85	166.11	19.33	20.31
41	42.33	43.43	171.45	172.43	21.12	22.23
51	44.45	45.33	173.45	174.35	22.13	23.44
61	45.83	46.91	174.21	175.12	23.45	25.12

In this section, the leaching of nutrients from the soils filled in the three dimensional apparatus was explained by categorizing these experiments into various combinations (Table 4.8). The percentage change in the concentrations of the nutrients in the leachate due to the change in geometric and hydraulic parameters (viz. H_1 , H_2 , and F) were computed by finding the difference in concentration at the same instant and averaging this value over the entire temporal observations (i.e. 1 min to 61 min).

A consolidated view of the average and standard deviation of the percentage change for all the combinations is given in Table 4.15. As evident, the average percentage change is more for potassium, followed by sodium and least for calcium. Interestingly, the standard deviation of percentage change is least for calcium and highest for potassium. Therefore, this observation on average and standard deviation of percentage change implies that the leaching of potassium is more sensitive to the change in geometric and hydraulic parameters (viz. H_1 , H_2 , and F).

Table 4.14 Comparison of concentrations of nutrients in leachates for different inflow intensities (Combination-VI: $H_1 = 8$ cm and $H_2 = 10$ cm)

Time interval (min)	Concentration of Na (mg/l)			Concentration of Ca (mg/l)			Concentration of K (mg/l)		
	$F=125$ ml/s	$F=150$ ml/s	$F=200$ ml/s	$F=125$ ml/s	$F=150$ ml/s	$F=200$ ml/s	$F=125$ ml/s	$F=150$ ml/s	$F=200$ ml/s
1	27.1	28.31	30.15	60.11	62.13	64.32	11.52	13.31	15.43
2	28.2	30.14	32.13	81.23	83.21	85.34	12.44	14.22	16.31
3	29.1	31.22	33.43	91.25	93.22	93.21	12.12	14.12	16.45
4	31.2	33.23	35.41	93.22	95.23	95.43	13.23	15.01	17.13
5	33.1	35.11	37.23	107.32	109.44	109.45	13.11	15.33	17.43
6	35.1	36.43	38.41	117.85	119.21	119.23	15.11	16.81	18.98
9	36.22	37.43	39.43	113.55	115.41	120.45	16.23	17.23	19.43
11	37.01	38.32	40.45	114.23	116.21	128.34	17.11	18.22	20.23
16	38.22	39.41	41.56	126.25	128.23	135.31	18.45	19.21	21.34
21	40.22	41.32	43.44	132.45	134.22	141.23	19.23	20.32	22.44
26	41.34	42.43	44.51	150.21	152.55	152.32	20.23	21.33	23.45
31	42.21	44.22	46.31	158.34	160.33	160.34	21.22	22.14	24.23
41	43.71	46.33	48.49	166.24	168.41	168.43	22.34	22.93	25.01
51	45.1	47.21	49.34	172.45	174.88	174.92	23.59	24.31	26.43
61	46.23	48.01	50.12	173.88	175.31	175.34	25.12	26.31	28.45

Table 4.15 Average and standard deviation of percentage change in concentrations of Na, Ca, and K in the effluent for different combinations

Combination	H_1 (cm)	H_2 (cm)	F (ml/sec)	Average % change			Standard deviation of % change		
				Na	Ca	K	Na	Ca	K
I	6	6 to 8	50	4.85	1.30	16.54	1.74	0.47	8.02
II	6	8 to 10	100	2.74	2.72	-22.93	2.56	0.99	15.97
III	6 to 8	10	125	0.57	-0.72	7.80	2.72	1.51	5.19
IV	6	8	50 to 60	3.98	0.51	6.57	1.09	0.39	4.60
	6	8	60 to 80	5.39	0.44	19.23	3.35	0.85	9.46
	6	8	80 to 100	3.54	0.35	27.25	4.48	1.43	5.22
V	6	10	100 to 125	2.54	0.90	8.11	1.03	0.43	2.98
VI	8	10	125 to 150	4.42	1.69	7.81	1.41	0.60	4.40
	8	10	150 to 200	5.23	1.99	10.59	0.76	2.89	2.13

4.5 Empirical formula for prediction of C_{Na} , C_{Ca} , and C_K

The large numbers of experimental observations from the short columns are utilized to develop empirical relations that can predict concentrations of the nutrients in the effluent from a column filled with combinations of landfill refuse soil and normal soil. The form in equation [4.1] is independently used for empirical formulations for Na, Ca, and K. Since there is more than one independent variable in [4.1], several possible regressive techniques – viz. linear, non-linear polynomials, logarithmic, and exponential relations, etc. are tested to arrive at an appropriate expression for the function f .

From the 19 sets of experiments (Table-4.1), there are 113 observational points for each nutrient – viz. Na, Ca, and K. The procedure followed was to use approximately 70 percent of the data to create the non-linear least square (NLS) empirical model and use this model to predict the nutrient concentrations of the remaining 30 percent data to validate the model. From the four groups of experiments based on H_I (Table-4.1), approximately 70 percent data from each group is chosen to formulate the empirical model. Therefore, the empirical model is developed using the seventy-seven data points (=68.15 %), and validated using the remaining thirty-six data points (=31.85 %). The exponential relations gave the best empirical form among the various regressive relations viz. – linear, polynomials, logarithmic, and exponential equations (Table 4.16). For example, the best possible empirical expression for Na, with the highest coefficient of goodness of fit or coefficient of determination ($R^2 = 0.7561$) between the observed and fitted values (Fig 4.15), was obtained while using the following exponential relation [4.2]:

$$C_{Na} = \exp(3.4676H_1 \times 10^{-2} + 2.2541H_2 \times 10^{-2} + 8.6440H_3 \times 10^{-3} + 5.486F \times 10^{-3} - 2.9215t \times 10^{-2} + 0.9028) \quad (4.2)$$

This empirical equation [4.2] is subsequently used to predict the concentration of Na in the effluent leachate for the remaining 36 independent data of the 19 set of experiments described in Table-4.1 and the results are compared (Fig 4.16). The predicted values match well with the observed values with a coefficient of goodness fit $R^2 = 0.8322$. Similar exercises are performed for the development and validation of empirical equations for concentrations of Ca and K. The empirical equation for Ca concentration is developed with $R^2 = 0.9006$ (Fig 4.17) using the 77 data points and this empirical equation [4.3] is validated with the 36 data points with a resulting $R^2 = 0.8868$ (Fig 4.18). Similarly, the empirical equation for K-concentration [4.4] is developed with a coefficient of goodness fit as 0.9609 (Fig 4.19). This empirical model is validated by predicting well, with a coefficient of goodness fit $R^2 = 0.9093$ (Fig 4.20), the K-concentrations in the effluent leachates of the remaining data.

$$C_{Ca} = \exp(3.0088H_1 \times 10^{-2} + 6.0428H_2 \times 10^{-2} - 4.4067H_3 \times 10^{-4} + 4.7432F \times 10^{-3} - 2.1163t \times 10^{-2} + 0.5008) \quad (4.3)$$

$$C_K = \exp(4.8057H_1 \times 10^{-2} + 3.3166H_2 \times 10^{-2} + 3.7039H_3 \times 10^{-2} + 9.4580F \times 10^{-3} - 1.7262t \times 10^{-2} + 0.4161) \quad (4.4)$$

Table 4.16 Various empirical formulas tested to the experimental data

Relation and Empirical Form	Nutrient	Coefficients							R ²
		a	b	c	d	e	f	g	
Linear $C = aH_1 + bH_2 + cH_3 + dF + et + f$	Na	0.159	0.144	-0.254	2.205×10^{-2}	-0.109	3.550	-	0.6525
	Ca	0.213	0.436	0.889×10^{-2}	2.141×10^{-2}	-0.142	-1.941	-	0.7862
	K	0.491	0.319	4.129×10^{-2}	6.875×10^{-2}	-0.146	-3.753	-	0.8745
Polynomial $C = aH_1 + bH_2 + cH_3 + dF + et^f + g$	Na	0.159	0.140	-0.213	2.135×10^{-2}	-3.223	0.327	9.497	0.6802
	Ca	0.213	0.432	5.097×10^{-2}	2.070×10^{-2}	-1.813	0.469	2.173	0.7939
	K	0.490	0.312	0.104	6.778×10^{-2}	-7.491	0.245	8.236	0.8862
Logarithmic $C = a \log H_1 + b \log H_2 + c \log H_3 + d \log F + e \log t + f$	Na	1.736	3.249	-1.974	1.183	-3.023	-0.408	-	0.7038
	Ca	2.315	8.995	1.582	1.408	-3.831	-22.474	-	0.7832
	K	4.469	6.885	3.953	4.288	-4.026	-35.553	-	0.8566
Exponential $C = \exp(aH_1 + bH_2 + cH_3 + dF + et + f)$	Na	3.467×10^{-2}	2.254×10^{-2}	-0.864×10^{-2}	0.548×10^{-2}	2.921×10^{-2}	0.902	-	0.7561
	Ca	3.008×10^{-2}	6.042×10^{-2}	-0.441×10^{-3}	0.474×10^{-2}	-2.116×10^{-2}	0.501	-	0.9006
	K	4.805×10^{-2}	3.316×10^{-2}	3.703×10^{-2}	0.946×10^{-2}	-1.726×10^{-2}	0.416	-	0.9609

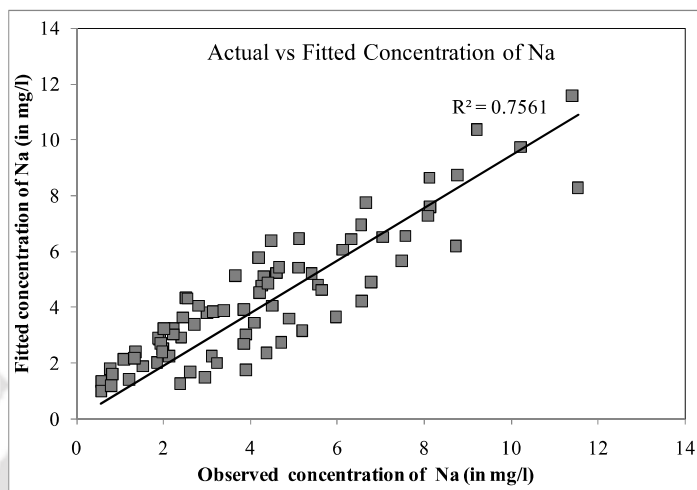


Fig. 4.15 Comparison of actual and fitted Na-concentrations in the development of empirical model [4.2] using 77 data point

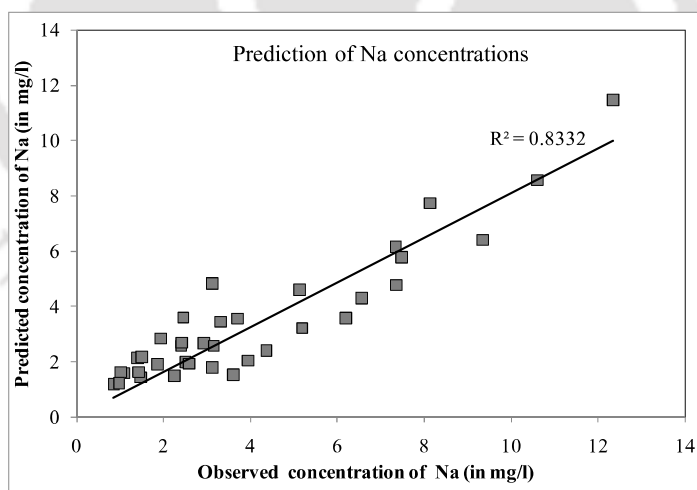


Fig. 4.16 Comparison of predicted and actual Na-concentrations in the validation of empirical model [4.2] using 36 data points

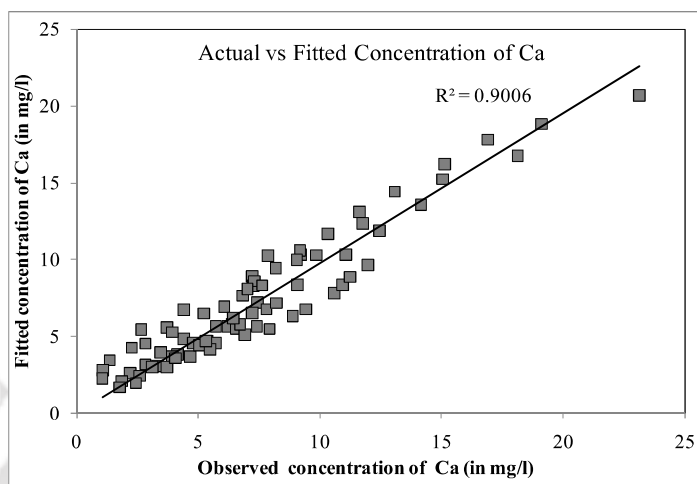


Fig. 4.17 Comparison of actual and fitted Ca-concentrations in the development of empirical model [4.3] using 77 data points

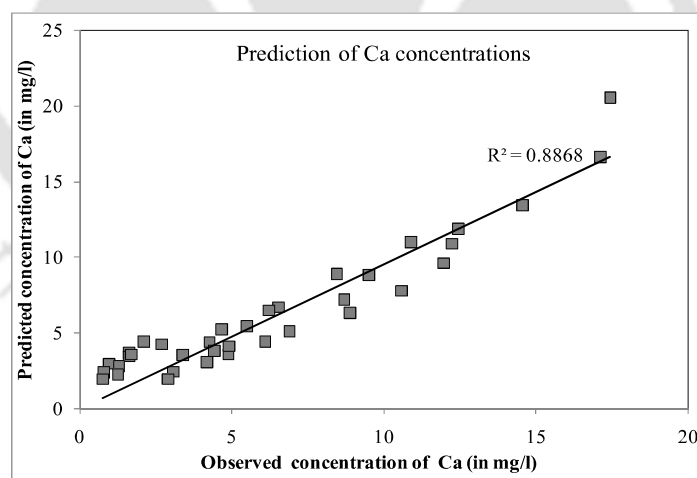


Fig. 4.18 Comparison of predicted and actual Ca-concentrations in the validation of empirical model [4.3] using 36 data points

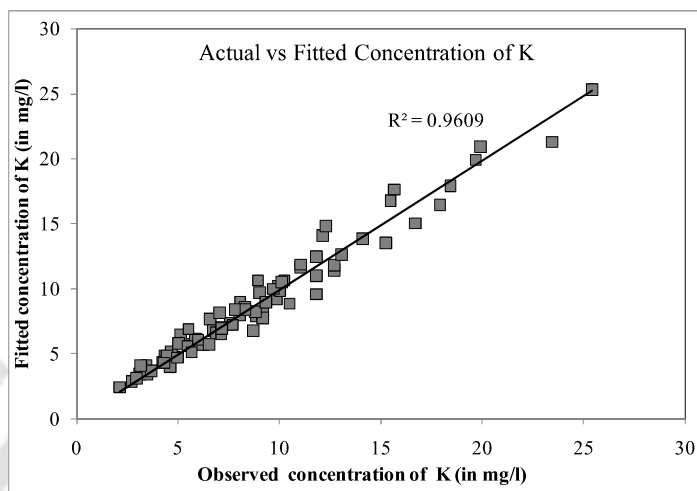


Fig. 4.19 Comparison of actual and fitted K-concentrations in the development of empirical model [4.4] using 77 data points

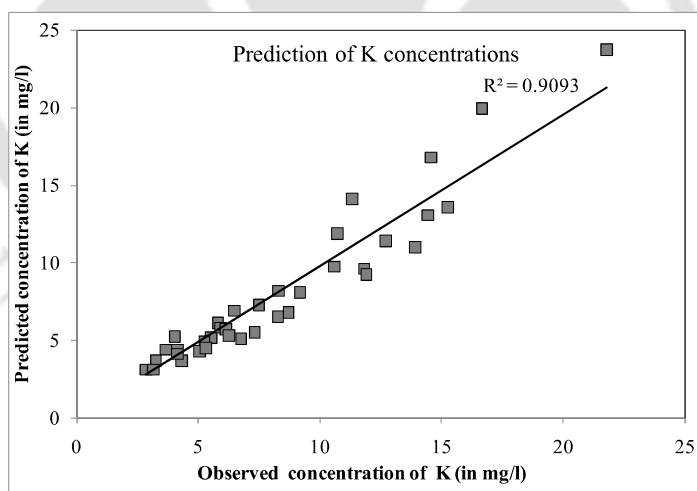


Fig. 4.20 Comparison of predicted and actual K-concentrations in the validation of empirical model [4.4] using 36 data points

The empirical models [4.2], [4.3], and [4.4] developed purely based on the experiments have following units for the independent variables. H_1 , H_2 , and H_3 are in centimetres (cm), F is in millilitres per second (ml/s), and the time t is in minutes (min). The dependent variable in the empirical model is the concentration of the nutrient in the effluent leachate and its unit is in milligrams per litre. The empirical models are further tested for their efficiency in predicting concentrations of nutrients for each category (or range) of the independent variables. The efficiencies of the models are tested by evaluating and comparing coefficients of correlations (R^2) between observed and predicted values for different categories of variable range (Table 4.17).

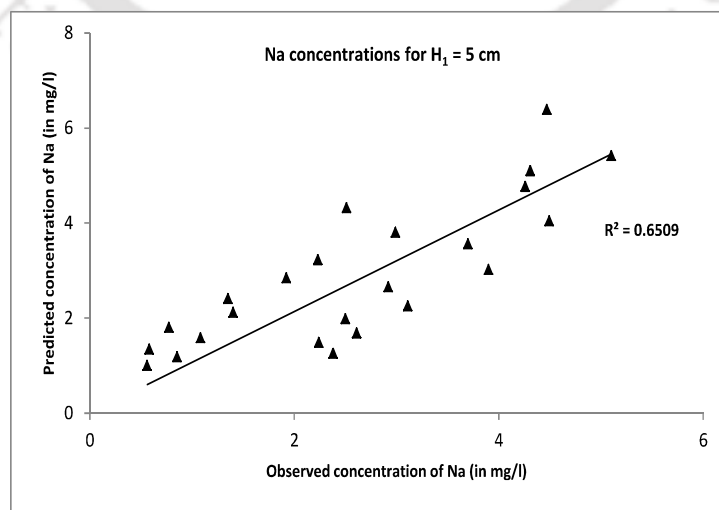
Table 4.17 Efficiency of the empirical models in terms of R^2 values for each range of the independent variables

Category of Variable	Value Range	Coefficient of Correlation (R^2)		
		Na	Ca	K
Landfill refuse soil height, H_1 (cm)	5	0.6509	0.7964	0.9207
	10	0.6965	0.7974	0.9237
	15	0.8323	0.9283	0.8907
	20	0.7476	0.9136	0.9405
Base soil height, H_2 (cm)	15	0.7769	0.2093	0.9184
	20	0.8076	0.4462	0.9675
	25	0.7215	0.7672	0.9266
	30	0.7882	0.9248	0.8678
Bonding depth, H_3 (cm)	8	0.6095	0.7391	0.8807
	10	0.7856	0.9056	0.9213
Filling rate, F (ml/s)	50	0.7170	0.8949	0.9652
	70	0.9060	0.9284	0.9492
	80	0.7011	0.6426	0.8682

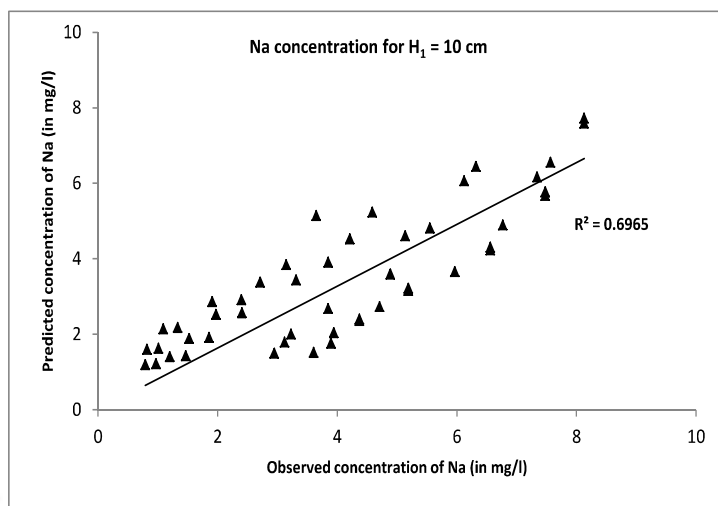
For example, the entire 113 independent data are categorized first with respect to the height of refuse soils viz. $H_1=5$, 10, 15, and 20 cm, respectively (same as groups 1, 2, 3, and 4). The empirical models predicted satisfactorily the concentrations of Na, Ca, and K for each category of H_1 . Similarly, the data set is categorized with respect to the heights of the base soil $H_2=15$, 20, 25, and 30 cm, respectively; with respect to ponding depths as $H_3=8$ and

10 cm, respectively; and with respect to filling rates $F = 50, 70$, and 80 ml/s, respectively. The predicted versus observed effluent concentrations of these nutrients for the above 13 categories can be plotted: for Na (Figs 4.21a-m), for Ca (Figs 4.22a-m), and for K (Figs 4.23a-m). The models predicted well for almost all of the categories (Table 4.17). However, the predictions of effluent calcium concentrations using empirical model [4.3] were poor for base soil categories $H_2=15$ cm and $H_2=20$ cm that can be cited as some limitation of the Ca-empirical model [4.3]. Despite this particular drawback, these empirical models [4.2, 4.3, and 4.4] are relevant as both Na-model [4.2] and K-model [4.4] predicted well with higher coefficients of correlations for all the 13 categories and Ca-model [4.3] predicted successfully for 11 out of 13 categories (Table 4.17).

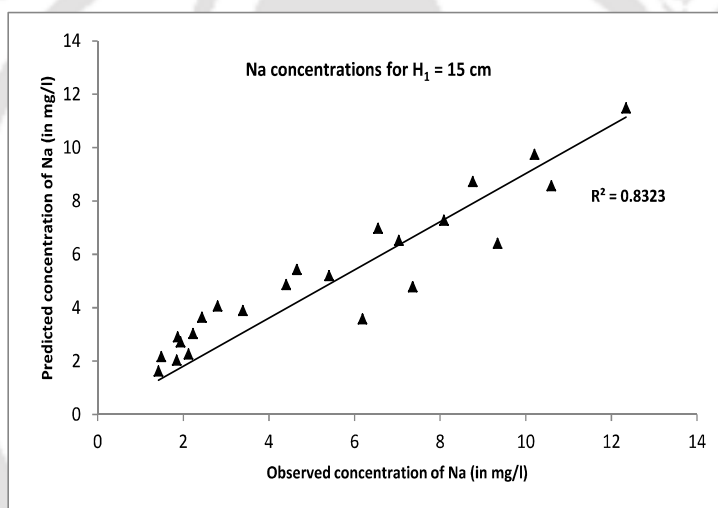
Fig. 4.21 (a-m) Predicted versus observed concentrations of Na in effluent leachates: a) $H_1 = 5$ cm; b) $H_1 = 10$ cm; c) $H_1 = 15$ cm; d) $H_1 = 20$ cm; e) $H_2 = 15$ cm; f) $H_2 = 20$ cm; g) $H_2 = 25$ cm; h) $H_2 = 30$ cm; i) $H_3 = 8$ cm; j) $H_3 = 10$ cm; k) $F = 50$ ml/s; l) $F = 70$ ml/s; m) $F = 80$ ml/s ↓



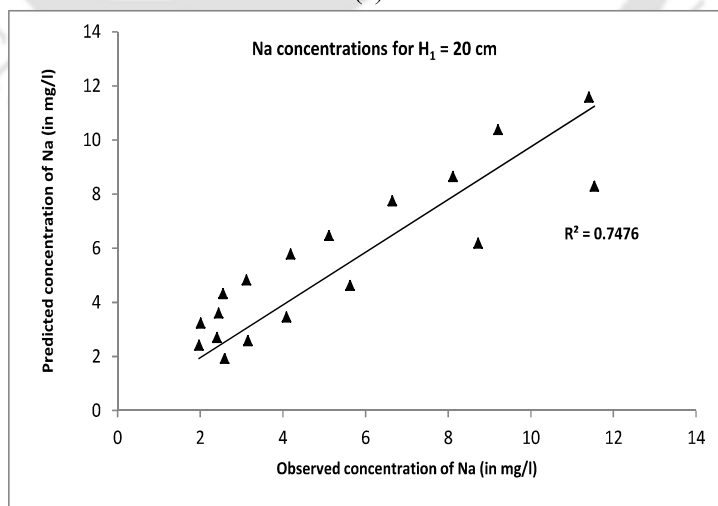
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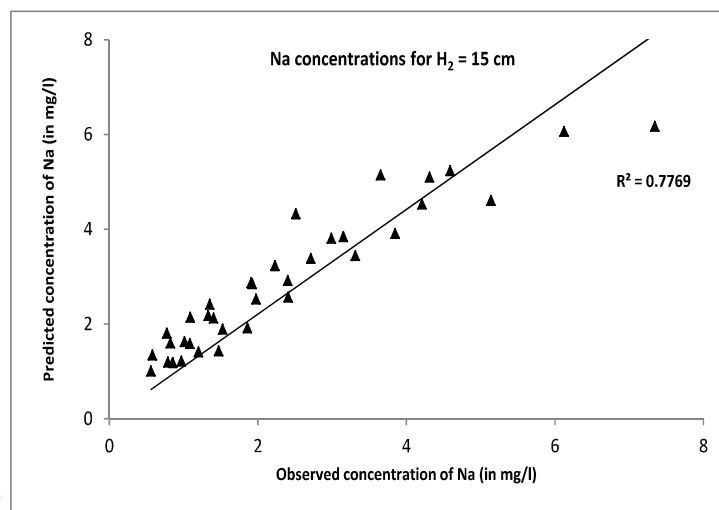
(b)



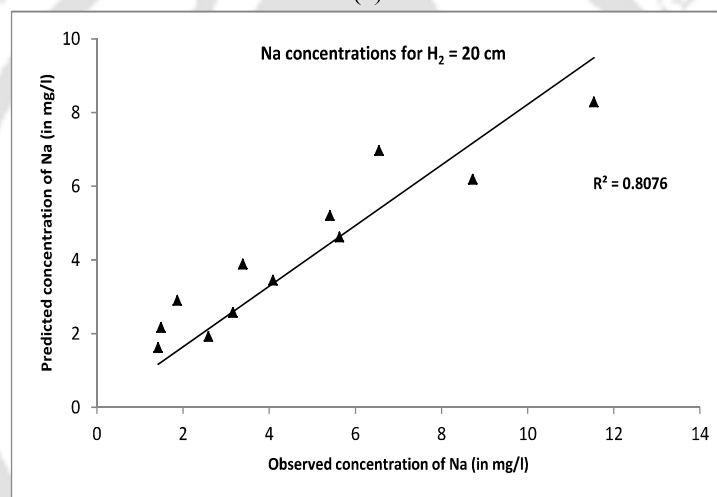
(c)



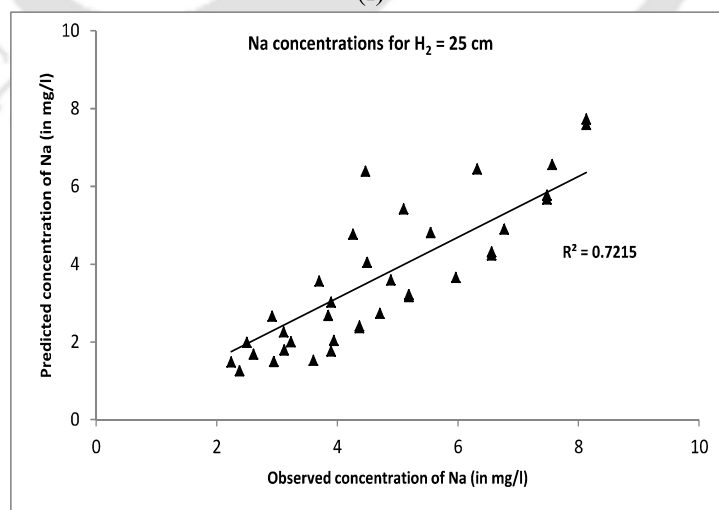
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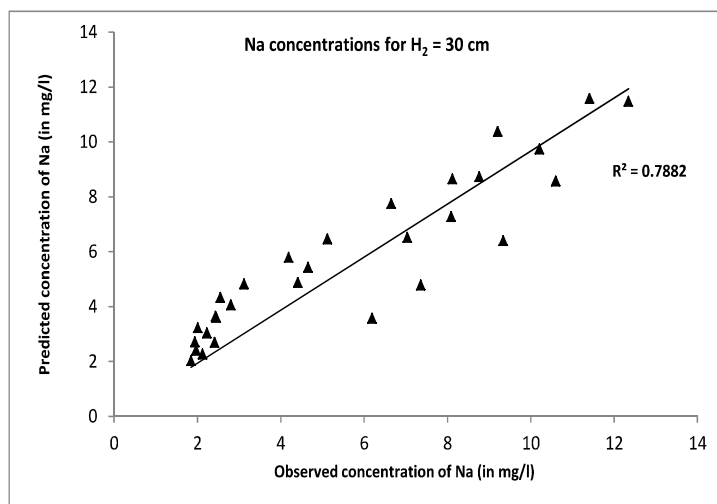
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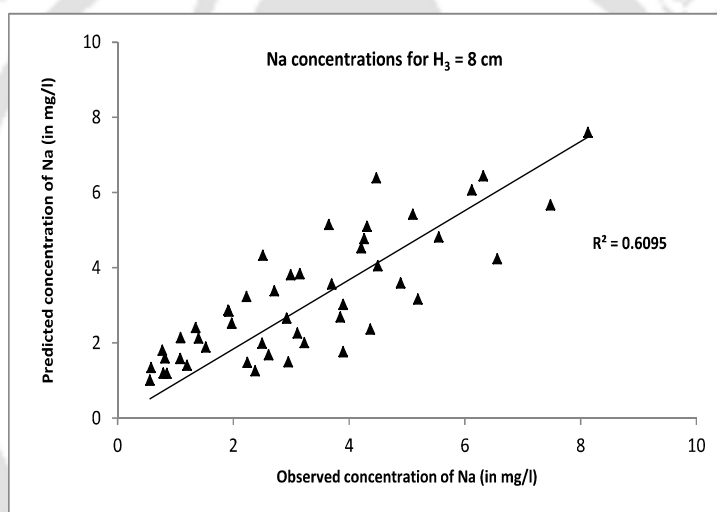
(f)



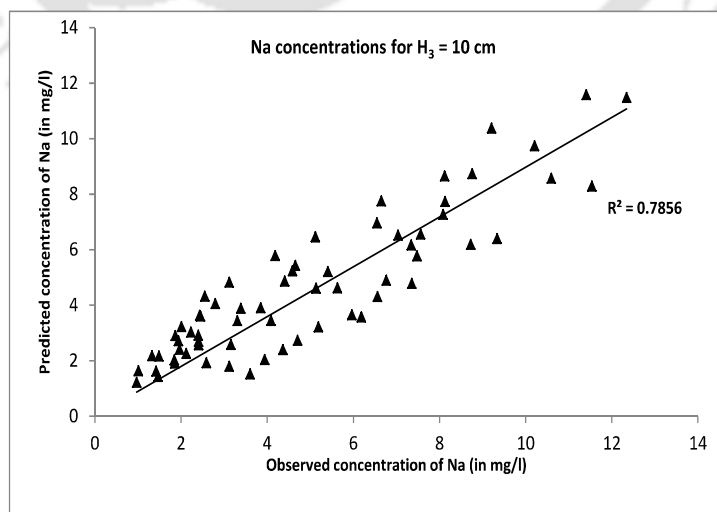
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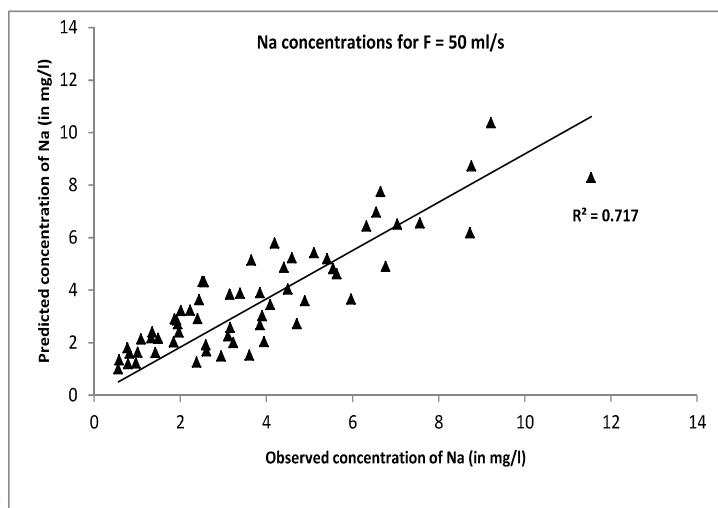
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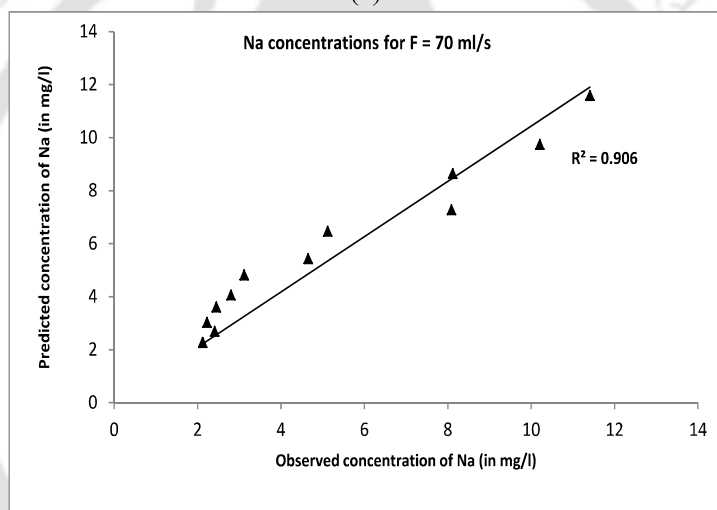
(i)



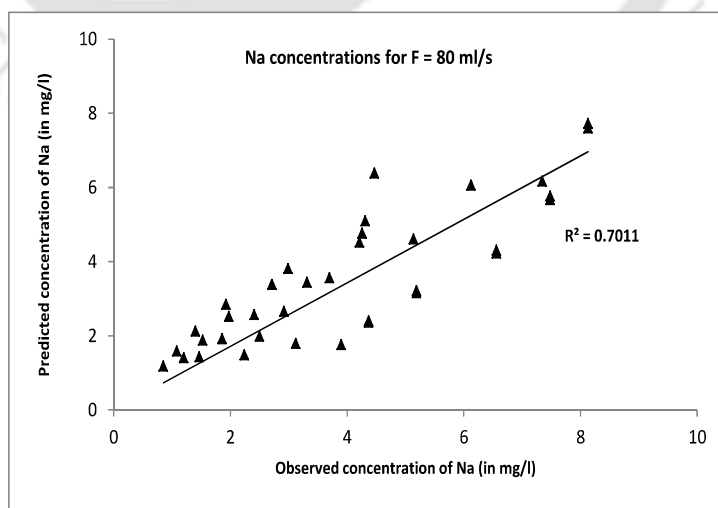
(j)



(k)

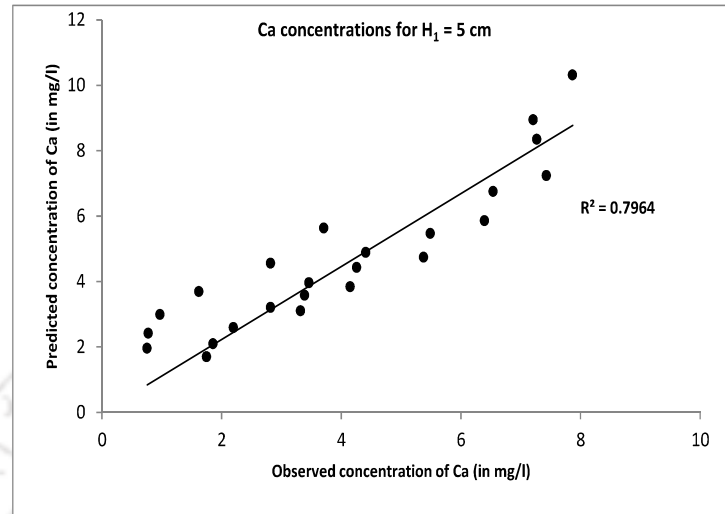


(l)

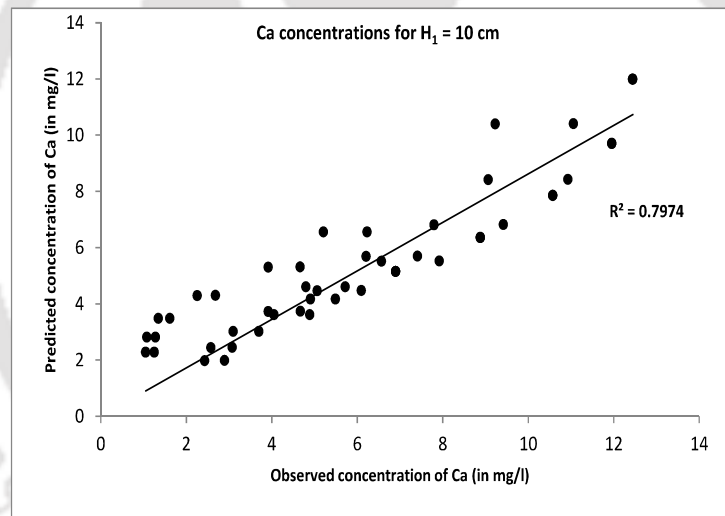


(m)

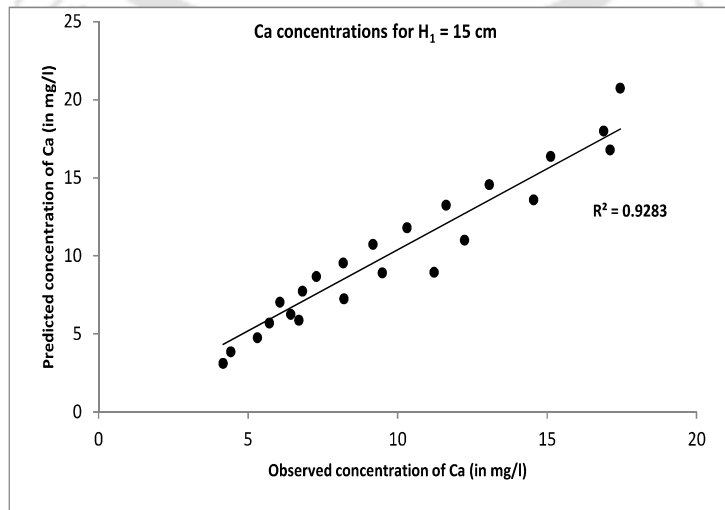
Fig. 4.22 (a-m) Predicted versus observed concentrations of Ca in effluent leachates: a) $H_1 = 5$ cm; b) $H_1 = 10$ cm; c) $H_1 = 15$ cm; d) $H_1 = 20$ cm; e) $H_2 = 15$ cm; f) $H_2 = 20$ cm; g) $H_2 = 25$ cm; h) $H_2 = 30$ cm; i) $H_3 = 8$ cm; j) $H_3 = 10$ cm; k) $F = 50$ ml/s; l) $F = 70$ ml/s; m) $F = 80$ ml/s ↓



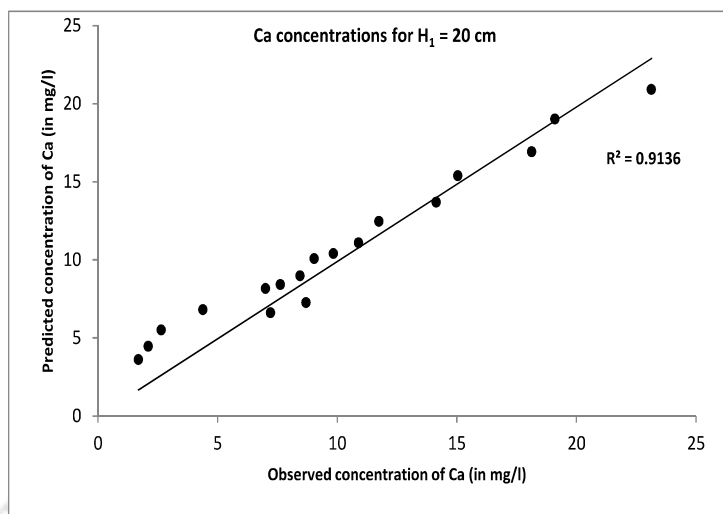
(a)



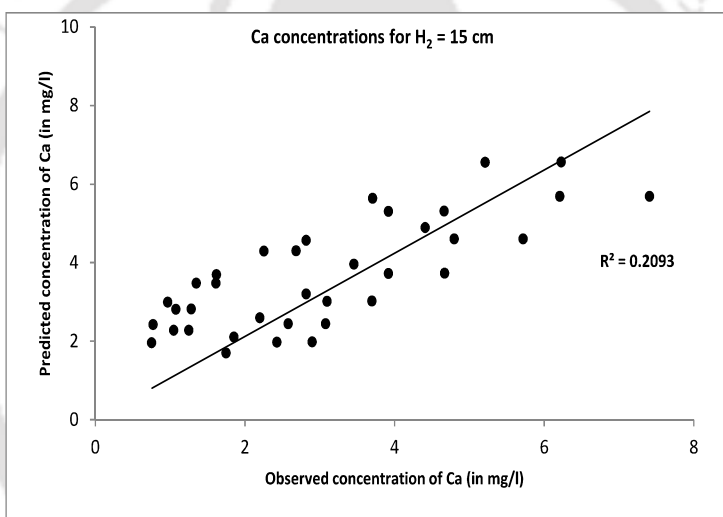
(b)



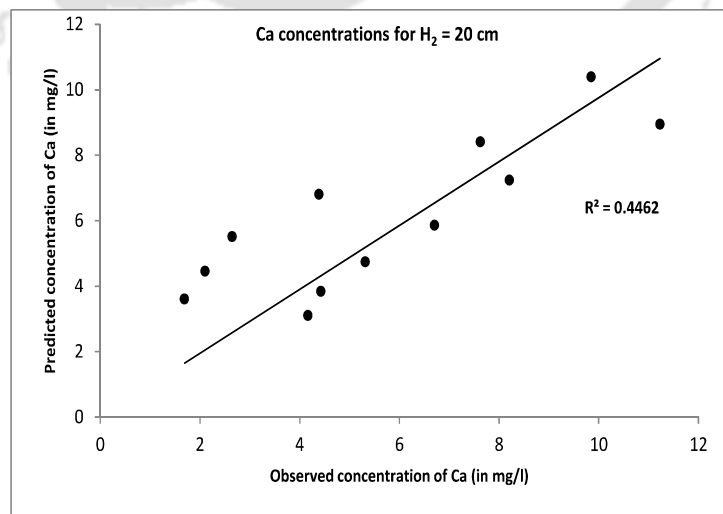
(c)



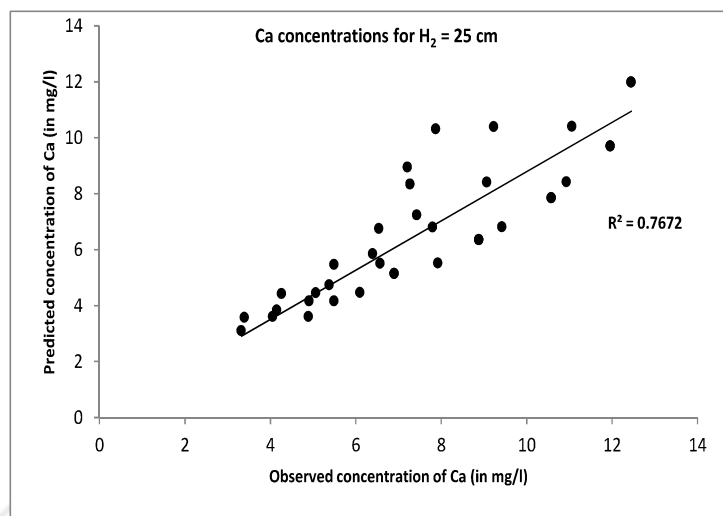
(d)



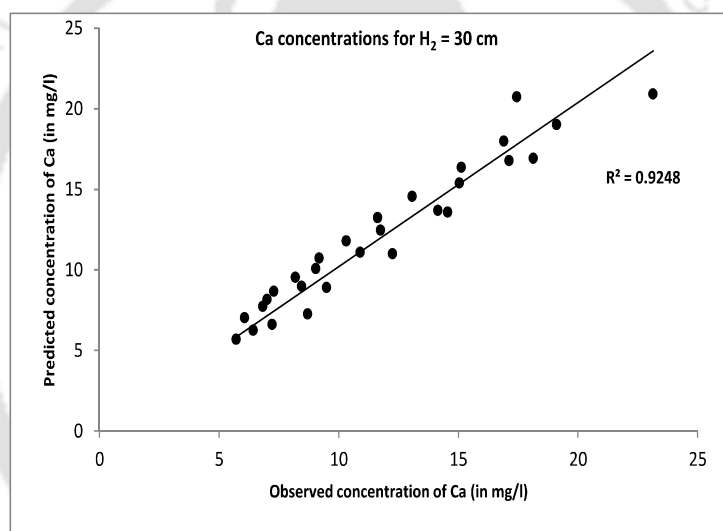
(e)



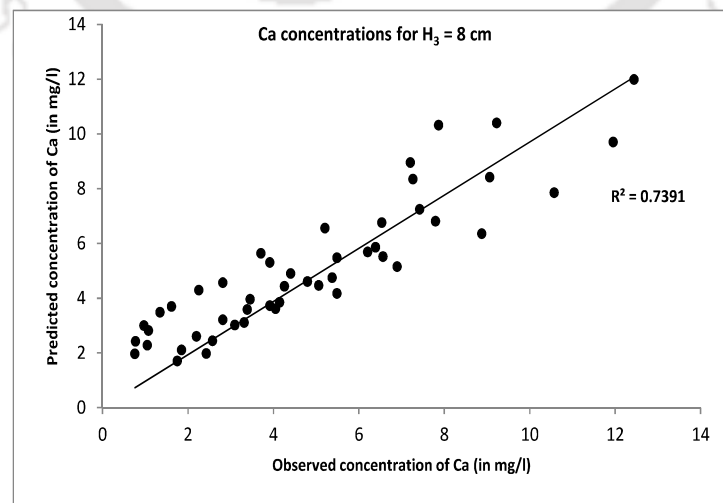
(f)



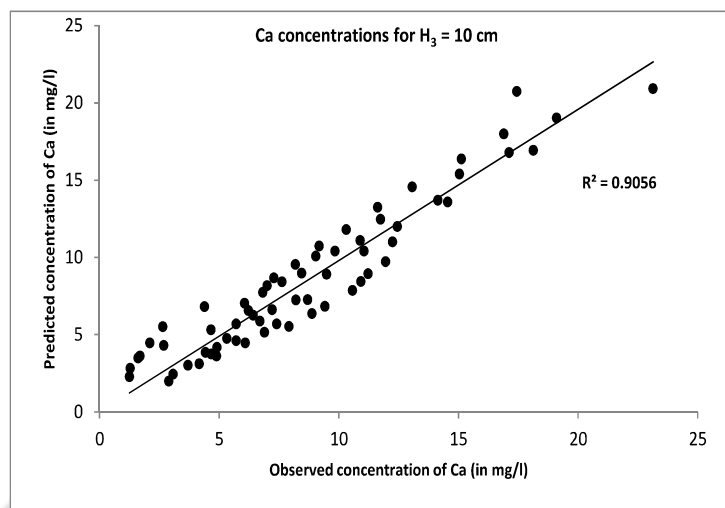
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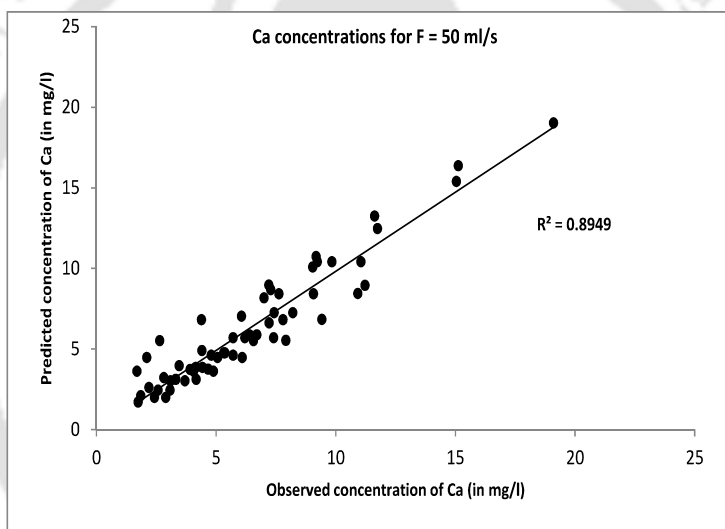
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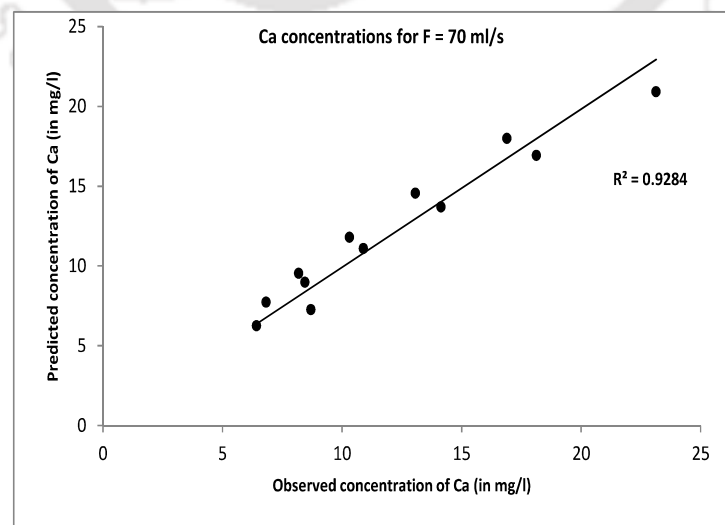
(i)



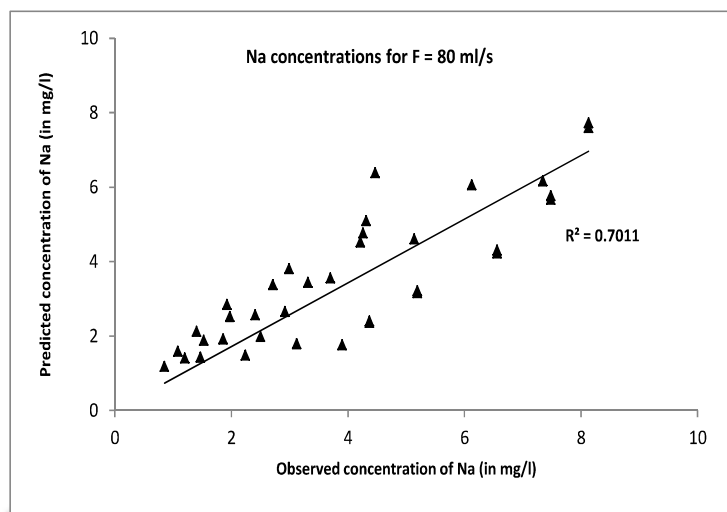
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(k)

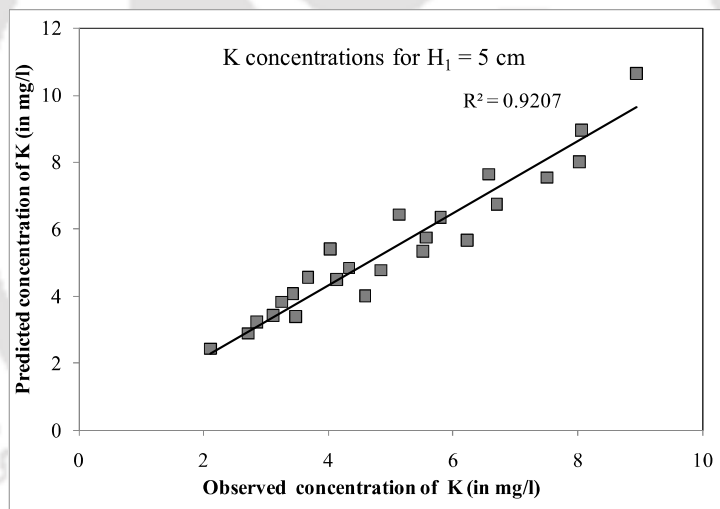


(l)

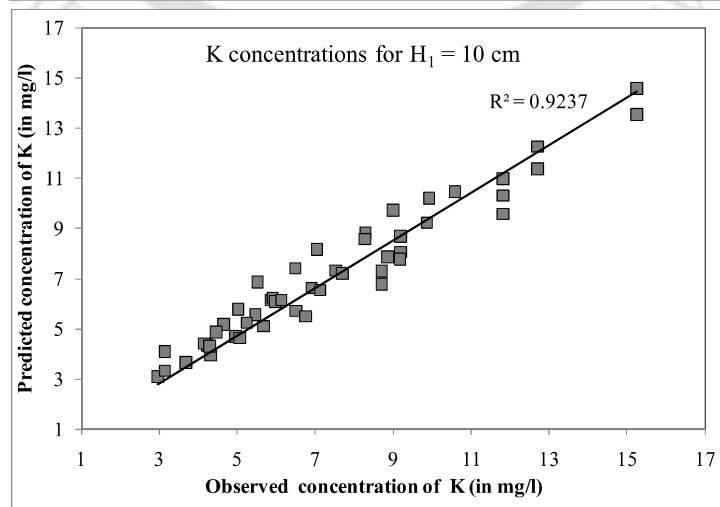


(m)

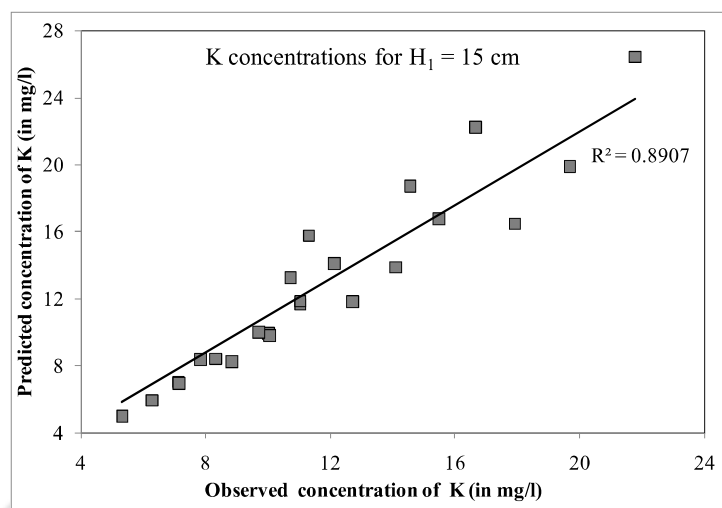
Fig. 4.23 Predicted versus observed concentrations of K in effluent leachates: a) $H_1 = 5 \text{ cm}$; b) $H_1 = 10 \text{ cm}$; c) $H_1 = 15 \text{ cm}$; d) $H_1 = 20 \text{ cm}$; e) $H_2 = 15 \text{ cm}$; f) $H_2 = 20 \text{ cm}$; g) $H_2 = 25 \text{ cm}$; h) $H_2 = 30 \text{ cm}$; i) $H_3 = 8 \text{ cm}$; j) $H_3 = 10 \text{ cm}$; k) $F = 50 \text{ ml/s}$; l) $F = 70 \text{ ml/s}$; m) $F = 80 \text{ ml/s}$ ↓



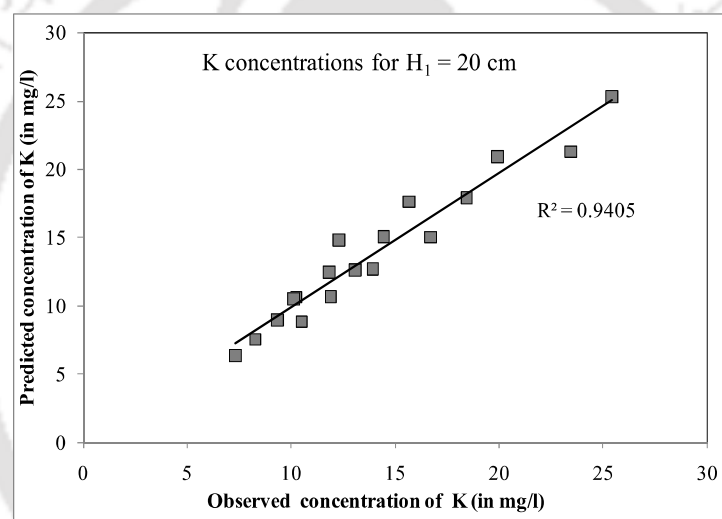
(a)



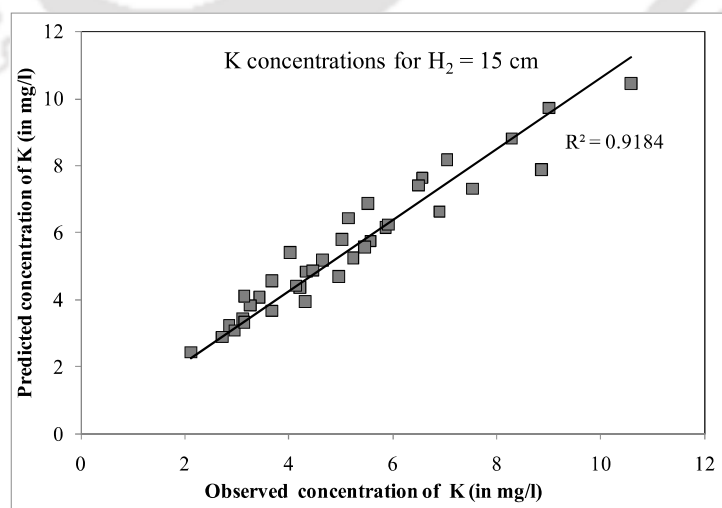
(b)



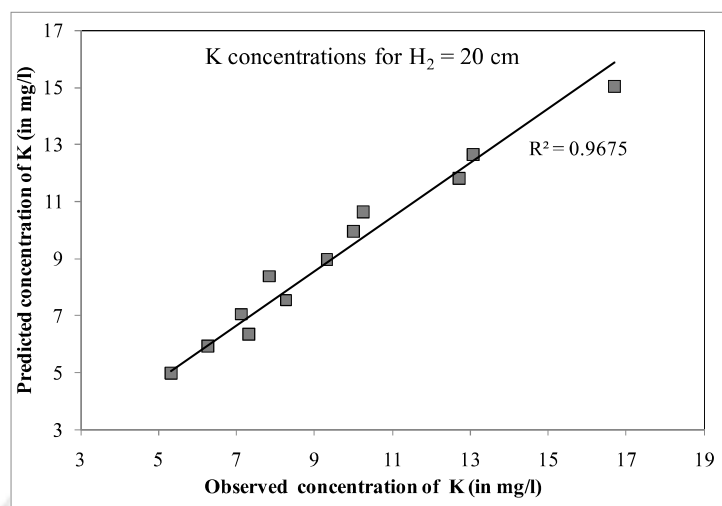
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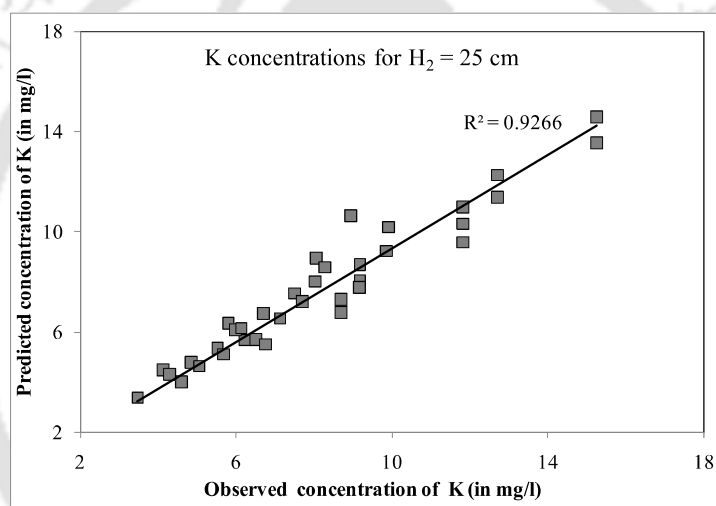
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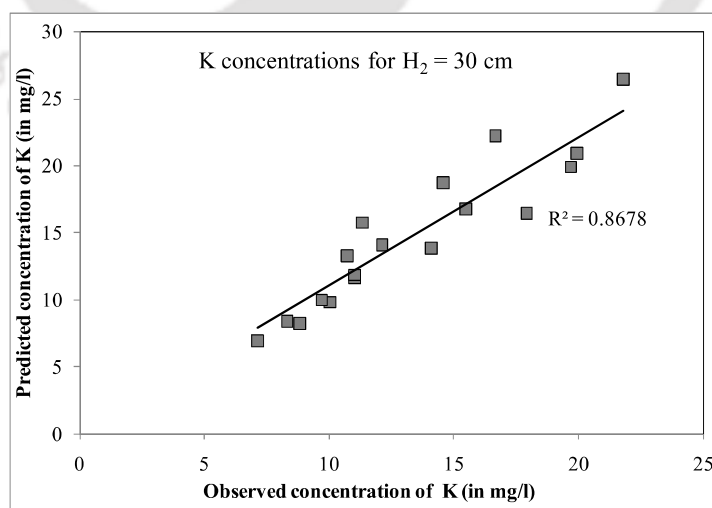
(e)



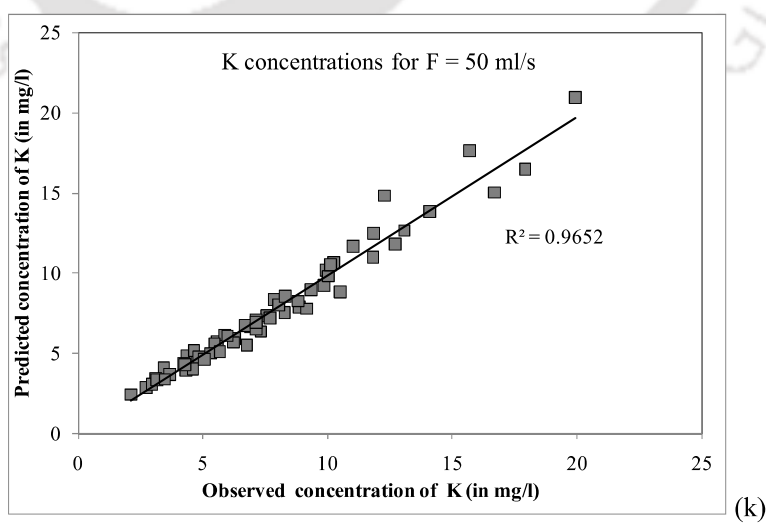
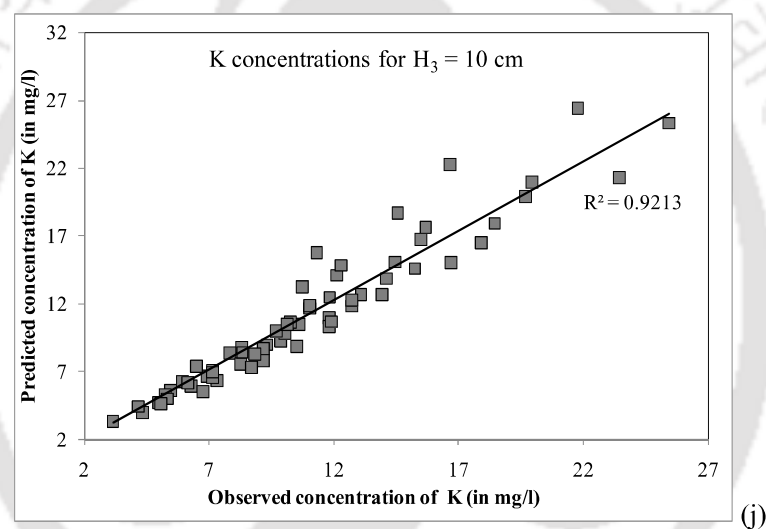
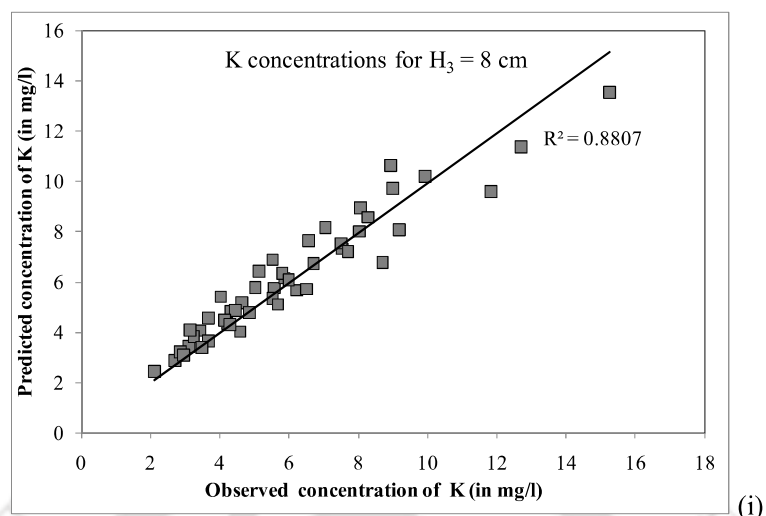
(f)

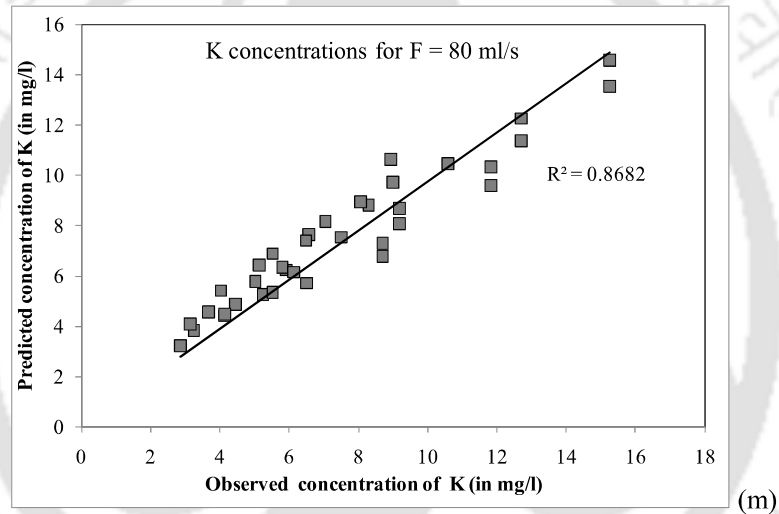
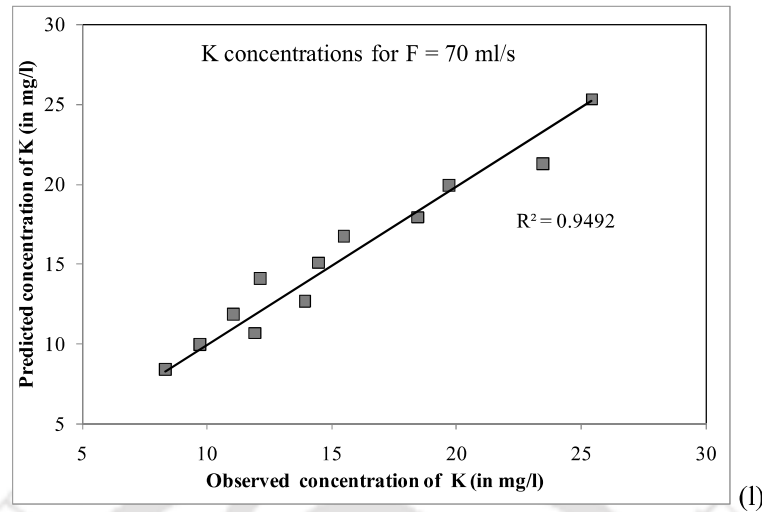


(g)



(h)





From the model [4.2], the coefficient of H_1 is more significant compared to the coefficients of other variables. This coefficient significance suggests that Na is more prominent in the landfill refuse soil compared to the base soil. Similarly, Ca is leached more from base soil compared to the landfill refuse soil as is evident from higher coefficient for H_2 in equation [4.3]. The concentrations of potassium (K) in the leachates are influenced by both the heights of landfill refuse soil and base soil as observed from the coefficients of H_1 and H_2 in equation [4.4]. The coefficients are also in agreement with the results that describes the influence of H_3 on leaching. Though the above predictive empirical models incorporate

various physical and temporal parameters, they may be more generalized by incorporating additional parameters like initial nutrient concentrations in the soils and its moisture content distributions, etc. that are beyond the scope of the present study and can be a potential future research.

4.6. Summary

This chapter illustrates the results from various experimental and empirical techniques, to analyse leaching of nutrients (Na, Ca, and K) and heavy metal (Zn) from landfill refuse soils and normal soils. The small cylindrical column and the heap shaped three-dimensional apparatus are used to analyse the leaching of nutrients. The long rectangular shaped column is used to analyse leaching of zinc (Zn) from the soils. Subsequently, the effects of geometric parameters like H_1 , H_2 , H_3 , and hydraulic parameters like filling rate (F) on the amount of leaching of these elements are interpreted in this chapter. Finally, the empirical relations, based on these parameters, are developed to predict the leaching of nutrients. The important conclusions and future scope of this research are presented in the next chapter.

CHAPTER

5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Summary

In this research, the leaching of nutrients like Na, Ca, and K, and heavy metals like Zn from the soil columns is monitored in the effluents by conducting flow experiments in the laboratory. The leaching experiments were performed in three types of apparatus – short cylindrical column, long rectangular column, and three-dimensional heap shaped column apparatus. The columns are filled with soils in different layers with the upper layer consisting of refuse soils collected from the uncontrolled waste dump landfill site at Boragaon, Guwahati, India and the bottom layer comprising of locally available normal soils. The layers of soils act as porous medium that allow percolation of water through it. Water is poured at the top of the column, at various filling rates, and it percolates through the pores in the soil layers. During the process of percolation, the water interacts with the solids and transfers mass of nutrients and metals into and/or from it. The liquid containing dissolved components reach the bottom of the column and emerge out as effluents that are

collected for further chemical analysis in the laboratory. The interaction of water with the solids inside the column may involve both dissolution as well as sorption and it depends on the magnitude of concentration of the components in the dissolved and solid phases. On preliminary investigation, the raw tap water used in the study was observed to contain some concentrations of Na, Ca, and K, whereas, the concentration of Zn was zero. Therefore, the magnitude of concentration of the above components in the effluents that are collected periodically illustrate whether those components are trapped into the soil or leached from the soil.

The effects of different parameters viz. height of landfill refuse soil H_1 ; height of normal base layer soil H_2 ; depth of ponded water H_3 ; inflow filling rate F ; and time t on the amount of leaching of nutrients (Na, Ca, and K), and metals (Zn) from columns were studied. The significance of these parameters may be attributed to the fact that H_1 resembles the tentative height of the refuse or landfill soil above the ground level; H_2 resembles the height of ground below the landfill soil and above water table; H_3 resembles the height of water ponding over the landfill soil due to precipitation; and F mimics the rainfall intensity. Column experiments with respect to several combinations of above parameters were conducted to evaluate the effects.

5.2 Conclusions from short cylindrical column experiment

In the short cylindrical column experiment, nineteen sets of experiments with different combinations of height of landfill refuse soil, height of normal base layer soil, depth of ponding, and inflow filling rate were conducted to determine the concentrations of Na, Ca, and K in the effluents. These experimental combinations were further grouped into four based on the height of landfill refuse soil (viz. $H_1 = 5, 10, 15,$ and 20 cm). In these

experiments the outflow, from the columns, appeared within the first 10 minutes and continued approximately for 60 minutes. Beyond this duration, the outflow was not measurable and hence insignificant. The main inferences from these experiments are summarised as follows:

- In the group-1 experiments (i.e. $H_1 = 5$ cm), sodium and calcium are trapped from the raw water into the soils as is evident from the effluent concentration curves. Moreover, the magnitudes of concentrations of Na in the effluents were mostly less than that of Ca in these experiments. The experiments revealed the leaching of potassium from the soils into the flowing water. Further, the magnitudes of concentrations of potassium, in the effluent leachates, were higher for larger heights of base soil that indicate more leaching of K from base soil than that from landfill soil.
- In the group-2 experiments (i.e. $H_1 = 10$ cm), for all cases, calcium is trapped into the soils from the raw water. The concentration of Na is greater than that of Ca for the experiments involving higher filling rates and relatively higher H_1/H_2 ratios. For lower H_1/H_2 ratio (i.e. higher H_2), there are more interactions of dissolved Na with the base soil that resulted in lower concentrations of Na than that of Ca. However, for higher H_1/H_2 ratio (i.e. lower H_2), the concentration of Na was higher than Ca because of less interaction of dissolved Na with the base soil. Further, the increase in the ponding depth and/or filling rate resulted in increase in the leaching of sodium from the landfill soils. In addition, the experimental observations also revealed that sodium leach initially from the soils and trapped into the soils in the later periods. Further, the experiments indicated the leaching of potassium from the soils into the flowing water in all the cases.

- In the group-3 experiments (i.e. $H_l = 15$ cm), the Na concentration curves exhibited leaching in the initial few time intervals and trapping in the subsequent periods. However, in the case of higher base soil height as well as higher filling rate, the Na concentration curve revealed leaching phenomenon. Similarly, for calcium, the C_{Ca} curves disclosed the leaching of the element in the initial periods followed by trapping of the same in the subsequent periods. However, for the case where the height of base layer is low, an exception was observed, wherein the Ca is trapped throughout the entire duration. Similar to the experiments in the previous groups, for this group also the concentration curves divulged leaching of potassium from the soils into the water.
- In the group-4 experiments (i.e. $H_l = 20$ cm), Na and Ca exhibit both leaching during the initial phase and trapping in the later phase. The magnitude of concentration of Na was less than that of Ca in the effluents. As usual, potassium exhibited leaching from the soils in all the scenarios.
- From the experiments of all the groups, it is concluded that Ca and K leach more from the base soil, whereas, for Na, it is uncertain whether it leaches from landfill soil and/or base soil.
- For different water ponding depths (H_3), it was observed that the nutrient concentrations in the effluent leachates were higher for larger ponding depths and inflow filling rates.

5.3 Conclusions from long rectangular column experiment

The long rectangular shaped column was used to measure the concentration of Zn in the effluent leachates. Since the measured concentration of Zn in the raw water, before using

it in the columns, is zero, the presence of Zn in the effluents indicates the leaching of the same from the soils. There were 45 experiments conducted on the long columns and these experiments were categorised into five groups based on the filling rates ($F = 100, 110, 120, 130$, and 140 ml/s). The important conclusions drawn from the long column experiments are:

- In almost all of these 45 experiments, the concentration of zinc, in the effluents, increased with respect to time. This indicates that there could still be considerable amount of Zn in solid form present in the soils and are not leached into the percolating water. In addition, the concentration curves also suggest that the equilibrium concentrations of Zn with the solids may not have reached during the experiments.
- For all the sets of experiments (viz. $F = 100, 110, 120, 130$, and 140 ml/s), the concentration of Zn is observed more in the effluents for cases involving larger heights of base soil. This indicates that, in addition to leaching from the landfill soils, Zn is added further from the base soils into the flowing water. This behavior is further substantiated by the observation of positive average percentage change in the concentration of Zn over the entire duration, due to increase in height of base soil. In addition, the increase in the height of landfill refuse (H_1) and ponding depth (H_3) also resulted in increase in the leaching of Zn from the soil column.
- The standard deviations for percentage change in Zn concentrations for all experimental cases involving $H_2 = 60$ cm were observed to be consistent. The consistent standard deviations imply that the experiments involving base layer soil height as 60 cm may be more representative for the column studies.

5.4 Conclusions from three-dimensional column experiment

The three-dimensional trapezoidal apparatus was used to study the leaching of nutrients (viz. Na, Ca, and K) from the soils with similar configurations described for the short-cylindrical and long rectangular columns. Ten experiments were conducted with various combinations of H_1 , H_2 , and F . The important conclusions drawn from this experimental study are:

- The experimental observations of concentrations of sodium, calcium and potassium in the effluent leachates revealed leaching of these elements from the soils into the percolating raw water, as the concentrations of these elements in the effluent leachates were higher as compared to that initially present in the raw water. Further, the leached concentration of Ca was significantly higher as compared to that of Na and K.
- The concentrations of Na, Ca, and K in the effluent leachate increased with time. The rate of increase was higher during initial periods as compared to that during the later periods (indicated by the slope of the relationship obtained between the leached concentration and the time).
- The base soil contributed to leaching of Na and Ca into the percolating water, as the concentration of these elements mostly increased with increase in height of normal base soil (H_2) for both lower and higher magnitudes of inflow intensity (F). For potassium, the leached concentration increased with increase in height normal base soil for lower magnitude of inflow intensity, whereas for higher magnitude of inflow intensity, the concentration of K in the effluent leachate mostly decreased with increase in height of base soil. This decrease in concentration of K indicated more trapping of it in the base soil of larger height, after getting leached from the landfill refuse soil.

- The magnitude of concentration of K in the effluent leachates increased with increase in height of landfill refuse soil (H_1). However, the concentrations of Na and Ca decreased slightly in the effluent leachates with the increase in height of landfill refuse soil. This decrease is attributed to relatively more trapping of Na and Ca from the percolating water into the lower portions of the landfill refuse soil.
- On analyzing the concentrations of the nutrients (Na, Ca, and K) with respect to different inflow filling rates (F), it is observed that the concentrations mostly increased with increase in inflow filling rate.
- The calculated average and standard deviation of percentage change in the concentrations of Na, Ca, and K in the effluent leachates (due to change in H_1 , H_2 , and F) revealed that the average percentage increase is maximum for K followed by Na and minimum for Ca, although the magnitude of leached concentrations of calcium in the effluent leachates are significantly higher as compared to sodium and potassium. This shows that an increase in H_1 , H_2 , and F has less effect on leaching of calcium from the soils as compared to sodium and potassium. Further, the computed standard deviation of percentage change is also maximum for K, which indicates that leaching of potassium is more sensitive to the change in H_1 , H_2 , and F .

5.5 Conclusions from the empirical model

The large numbers of experimental data from the short cylindrical column experiments were utilized to develop empirical relations to predict nutrient (Na, Ca, and K) concentrations in the leachates with respect to the refuse soil height, base soil height, ponding depth, and filling rate. The inferences from the empirical modelling studies are:

- The exponential empirical models predicted well the concentrations of nutrients for the independent experiments that were not part in the empirical model development. Higher correlations of predicted concentration values with the actual values substantiated the worth of the exponential equations.
- From the exponential empirical model for Na, the large coefficient of H_1 signifies that Na is more prominent in the landfill refuse soil as compared to the base soil.
- Ca leaches more from base soil (H_2) as compared to the landfill refuse soil that is evident from higher coefficient for H_2 in the exponential empirical model for Ca.
- The concentrations of potassium (K) in the leachates are influenced by both the heights of landfill refuse soil and base soil as observed from the coefficients of H_1 and H_2 in the exponential empirical model for K.

5.6 Limitations of the Study

The objective of the study was to interpret the leaching of nutrients like Na, Ca, and K and a heavy metal, Zn from the combination of landfill refuse and normal soils. The inferences from this study can be used as a precursor for more detailed studies on leaching from landfill soils and in particular from Boragoan landfill soil. Though the research involved extensive experimental and empirical analyses, however, some inadvertent limitations may be present that are beyond the research's scope. Some of the limitations are:

- The properties of soil layers may vary in different locations within a landfill site. In addition, some properties of soil may vary with time. Therefore, it is difficult to draw general inferences on leaching in landfills.
- The pH and organic content of soils were not measured, which may be influential in leaching.

- In most of the cases, the duration of the experiments was 60 minutes because after 60 minutes the effluent outflow rate was very low. Therefore, general conclusions cannot be drawn from this study for longer duration field conditions.
- Efforts were made to simulate the inflow filling rate to mimic the rainfall intensity. However, more sophistication is required in simulating the actual rainfall intensity.

5.7 Scope for future work

The vast experimental studies performed in this thesis provided some insights into the nutrient and metal leaching from the Boragaon landfill soils. The present investigation has the scope for further research in continuation and improvement to the landfill leaching study. Some of the suggestions for the future work proposed are:

- The present experiments were of comparatively short durations and the leaching studies involving longer duration experiments can be planned.
- The change in concentrations of the nutrients and the metals in the soils before and after leaching can be examined through various micro-structural studies (XRD, SEM, etc.).
- Hydraulic and chemical parameters for the one-dimensional reactive transport models can be generated from the leaching experiment by collecting samples from various heights of the column and analyzing them.
- The empirical models, developed in this study, can be improved further by incorporating additional parameters like initial nutrient concentrations and moisture content distributions in the soils.

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List of Publications from this Research

International Journal:

1. Barman, P.J, Kartha, S.A., Pradhan, B. (2015) "Empirical approach to predict leached nutrients from landfill site"*Environmental Science and Pollution Research*, vol. 22, pp. 6619-6633.
2. Barman, P.J, Gupta S, Kartha, S. A, Pradhan, B.(2012). "A Study on leaching behavior of Na, Ca and K using Column leach test"*International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering* vol:6, no10,pp 679-683.

International Conferences:

1. Barman, P., Kartha, S. A, Pradhan, B.(2010). "*Landfill leaching: An Experimental Investigation using column leach Apparatus*" presented at the International Conference on Hydro science and Engineering (ICHE 2010) 25-30 August 2010,IIT Chennai.
2. Barman, P., Kartha, S. A, Pradhan, B.(2010). "*Effect of height of Contaminated Soil in Column Leaching: An Experimental Investigation*" presented at the International Perspective on Water Resource and Environment (IPWE 2011) 2-5 January 2011, Singapore.

National Conference:

1. Barman, P., Kartha, S. A, Pradhan, B. (2010). "A Study on Landfill leaching using three dimensional column leach apparatus" presented at the National Conference "Recent Advances in Civil Engineering-2011" held in Banaras Hindu University on 14-16th October 2011.