
Acid rain: past, present, and future

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Abstract: During 1970s, acid rain had devastated several regions of North America and Western Europe. Since then counter measures implemented in these regions have gradually brought the problem under some control. But has the world nullified what was once a very strongly perceived threat of acid rain? Far from it; studies conducted in recent years show that acid rain is now as severe a threat to the developing world, especially India and China, as it was earlier to some of the developed countries. Even the latter have only partially recovered from the earlier episodes of excessively acidic rain and still have a long way to go. The purpose of this review is to call attention towards the still very real threat of acid rain in the context of its past and the present. This paper recapitulates the definition of acid rain, traces its history, and identifies its origins. It then discusses the impact of acid rain, especially the trans-national and trans-regional issues associated with it. The prognostics for developing countries are highlighted. The measures to control and prevent acid rain are then recapitulated.

Keywords: acid rain; global warming; sulphur oxides; nitrogen oxides; formic acid; biota; buildings.

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1 Introduction

Up till mid-1970s, it was not generally realised that pollution caused in one region or country can seriously harm other regions situated far away. Then, one by one, three phenomena came into global view which changed this perception: acid rain, ozone hole, and global warming. We now know that generation of pollution, however small, at even the remotest part of the earth can contribute to the overall environmental degradation of the earth and can impact people living far away.

It was acid rain which made the world sharply aware of the global impact of the regional pollution episodes. As detailed later in this paper, one instance after another occurred when acidic rain was seen to fall over areas, such as forests and remote lakes, where there was no industrial or other developmental activity. Gradually, it became apparent that meteorological factors sent acidic air pollutants like SO_x and NO_x from one region to the other where falling rain dissolved those pollutants and became highly acidic by the time it hit the earth or the objects connected to the earth (Radojevic and Harrison, 1992).

In subsequent years, the world was to learn about ozone hole which is also a 'global' phenomena caused by local emissions. Greenhouse effect was already well-known but the realisation that due to increased emissions of greenhouse gases the globe is getting alarmingly warmer dawned upon the world during the 1980s. For the next two decades, the global scientific community was sharply divided on whether global warming is a real threat or more of sensation mongering (Abbasi and Abbasi, 2011a; Abbasi et al., 2000, 2011). But by the turn of the millennium the impact of global warming had begun to hit the world – at intensities, frequencies, and scales – much greater than and much sooner than most of us had expected. The impact has been so overwhelming that concerns for acid rain and ozone hole which were once perceived to be very serious threats, seem to have receded from the public consciousness. But acid rain is far from a solved problem. The regions of the world which were initially the worst effected – the UK and the USA –

have recovered slightly but by all accounts the Asian region, particularly India and China, are heading the way the UK and the USA once were.

The aim of this paper is to recapitulate the nature of acid rain and to enumerate the factors which cause it. In the backdrop of a brief history of acid rain, this paper describes the transboundary issues associated with it and assesses the myriad of ways in which acid rain effects the biotic and the abiotic components of the environment. An overview of measures possible, and used, to control acid rain is then presented. The concluding part of the paper emphasises the fact that acid rain continues to lurk as a serious threat and that it would be simplistic to believe that if in a particular region acidification of rain is not presently causing proportional acidification of receiving water and soil, this shall continue to be so indefinitely. If not checked acid rain would gradually wear down the acid-assimilative capacity of the receiving environments.

1.1 What is acid rain?

It can be said that pollution is like a boomerang for mankind. People try to fling their pollutants away with all the force at their disposal... only to have it come back and hit them at unexpected spots and in an unpredictable manner. Like the nemesis. Acid rain is an example of pollution humans try to send away... far away using taller and taller stacks to discharge acidic gases. And it comes back to haunt them!

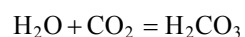
Acid rain is normal rain acidified by certain air pollutants. Whereas the normal rain cleans, rejuvenates, and enriches the environment, acid rain dirties and damages it.

The measure of acidic strength of any medium is done through its pH (which in turn is the negative logarithm of the hydrogen ion activity of the medium). If the pH is more than 7 the medium is alkaline (or basic). A pH of less than 7 indicates a net acidic character. The lower the pH, the stronger the acidity; whereas a substance with a pH of 1 is 'very strongly acidic', a substance with a pH of 6 is only mildly or 'weakly' so.

Rain occurs when water vapour condenses in clouds and falls to earth. As it begins to fall the rain is neutral – neither acidic nor alkaline (Charlson and Rodhe 1982). While it travels through the air, it dissolves floating chemicals and pushes down particles that are suspended in the air. In clean air the rain picks up only materials that occur naturally, such as dust, pollen, some carbon dioxide (which forms the mild carbonic acid) and chemicals produced by lightening and volcanic activities. These substances make the rain slightly acidic, with a pH of about 5.7. As explained below; this level of acidity is not considered dangerous.

Natural rainwater interacts with carbon dioxide (CO₂) in the atmosphere, forming carbonic acid (H₂CO₃). Some of the carbonic acid in the rainwater then breaks down (dissociates), producing more hydrogen ion and bicarbonate ion, both of which are dissolved in the rainwater.

The two reactions are as follows:



The hydrogen ion produced by the second reaction lowers the pH of the rain-water. How far it lowers it from the neutral value of 7 depends on how much carbonic acid is in the water as a result of the first reaction. The concentration of carbonic acid, in turn, depends

on how much carbon dioxide is in the atmosphere. In other words, when more CO_2 is present, more acid is produced, and the water becomes more acidic.

The Earth's atmosphere contains, on average, approximately 0.3% carbon dioxide. Using this value in the two reactions above, the concentration of H^+ in rainwater at chemical equilibrium is $10^{-5.7}$ moles per litre. This concentration is equivalent to a pH of 5.7, and most unpolluted rainwaters have indeed found to have a pH close to 5.7.

This slightly acidic rainwater reacts with land-derived dust particles in the atmosphere. These reactions result in the rainwater gaining low concentrations of dissolved calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), and other elements. The reactions also cause the pH to rise a little.

Sea spray, carried aloft by winds blowing across the ocean, also contributes to dissolved constituents in rainwater. Although dissolved minerals from spray are more abundant in coastal areas, they occur throughout the atmosphere. Sea spray is the primary source of chloride (Cl^-) in rainwater and a significant amount of sodium ion (Norman et al., 2001; Menz and Seip, 2004).

This is, broadly, the status of unpolluted rainwater. 'Acid rain' is the name given to rain if it is pH is less than 5.6.

How does acid rain form? When rain falls through polluted air, it comes across more acid-forming substances and in higher concentrations than otherwise (Granat, 1972; Calvert et al., 1985; Fowler et al., 2005). Among the chemicals frequently occurring in polluted air at higher-than-normal concentrations are sulphur oxides (SO_2 and SO_3 , commonly referred as SO_x), and nitrogen oxide (NO_2 , N_2O , and NO , commonly referred as NO_x). In some situations, hydrochloric acid vapour and mists of other acids such as phosphoric acid may also be present. These gases dissolve in falling rain making it more acidic than natural rain. This leads to acid rain. Acid fog is formed when chemical pollutants are dissolved in very moist air (Abbasi, 1998a). This causes changes in the pH of the receiving systems in the same way that acid rain changes the pH of the soil or the water in lakes and rivers.

When fossil fuels – oil, coal, and gas – are burned in industrial plants or automobile engines, large amounts of sulphur oxides and nitrogen oxides are released into the air. A single industrial smokestack can produce as much as 500 metric tons of sulphur oxides each day (Khan and Abbasi, 1999a). Most of it is sulphur dioxide, which becomes sulphuric acid in moist air.

Nitrogen oxides and carbon particles produced by automobiles and other motor vehicles are so plentiful in some large cities that the air is coloured by them (Abbasi, 1999; Abbasi et al., 2012). Nitrogen oxides also enter the air from the breakdown of agricultural fertilisers (Abbasi and Abbasi, 2012). These eventually form nitric acid in moist air. Like sulphuric acid, nitric acid corrodes many metals, and strong concentrations of nitric acid can cause burns on skin.

Amongst natural sources of acid rain, other than volcanoes and geysers which also contribute SO_x and NO_x , the most significant is formic acid (Sanhueza et al., 1991). Biomass burning (Abbasi et al., 1995; Abbasi and Abbasi, 2010a) due to forest fires causes emissions of formic acid (HCOOH) and formaldehyde (HCHO) into the atmosphere. A large fraction of formaldehyde gets oxidised to formic acid in the atmosphere. During the days prior to the rainy season in tropical areas, forest fires are common. In this period, photochemical activity in the atmosphere is also high. Thus higher emissions of HCOOH and HCHO , combined with swift conversion of HCHO to

HCOOH due to photooxidation, causes acidity in the rain during the first few days of rainfall over tropical forests.

Millions of metric tons of sulphuric acid and nitric acid fall in rain on earth each year, principally on the USA, Canada, Europe, the erstwhile USSR, India, and China (Hendrey and Wright, 1976; Rodhe et al., 1995; Jeng-Peng and Bhargava, 1996). The concentrations of these acids are too weak to cause burns, but they do produce other severe effects (La Bastille, 1981). Other acids also occur but in smaller amounts. Hydrochloric acid often comes directly from smokestacks. Carbon monoxide and carbon dioxide are produced by automobiles. These become carbonic acid.

After spending billions of dollars, on reducing emissions of acid-forming gases, the developed countries have managed to reduce the acidity of their rainfall just 'by up to 25%'. As a consequence, some sensitive lakes and streams in the North-eastern USA are showing signs of recovery. Further, sulphate concentrations in the air have decreased, leading to improved air quality and fewer instances of respiratory problems (e.g., asthma and chronic bronchitis). Visibility has also improved in some parts, including areas with scenic vistas, such as Acadia National Park in coastal Maine.

Although these are the positive effects, emissions and acid deposition still remain high in these countries compared to background conditions (Fowler et al., 2005). Only deeper emission cuts will lead to greater and faster recovery from the past effects of acid deposition. On the flip side is the increasing contribution now coming from Asia, especially from the fast-growing economies of India and China.

When the situation in North America was at its worst during the 1970s, the acids generated in the air due to pollution had changed the normal pH of rain from 5.6 to an average of 4.5 over the entire Eastern USA and Canada. A pH of 4.5 is more than ten times as acidic as a pH of 5.6. Some areas had received acid rain with a pH of 3.0, which is as acidic as vinegar (Abbasi et al., 2000).

One of the areas thought to be still most severely affected by acid rain is the scenic Adirondack Mountain region of the New York State. But there are no heavy industries or factories in this area and not enough automobiles to produce much pollution. Where does the acid rain in the Adirondacks come from? Evidently, air pollutants manage to travel over hundreds and even thousands of kilometres from their points of origin. Many factories have smokestacks well over 100 metres (328 feet) high. When hot polluted air is let off at such a height, it obviously gets carried by winds to great distances and effects areas such as Adirondack Mountains situated far away.

Pollution from Canada is carried by winds into the USA. Norway and Sweden receive acid rain created by pollutants travelling north from England, Germany, Italy, France, and Austria (Rodhe et al., 1995). As mentioned earlier, these happenings have made the world more aware than ever before of the global impacts of local environmental problems and have inspired nations across the world to take joint initiatives in mitigating the damages caused by acid rain (Galanter et al., 2000).

2 A brief history of acid rain

The earliest documented use of the term acid rain is found in a 1872 book *Air and Rain: The Beginnings of Chemical Climatology* authored by Smith (Smith, 1872; Gilbert, 1987; Abbasi, 1999; Abbasi et al., 2000). Even prior to that Smith had been studying

atmospheric acidity in the industrial town of Manchester, England, since several years and had suspected that the soot of the industries were responsible for the rainwater acidity. He found that sulphuric acid was present in the rainwater falling over Manchester (Hidey, 1995).

During 1950s, investigations on mysterious fish kills, suspected to be associated with water acidification in Norway and Sweden, led Scandinavian scientists to express concerns about the origins of the acidity (Leivestad et al., 1976; De Costa, 1980). Around the same time, Gorhams (1955) documented acidification of rain falling over England. Such efforts were stimulated in the 1960s by the more obvious links seen between fish (especially salmon and trout) kills in Scandinavian lakes and acid deposition. By 1965, the pH of rainwater in Sweden was about 4 or less! Early 1960s also saw the symptoms of acidification of rain appearing in the USA. With every passing year more and more evidence of acid rain piled up (Almer et al., 1987). The concerns grew in intensity to a point when the issue of acid rain was raised in the 1972 United Nations Conference on the Environment. The reason for provoking an international debate was the belief that the transport of air pollutants from some countries were acidifying the waters of some other countries. It was suggested that rain and snow in many industrial regions of the world were between five and 30 times as acidic as would be expected in an unpolluted atmosphere (Jickells et al., 1982). In 1974, over the Northeast USA, the pH of rain and snow was found to be around 4.0 (Likens and Butler, 1981).

Until the mid 1970s, the problem of acid rain was mainly confined to North America and Scandinavia, but thereafter pH of precipitation well below 4.5 in much of Central and Northern Europe was recorded (Odan, 1976; Park, 1987). US records include a rain of pH 2.7 at Kane in Pennsylvania and a rain of pH 1.5 falling over Wheeling in West Virginia in 1979 (La Bastille, 1981). At Banchory in Northeast Scotland, the pH of rain was sometimes as low as 3.5 (Last and Nicholson, 1982).

By the mid-1970s, surveyors in Northeast America began to report observations of apparent acidification of remote lakes and the parallel deterioration of fisheries. The deterioration in the water quality of lakes in Southern Ontario and the Adirondak Mountains caused particular concern (Likens and Bormann, 1974; Abbasi et al., 2000). A few years later, forest scientists in Europe and North America began to speculate about the role of acid deposition in the disease and death of forest trees. As a result of international concerns, aggressive research programmes to characterise the extent and severity of acid rain exposure were initiated in both Europe and North America. Mounting circumstantial evidence that pollution from industrialised areas could affect remote regions far distant from the points of origin of the pollutants prompted efforts towards multi-national collaboration for the control of sulphur and nitrogen oxide emissions (Menz and Seip, 2004).

In the 1980s, the USA initiated one of the largest publicly funded research programmes ever attempted on a single issue – acid rain. After a ten year congressional authorisation, the US National Acid Precipitation Assessment Program (NAPAP) completed its work. This effort was closely paralleled by a Canadian research programme. These two projects provided a large body of knowledge about acid deposition and its environmental effects in much of the North America. NAPAP was re-authorised to investigate and report on the effectiveness of the acid rain reduction programme legislated in 1990 for the USA.

From mid 1980s, developing countries such as India and China began systematic monitoring of rainwater quality with particular emphasis on acidification (Ayers et al.,

1996). These efforts have grown in intensity over the years and so have efforts on the control of acid-causing pollutants (Granat et al., 2001; Kulshrestha et al., 2003; Das et al., 2005; Singh and Agrawal, 2008).

It must be emphasised that 'acid rain' encountered in the latter half of 20th century was essentially a product of aggressive industrialisation in the developed countries. But mankind had experienced acid rain earlier, too, even though its frequency; intensity and spread are now much larger than they were ever before. Volcanic eruptions have been known to have caused acid rain even in ancient times (Smith, 1872). During the last two centuries, the increasing use of fossil fuels has led to a gradual increase in the emission of sulphur and nitrogen oxides and hence a corresponding increases in the rainfall acidity. This process has been hastened by the spurt in industrialisation in the twentieth century and exponential growth in fossil fuel consumption (Abbasi and Vinithan, 1997; Abbasi et al., 2012). There are records of changing diatom population in the lakes of Galloway, Scotland, which reflect increase in acidity of the lake water during the last two centuries due to acid rain (Chari et al., 2005a, 2005b). There is also historical evidences of disappearance of bogmoss (*Sphagnum sp*) from the prieries at the time of industrial revolution, as bogmoss is very susceptible to SO_2 . Many species of lichens are intolerant to sulphur dioxide and the absence of lichens in industrial areas in Britain indicate a likely impact of acid rain falling in the region over the last two centuries (Abbasi et al., 1998). Nordic countries are among the regions seriously affected by acid rain emanating from the UK and other west European countries.

3 Origin of acid rain

3.1 How is acid rain formed?

Precipitation removes gases and particulates from the atmosphere by two processes:

- 1 *rain-out*, which is the incorporation of particles into cloud drops which fall to the ground
- 2 *washout* which occurs when material below the cloud is swept out by rain or snow as it falls.

Pollutants may also undergo direct contact or gravitational settling which is termed as dry deposition (Park, 1987; Moiseenko, 1994; Abbasi and Khan, 2000a). After deposition, acidic products may be neutralised by alkaline soils or carried by seepage and runoff into lakes, thus contributing towards acidification of the water and affecting the aquatic ecosystem.

3.1.1 Acid-forming compounds in atmosphere

There are three main compounds that cause acidification of rain in the atmosphere. They are:

A Sulphur compounds and radicals:

- 1 sulphur dioxide (SO_2)
- 2 sulphur trioxide (SO_3)

- 3 hydrogen sulfide (H_2S)
- 4 sulphate ions (SO_4^{2-})
- 5 sulphuric acid (H_2SO_4)
- B Nitrogen compounds and radicals:
 - 1 nitric oxide (NO)
 - 2 nitrous oxide (N_2O)
 - 3 nitrogen dioxide (NO_2)
 - 4 nitrate (NO_3^-)
 - 5 nitric acid (HNO_3)
- C Chlorine and hydrochloric acid:
 - 1 chlorine (Cl_2)
 - 2 hydrochloric acid (HCl)
- D Other acids:
 - 1 formic acid
 - 2 acetic acid
 - 3 propionic acid
 - 4 higher fatty acids (n-pentanoic, hexanoic, heptanoic etc acids)
 - 5 phosphoric acid
 - 6 trichloroacetic acid.

The carboxylic acids mentioned above contribute 16% to 36% of rain acidity (Bastidas and La Iglesia, 2007). At some tropical sites in Africa and South America, organic acids have reportedly contributed between 40 and 80% of the total rainfall acidity (Bashkin and Radojevic, 2003). In regions of tropical rain forests formic acid (resulting from forest fires before rainy season) may cause occasional acid rain.

One of the major sources of carboxylic acids is the combustion of biomass (Abbasi et al., 1995; Abbasi and Abbasi, 2010a). Smoke from fire events may contain 300–500 ppb of formic acid and 3,000–5,000 ppb of acetic acid. Industrial sources of carboxylic acid emissions include plants processing biological materials, such as food, paper, wood, etc. Vinegar is an important source of acetic acid vapours in food processing plants (Bastidas and La Iglesia, 2007).

In the atmosphere substances such as ammonia, calcium carbonate, and magnesium carbonate that neutralise acids are also present and the ‘net’ acidity of the rain depends on the mix of chemicals suspended in the air through which the rain falls. In addition to the principal ions mentioned above, besides HCO_3^- , and CO_3^{--} , K^+ , and Na^+ also play a part in influencing the pH of the rain (Abbasi and Abbasi 2011b; Abbasi and Vinithan, 1999).

3.2 Sources of the acid-causing compounds in the rain

The sources of the above mentioned chemicals are natural as well as manmade (Park, 1987; Abbasi et al., 2009). In some situations – such as in regions of volcanic eruptions (which emit SO_x , NO_x) or forest fires (which lead to formic acid as briefly explained earlier) – natural sources can play an important role but the contribution of anthropogenic

sources outweighs the contribution of natural sources in the acidification of rain (Abbasi and Vinithan, 1997; Abbasi and Abbasi, 2000).

3.2.1 Sulphur oxides

The three main natural sources of sulphur oxides are:

- 1 seas and oceans
- 2 volcanic eruptions
- 3 biological processes in the soil such as the decomposition of organic matter by micro-organisms.

These do not give a continuous input but are irregular, both in time and space.

The man-made sources of emission of sulphur oxides are:

- a burning of coal (contributes 60% of SO₂)
- b burning of petroleum products (30%)
- c industrial production of sulphuric acid, metallurgical industries and chemical industries.

About 100 million tonnes per year is released by these anthropogenic activities (Streets et al., 2000).

3.2.2 Nitrogen oxides

Natural sources of nitrogen oxides are:

- 1 lightening
- 2 volcanic eruption
- 3 biological activity.

The anthropogenic sources are:

- a power stations
- b vehicle exhausts
- c industries.

Together they emit about 90 million tonnes of nitrogen compounds per year (Lee et al., 1997; van Aardenne et al., 1999).

Spatially, the concentration of these emissions may vary depending on the population and the industrialisation of the region. It has been estimated that 90% of fossil fuel consumption is in the Northern hemisphere, but the economic growth in China and India in recent years have put these two countries among the world's major fossil fuel consumers (Abbasi et al., 2011).

Evidence of a ten-fold increase in atmospheric nitrate concentrations in North America and a five-fold increase in Europe since the turn of the century has come from the analyses made at the agricultural stations in North America and Europe. There is also indirect evidence preserved in the chemical impurities locked up in polar snow and ice.

This evidence has come because it is possible to determine the exact age of different levels of pollutants within the ice matrices by radio-analytical techniques. Recent analyses of ice cores from Greenland indicate that atmospheric concentrations of sulphate and nitrate were variable but low before the turn of the century (Abbasi and Arya, 1995). But, since 1900, they have increased exponentially – nitrates have doubled and sulphates have trebled. The Greenland studies also indicate the widespread distribution of the nitrogen oxides caused by aerial dispersion.

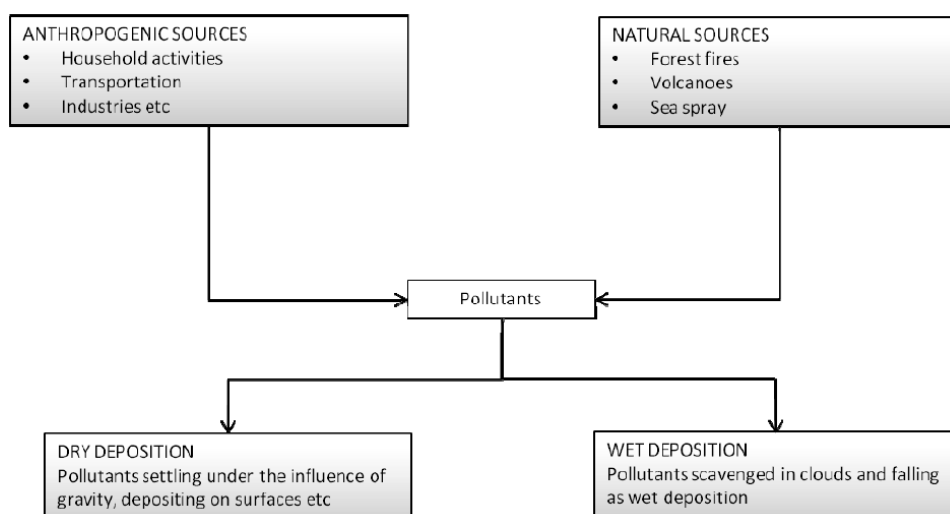
4 Chemistry of acid rain

Basically, six steps are involved in the formation of acid rain:

- 1 the atmosphere receives oxides of sulphur and nitrogen from natural and manmade sources
- 2 some of these oxides fall directly back to the ground as dry deposition – either close to the place of origin or some distance away
- 3 sunlight stimulates the formation of photooxidants (such as ozone) in the atmosphere
- 4 these photo-oxidants interact with the oxides of sulphur and nitrogen to produce H_2SO_4 and HNO_3 by oxidation;
- 5 the oxides of sulphur and nitrogen, photo-oxidants, and other gases (like NH_3) dissolve in the droplets of clouds and rain to produce acidic cations (H^+ and NH_4^+), sulphates (SO_4^{2-}) and nitrates (NO_3^-);
- 6 acid rain containing ions of sulphate, nitrate, ammonium and hydrogen falls as wet deposition.

The various ways of introduction, transportation, dispersion, and deposition of the pollutants on the earth's surface are shown in Figure 1.

Figure 1 Emission, transport and mechanisms of deposition of atmospheric pollution



4.1 Chemical reactions involved in acid rain

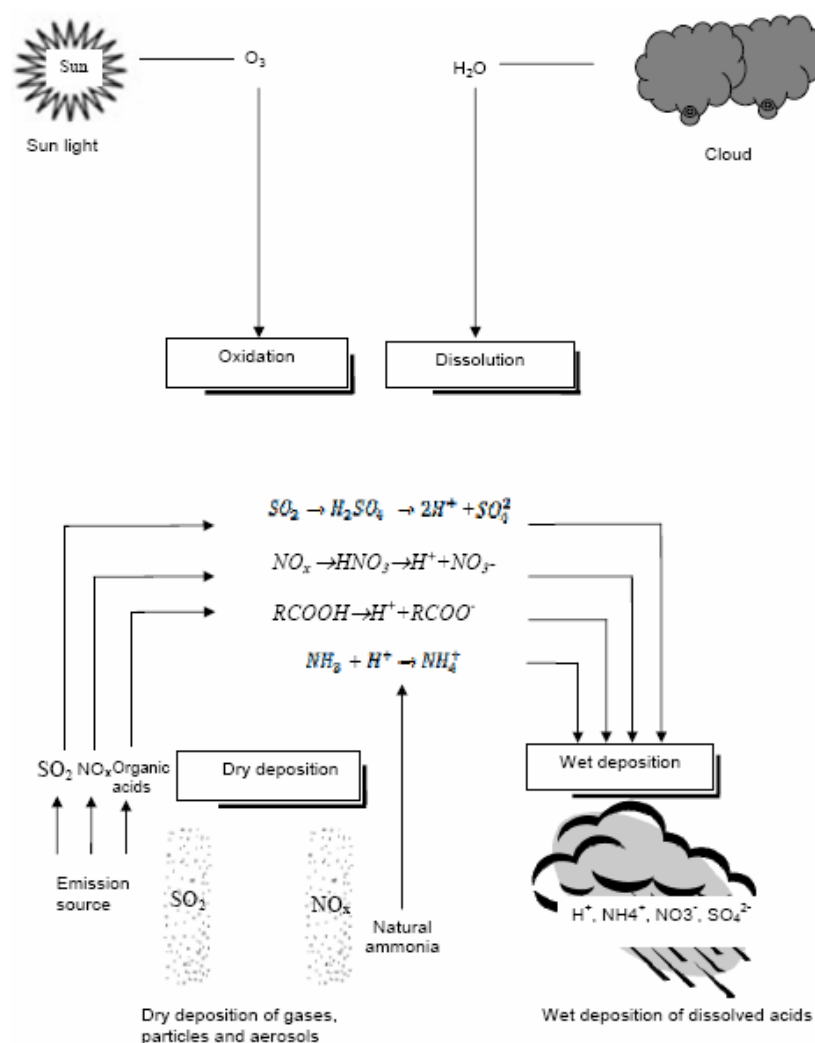
4.1.1 Oxidation of sulphur dioxide

In the atmosphere, sulphur dioxide gets oxidised to sulphur trioxide which reacts with water or alkalis to give sulphuric acid or sulphates. The acid or sulphates, in particular ammonium sulphate and bisulphate, occur as aerosols. The process is illustrated by the following equation:



The oxidation step proceeds in one or more of the three ways namely – catalytic oxidation, photochemical oxidation, and oxidation by radicals (Figure 2).

Figure 2 Chemistry of acidic precipitation

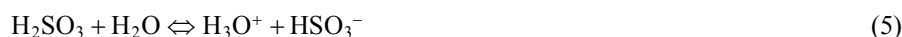


4.1.1.1 Catalytic oxidation

The reaction



is slow in clean air but is catalysed by aerosols containing metal ions like Mn_2^+ and Fe_3^+ . Surfaces such as buildings may also act as catalytic centres. The reaction is swifter in places where the relative humidity is more than 32%. The solubility of SO_2 in water is a function of pH and can be described by the equilibria:



The sulphur species in water are either covalent or ionic, the latter being more soluble due to the high dielectric constant of water.

4.1.1.2 Photochemical oxidation

SO_2 absorbs solar radiation producing excited states, which then react by a variety of routes to give SO_3 .

4.1.1.3 Oxidation by free radicals

Hydrocarbons and nitrogen dioxides, both increase the rate of oxidation of SO_2 to free radicals. These are mostly components of automobile emissions or secondary products.



This reaction is slow in gas phase and rapid in solution



Other feasible reactions are:



The dissolution of SO_3 in water gives sulphuric acid which can reduce the pH of the rain to as low as 2.

As stated earlier, carboxylic acids are released into the atmosphere as a result of biomass combustion and industrial processes. Upon dissolution in the falling rainwater, they release H^+ ions, adding acidity to the water.

A pictorial representation of the major reactions in the formation of acid rain is given in Figure 2.

5 Long-range transport of acidic chemicals

In general, concentrations of pollutants in the atmosphere which cause acid rain tend to decrease exponentially with distance from the source to unobjectionably low levels within 100 km (Downing et al., 1997; Khan and Abbasi, 1999b; Krajick, 2001). However, if several sources are aligned roughly along the direction of prevailing winds, cumulative concentrations can build up and remain elevated for substantial distances (Bartlett et al., 2000; Wilkening et al., 2000). These concentrations can be large enough to overwhelm the capacity of atmosphere to disperse or neutralise them (Khan and Abbasi, 1999c, 1999d). The long-range transport of air pollutants relates to this cumulative and persistent effect, as well as the atmosphere's ability at times to transport large volumes of air for long distances with relatively little mixing of (or dilution by) clean air (Wagh et al., 2006). Radioactive tracer studies of dispersion of polluted air by various direct and indirect means have suggested that a zone of influence of large sulphur and nitrogen oxide sources can be persisting for hundreds of kilometres downstream (Bouwman et al., 2002). This long-range cumulative effect creates the potential for relatively high levels of acid deposition over distances exceeding 1,000 km, affecting pristine areas far from industrial-urbanised environments (Bhatti et al., 1992; Khan and Abbasi, 2000a, 2001a). Thus, the phenomenon of acid rain is generally not identified with localised air pollution problems in and around large sources or at urban areas but with larger scale regional effects (Wang and Wang, 1995; Khan and Abbasi, 1998a, 1998b, 2000b).

5.1 Factors affecting SO_x and NO_x emissions

The main factors affecting SO_x and NO_x emissions are (Park, 1987; Abbasi et al., 2000; Fredric and Hans, 2004):

- a Coal-fired boilers – nearly all of the sulphur present in the fuel is converted to SO_2 and gets emitted to the atmosphere along with other flue gases (Cullis and Hischler, 1980; Abbasi, 1999; Abbasi and Abbasi, 2011c).
- b Oil-fired boilers – they also emit significant concentrations of sulphur oxides due to the presence of sulphur in fossil oil. For this reason, low-sulphur sources of oil, such as the ones available in Abu Dhabi, are termed 'sweet' and are preferred over oil of higher sulphur content.
- c Alkaline vapours such as ammonia – these if present in the atmosphere; neutralise the sulphuric/nitric acids thereby increasing the pH of the rain or snow (Galloway and Cowling, 2002).

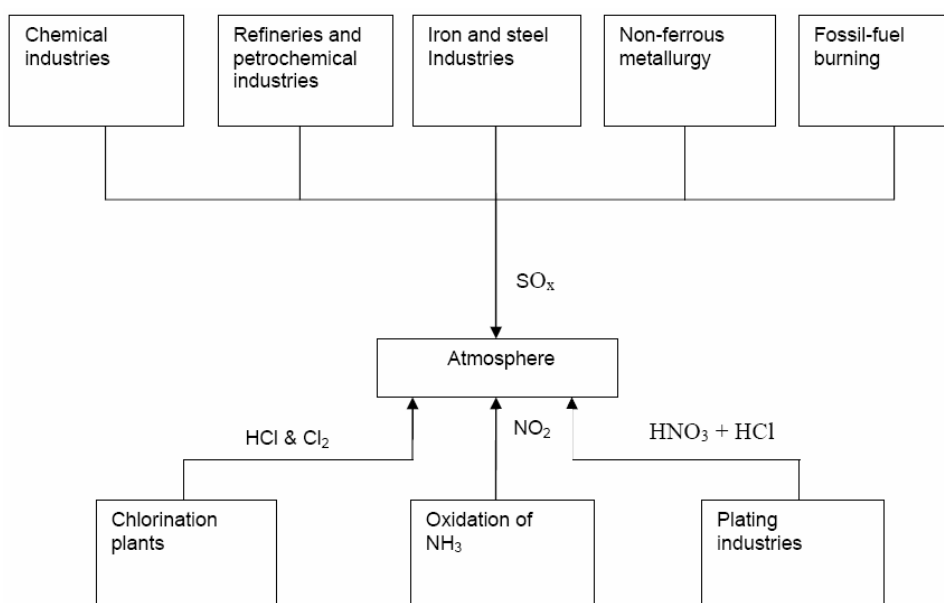
- d Dusts – natural or man-induced dusts from wind-blown soil are generally alkaline and may react with and neutralise strong acids in the atmosphere. Coal fired fly ash which is alkaline in nature may also help in the neutralisation process. Typical industries and processes which lead to emissions of sulphuric, nitric and hydrochloric acids are (Figure 3):
- 1 Refineries– sulphur is a natural substance present in all crude oils, distributed in the form of hydrogen sulphide, mercaptans, thiophenes and polysulphides (Khan and Abbasi, 1998c, 2001b).
Refinery processes lead to the emission of as much as 3,500 ppm of sulphur dioxide in flue gases. Fuel burning also produces nitrogen oxides but refinery processes produce only 2% of total nitrogen oxides whereas heaters and boilers account for much higher proportion (Khan and Abbasi, 1996).
 - 2 Iron and steel – Even though the main pollutants in this industry are particulates and dust, gas cleaning is effected at different stages in the process with oxygen inlet in order to remove sulphur. This results in SO_x emissions.
 - 3 Non-ferrous metallurgy – Non-ferrous smelter operations based on sulphide feeds generate large quantities of sulphur dioxide admixed with air or fuel products (Figure 3).
 - 4 Chemical industries – Sulphuric acid is a potential raw material for any industry and is manufactured in large quantities. A typical 500 tons/day H₂SO₄ plant discharges about 6.5 tons/day of SO₂ which is slightly more than the SO₂ released from fuel burning in a 200 MW power station in one hour. The processes wherein acidic fumes liberate and escape in environment have already been described in Section 1.1. In addition to SO₂ and SO₃, sulphuric acid mist is also formed (Abbasi and Ramesh, 2003). Nitric acid, another important raw material also leaves some gas discharges into the environment. It is often produced by the oxidation of ammonia over platinum-rhodium catalysts and the resulting NO₂ is absorbed in water. The gases emerging from stacks usually contain nitrogen (95%), oxygen (3%) and NO_x (500–5,000 ppm) often resulting in a brown plume (Khan and Abbasi, 1997a). In UK, a limit of 1,000 ppm for stack gas NO₂ was set, whereas EPA has specified 200 ppm.
Another major industrial acid, namely hydrochloric acid, arises from all chlorination plants (such as in vinyl chloride, ethylene dichloride production). Chlorine is another gas which escapes into the environment from several industrial places, often due to container failure (Khan and Abbasi, 1997b; Abbasi and Abbasi, 2007a, 2008; Abbasi et al., 2010).
Phosphoric acid mists also escape into the atmosphere during phosphoric acid manufacture. These can be completely removed by employing the same mist eliminators used in sulphuric acid manufacture. In the fertiliser plants, a lot of ammonium and diammonium phosphates are manufactured. The usual pollutants that go into the atmosphere in the fertiliser industry are sulphur oxides, sulphuric acid, ammonia and hydrogen chloride (Khan and Abbasi 1999c; Abbasi and Abbasi, 2007b).

- 5 Plating industries – metal leaching operations for copper and other metals leave nitric acid fumes in the environment. Hydrochloric acid is often used in metal cleaning stages prior to electroplating and since its vapour pressure is rather high, it is always dispelled into the atmosphere, especially at elevated temperatures (Singh and Agrawal, 2008).

In electrolytic applications such as chromium plating, anodising and descaling operations, hydrogen is generated at the cathode and oxygen at the anode. The freshly generated gases escape from the solutions with great speed along with significant quantities of chromic acid and sulphuric acid droplets thereby contributing to atmospheric pollution (Khan and Abbasi 1997c).

- 6 Miscellaneous – Acidic substances originating from synthetic textile, paper, food, pharmaceuticals, aerospace, and ordnance industries also contribute to release of acidic gases into the atmosphere (Ramasamy et al., 2004).

Figure 3 Contribution of acid-rain forming substances to atmosphere by different sources



6 Distribution of acid rain

6.1 The acid rain 'hot spots'

Acid rains and the oxides that create them are often transported to distances far away from their points of origin by the wind so that the adverse effects of pollution are experienced at places remote from the place of genesis (Abbasi, 1998a; Berge et al., 1999; Wilkening et al., 2000; Larssen et al., 2006). This gives rise to problems in handling the resultant pollution as the search for the culprit may well turn out to be a wild goose chase. The problem is further compounded by the fact that the environmental

damage caused by acid rain is not uniform, but area-specific, depending upon the geographical and geochemical aspects (Li and Gao, 2002; Tanner and Law, 2003; Hsiao et al., 2007).

The areas which are prone to acid-rain attacks have some common characteristics:

- a they are concentrated in the industrialised belts
- b they are often upland and/or mountainous areas, which are well watered by rain and snow
- c due to the abundance of water, they possess numerous lakes and streams and also have more land covered with vegetation
- d being upland, they often have thin soils and glaciated bedrock.

Many parts of Scandinavia and North Europe (particularly West Germany and upland Britain) share these features. Across the Atlantic there are a number of acid rain 'hot spots' including Nova Scotia, Southern Ontario and Quebec in Canada, the Adirondack Mountains in New York, Great Smoky mountains, parts of Wisconsin, Minnesota, and the Colorado Rockies of the USA. Elsewhere in the world acid rain hot spots exist where the atmospheric concentration of acid-forming substances is high and the soils are either acidic or have poor buffer capacity (Kuylensstierna et al., 2001; Wang et al., 2004).

Rains and snows with a pH of 4.3 or lower have regularly fallen over many of the highly industrial areas of the Northern hemisphere, especially North America and Northern and Western Europe (Table 1). The deposition of one of the major contributors to acid rain in European countries is presented in Table 2. The pH of precipitation in Southern Scandinavia had fallen to 4.2–4.3. The Southeast Canada has had rains with a pH range of 4.1–4.6. Many parts of North America have had an acidic precipitation of pH 3.5–4.2. In Britain rains between 1978 and 1980 had a pH ranging 4.0–4.3 (RGAR, 1987; Abbasi et al., 2000; Goodwin et al., 2004).

The worst hit areas with a pH below 6 have been Southern Norway, Sweden, Adirondack Mountains in New York, Southeastern Ontario and some parts of Eastern Canada (Watt et al., 2000). Southern Norway had completely lost its fish population in 20% of the 700 lakes by late 1970s. The Adirondack Mountains had lost the fish populations in 90% of its lakes.

Table 1 Acidification of rain in developed countries

<i>Location</i>	<i>Past pH</i>	<i>Present pH</i>
Southeast England	4.5–5.0 (1956)	4.1–4.4
Eastern Scotland	NA	4.2–4.4
Southern Norway	5.0–5.5 (1956)	4.7–5.3
Southern Sweden	5.5–6.0 (1956)	4.3–5.3
Japan (around Tokyo)	NA	4.5–5.3
Canada (Quebec)	NA	4.5–5.3
Black forest (Germany)	NA	4.2–5.3

Table 2 Deposition of SO_x in European countries

<i>Country</i>	<i>SO_x deposition (g of sulphur per sq. metre) annual average</i>
Netherlands	2.98
Belgium	3.31
Britain	2.61
Portugal	0.73
Spain	1.17
Luxemburg	2.32
France	1.14
Switzerland	1.67
Germany	2.54
Denmark	1.74
Norway	0.67
Sweden	0.68
Finland	0.60
Czech and Slovak Republic	5.20
Poland	4.01
Hungary	3.29
Austria	2.22
Italy	1.71
Yugoslavia	1.98
Romania	1.40
Bulgaria	1.94
Greece	0.81
Turkey	0.25
Albania	0.97

Source: Abbasi et al. (2000); Fredric and Hans (2004)

A brief account of what is happening in Poland may sum up the situation. The Polish coal called 'black gold' due to its role in Polish industry, contains 1% to 4% sulphur. An estimated 3 million tons of sulphur dioxide are reportedly emitted into Poland's polluted atmosphere every year as a consequence of the use of their 'black gold'. Together with 'imported' sulphur dioxide from abroad, about 4 million tons of SO₂ falls to the ground in Poland every year, amounting to an average value of about 10 tons of sulphur compounds per square kilometre of area. This figure ranks Poland, a relatively small country, in seventh place of total SO₂ generators behind the USA, Russia and former Soviet Union, Canada, Great Britain, and the Democratic Republic of Germany. The effects of such overdoses are horrifying. SO₂ fumes with other pollutants are reportedly either causing or contributing to about 600 additional deaths per 100,000 inhabitants every year. People living in Poland are vulnerable to the increased rates of respiratory and circulatory diseases, allergies and leukaemia. To make matters worse, scientists speculate that even greater amounts of sulphur dioxide will be coughed into the atmosphere from Polish factories, power plants and home heating systems due to increasing consumerism there.

Among the developed countries of Asia, acid rain is being encountered often in Japan and Singapore (UN, 2000). In a study carried out from November 1999 to October 2000 in Singapore (Hu et al., 2003), the rainwater was found to be typically acidic, with a mean pH of 4.2. Sulphate was the most abundant ion and was present at levels comparable to the ones reported for other industrialised regions. The pollutants in rainwater were derived from long range as well as local (industry and traffic) sources.

6.2 *Acid rain and developing countries*

Even though acid rain was first noticed in developed countries and levels and impacts of acid rain in those regions have been extensively studied, instances of acid rain and its harmful impacts are beginning to become common in developing countries as well. Harte (1983) found that the pH of rain falling over Amne Manchim town in China was as low as 1.3, probably the most acidic rain ever recorded. Acid rain is observed frequently in fast-developing countries, especially China, South Korea, and Hong Kong (Bashkin and Radojevic, 2003; Xie et al., 2004; Gao et al., 2009). Episodes of acid rain have also been occurring in Thailand, Philippines, Pakistan and Indonesia (Balasubramanian et al., 1999; Rodhe et al., 2002).

In India, which is the second most populous country in the world and is also the country with second largest land mass in Asia the first report of acid rain came from Bombay in 1974. A rainfall of pH 3.5 was reported (Burman, 1985). Since then instances of acid rain are being continuously reported from metropolitan cities (Khemani et al., 1989a, 1989b; Ravichandran and Padmanabhanmurty, 1994; Parashar et al., 1996; Kulshrestha et al., 1996, 1998; Jain et al., 2000). According to Khemani et al. (1989a, 1989b), and Singh and Agrawal (2008), the mean pH value of rainwater at Delhi was as high as 9.1 during 1963 but had fallen to 6.2 by 1984. A typical study conducted at the heavily industrialised Udyogamandal area in Kerala State revealed that it often receives acid rain; the pH going as low as 4.3 (Abbasi, 1999). A study conducted at Trombay, Mumbai revealed high incidence of acidic and sulphate components in air (Abbasi, 1998b). In India, annual SO₂ emission is doubling with every passing decade due to increased fossil fuel consumption and lowering of soil pH has been reported from North-eastern India, coastal Karnataka and Kerala, parts of Orissa, West Bengal and Bihar (Abbasi et al., 2000). Levels of noxious fumes and dust are more than twice the permissible levels in Agra; they are corroding the marble of the well-known monument Taj Mahal, jeopardising its grace and glitter. This phenomena has been described as 'marble cancer'. Indeed, reports on the corrosion of the Taj Mahal had helped in focussing public attention on the threats India faces from acid rain. This realisation was forcefully brought home when, in 1994, the Supreme Court of India ordered closure of the oil refineries and other industries implicated in corroding the Taj with their acidic emissions.

Indian soils are regarded as having good buffer capacity (Granat et al., 2001) which is one of the reasons why acid rain has not yet caused as serious impact in India as it has in several other regions of the world. Presence of airborne dust in India's most industrialised cities also reduces the acidity of the rain falling through it (Kulshrestha et al., 1996, 1998). But these natural defences against acid rain do not have unlimited capability. Both can, and do, buckle down if faced by continuous and high acidity in the rain. Granat et al. (2001) encountered acid deposition in the Bhubaneswar countryside and attributed it to two factors:

- 1 their measurements were made in a vegetation covered area with no local dust sources (hence no buffering by dust was available)
- 2 long-range transport of alkaline dust was probably rather small in that part of India (which also prevented buffering of the falling acid rain).

Granat et al. (2001) have noted that the deposition of acidity recorded in their study was small but the situation is likely to worsen because there is no buffer against additional acidity from the predicted increase of anthropogenic emissions of acidifying components. The situation with regard to non-suspended solid (NSS) SO_4^{-2} deposition in India is now close to that in Northern Europe (Sweden) in the early 1950s, a region that later become severely hurt by acid deposition when the emission of SO_2 in Europe increased. The calculated potential acidity deposition (worst case) by Grant et al. (2001) showed that already the present input from the atmosphere may be harmful to sensitive ecosystems.

In another study, by Norman et al. (2001), the monthly medians of pH at Bhubaneswar were found to be below 5.0 during October–December, and as low as 4.5 during November. The median pH in rain samples with trajectories that had remained within 400 km from the sampling site at Bhubaneswar during the previous five days was slightly below 5.0 (4.97). These low pH values were mainly due to a large contribution of sulphuric acid. Such a low pH had not been reported previously from rural sites in India. Samples from Bhubaneswar with trajectories that had remained over the Indian continent during 3 out of the 5 last days were found to have more than twice as high concentrations of NH_4^+ , SO_4^{2-} and Ca_2^+ as the other samples.

The fact that the impact of acid rain on Indian territory is gradually becoming apparent is also reflected in a study by Kulshrestha et al. (2003). They have found that two of the rainfall events over Hyderabad were acidic ($\text{pH} < 5.6$). More recent studies over Bhubaneswar by Das et al. (2005) suggest that there might be poor buffering against any further additional acidity; in other words that region may experience increasingly more severe acid rain in years to come.

In China, the first reports of acid rain appeared in the 1980s (Zhao and Sun, 1986; Zhao et al., 1988). With time the area effected by acid rain as well as the acidity of the rainwater have been increasing in China. Between 1986 and the present, the areas suffering from acid rain in China have extended north-wards from the south of Yangtze River to the whole of East China. Results from an acid rain survey conducted in 82 cities from 1991 to 1995 had indicated that the annual average pH value of the precipitation was lower than 5.6 in nearly half of those cities or in 87% of the southern cities. The lowest pH recorded in the survey was 3.52. In addition, the frequency of acid rain was very high (Bashkin and Radojevic, 2003).

The chemical composition of acid rain in China is generally different from that in Europe, with lower pH values and higher sulphate, calcium, ammonium and lower nitrate concentrations. In some cases, the fluoride concentration in precipitation appears also to be high in China, owing possibly to the combustion of coal with a high fluoride content. China's ammonia emissions are also large, about 3 times greater than the NO_x emissions. But whereas the ammonia emissions do neutralise some of the rainfall acidity (or even make it alkaline), this advantage is nullified by the soil acidification which ammonia causes through nitrification (Galloway and Cowling, 2002). Moreover, reduction of ammonia emissions is an exceedingly difficult task (Kaiser, 2001).

A major cause of acid rain in China is the extensive use of coal, which accounts for about 70% of the energy production. Consumption of coal and oil and subsequent emissions of SO₂ have increased rapidly since the 1970s. After a couple of years of apparently decreasing SO₂ emissions, the rate of increase is currently faster than ever. The total emissions of SO₂ to the atmosphere in China were ~22 million metric tons (t) in 2003 (SEPA, 2004). This is more than the total anthropogenic European emissions of 17 million t in 2002 (excluding ships) and over twice the US emissions of 10 million t in 2002 (Larssen et al., 2006). These figures reflect the extent to which China has become vulnerable to the threat of acid rain. Indeed, since the 1990s, the territory of China's south and southwest has become the third largest acid-rain-prone region in the world.

Moreover, developing countries are increasingly utilising rooftop rainwater harvesting for household needs. When the falling rain is acidic it is prone to dissolve in it unacceptable levels of heavy metals from the rooftop material, conduits, and linings of storage tanks (Abbasi and Soni, 1983, 1984; Meera and Mansoor Ahammed, 2006; Abbasi and Abbasi, 2009, 2011b). In this manner, also, acid rain poses a major threat.

6.3 Safe areas

There are two types of 'safe areas' where acid rain is not a problem. One comprises areas that simply do not receive acid rain or the gaseous oxides of sulphur and nitrogen due to their location. Almost all of the Southern hemisphere is thus protected, as also most of the tropics and parts of the Northern hemisphere. The other type is areas that receive acid precipitation but can withstand it. Many areas provide a natural resistance (buffering) to acidification with counter action offered by alkaline soils or limestone beds which neutralise acid inputs. Other forms of buffering are offered where airborne alkaline dust neutralises acid rain before it reaches the ground (Khemani, 1993; Kulshrestha et al., 2001). Several regions such as mid-Western USA and most parts of India have good buffering capacity but if such regions are persistently showered with acid rain the soil may gradually lose its neutralising ability.

7 Impact of acid rain

The process of acidification often remains undetected until damage has occurred. In some instances, organisms which are acid sensitive may serve as indicators of the initial stages of acidification. For example, lichens serve as good bioindicators for air pollution. In the vicinity of pH 6.0, several animals decline that are important food items for fish; these include freshwater shrimp (*Gammarus lacustris*) other shrimps like *Mysis relicta*, crayfish, snails and some small mussels (Abbasi et al., 1989).

The wide-ranging impacts of acid-rain on the ecosystem include the effects on its components as enumerated below:

7.1 Freshwater aquatic ecosystems

The effect of acid rain on the chemistry of surface water is determined by the geochemistry, geomorphology and hydrodynamics of the watershed and the waterbody. These factors determine the capacity of water to neutralise acids and absorb or release metals (Andersson et al., 1978; Almer et al., 1987; Abbasi et al., 2000, 2009).

In a group of lakes in Southern Norway surveyed in 1933 to 1941 and resurveyed in 1971 to 1975, the pH declined by 0.8 to 1.8 units (Gjessing et al., 1976). Many of these lakes now have $\text{pH} < 5.5$. Watt et al. (1983), who resurveyed 19 lakes in Nova Scotia that were originally surveyed in 1955, found that pH had declined in all of them.

In the Adirondack Mountain regions of New York, 51% of the lakes above 610 m elevation had a pH of less than 5.0 in 1975; when 40 of these lakes were surveyed during 1929 to 1937 only 2 (5%) had pH less than 5.0 (Schofield, 1976). Lakes that have $\text{pH} < 5.5$ and are not high in dissolved organic matter are believed to be highly susceptible to acid precipitation (Driscoll et al., 2001). Before we proceed, we must clarify that there are a large number of natural lakes which have pH less than 5.5 but such naturally acidic lakes have several features different from the lakes which have become acidic due to receipt of acid rain within a short span of time (3 to 4 years or lesser). The difference is summarised in Table 3.

Table 3 Characteristics of naturally acidic lakes and anthropogenically acidified natural lakes

<i>Naturally acidic lakes</i>	<i>Anthropogenically acidified lakes</i>
Brown to yellow colour caused by humic substances (peat, tannins, etc.)	Very clear water caused by reduced primary productivity (i.e., lack of phytoplankton and consequently zooplankton), precipitation of organic matter by aluminium, and dissolution of iron and manganese colloids. Inorganic acids (particularly sulphuric and nitric acids) predominate in these lakes.
Concentrations of dissolved organic carbon are high while transparency is low	Dissolved organic carbon concentrations are low, (seldom exceeding a few milligrams per litre) whereas the transparency is high.
Low pH (below 5) but well buffered: these lakes generally have a greater acid neutralising capacity (by organic and inorganic buffers and actions of microorganisms). This suggests that brown-water lakes would be less sensitive to the acidifying effects of precipitation.	Poorly buffered: once the bicarbonate alkalinity is exhausted, the pH decreases rapidly, giving little time for the species to adopt.
Abound with aquatic life	Some of the more sensitive taxa, such as blue-green algae, some bacteria, snails, mussels, crustaceans, mayflies, and fish are either reduced or eliminated.
Presence of humic, fulvic, and other organic acids keeps availability of toxic metals in check	No such cushion available

Source: Hendrey and Wright (1976), Almer et al. (1987) and Moiseenko (1994)

In natural water bodies metals such as zinc, cadmium, nickel, manganese, chromium, copper and mercury form complexes with naturally occurring ligands such as fulvic acids and phosphates. In the complexed form the bioavailability, and consequently the toxicity, of these metals is greatly reduced (Abbasi, 1987, 1988a, 1988b, 1998c, 1989a, 1989b; Abbasi and Soni, 1983, 1984, 1986, 1993; Soni, 1991). pH also effects the mobility of the metals, present in sediments, towards the overlaying water through direct dissolution; the solubility of most metal compounds in water gets lower as the pH is increased (Abbasi et

al., 1988, 1992, 1994). When a lake gets acidified the metal-fulvic acid complexes are destabilised releasing metal ions. Reduction in pH also increases mobility of the metal compounds from the sediments to the overlaying water. The combined effect of these two phenomena is increase in the concentration of metals in water. The concentration often increases to levels that cause chronic toxicity, even acute toxicity, to aquatic organisms (Abbasi, 1986, 2001; Abbasi et al., 1995; Abbasi et al., 1988, 1994, 1998, 2002; Cronan and Schofield, 1979).

Acidified lakes in Norway, Sweden and Canada (Ontario) have higher concentration of zinc, lead, copper, cadmium and nickel than similar lakes in non-acidified areas, and these metals have been detected in precipitation in these areas (Wright and Gjening, 1976; Chester, 1986; Abbasi et al., 1998, 1999).

Acidified lakes are most likely to be found in regions where bedrock and soil are low in naturally occurring acid neutralising materials. In regions where limestone is abundant, acid precipitation gets neutralised easily.

Acidification causes adverse effects on all trophic levels of aquatic biota (Likens, 1985) in surface water, from decomposers to fish and amphibians (Table 4). Studies in acidified surface waters, and *in vitro* laboratory experiments have shown that microbial activity is reduced at low pH, and species dominance shifts from bacteria to fungi.

Table 4 Effects of decreasing pH on aquatic organisms

pH	Effect
8.0-6.0	Decreases of less than one-half of a pH unit in the range of 8.0 to 6.0 are likely to alter the biotic composition of lakes and streams to some degree in the long run. However, the significance of these slight changes is not great. Decreases of one-half to one pH unit (a three-fold to ten-fold increase in acidity) may detectably alter community composition. Some species may be eliminated.
6.0-5.5	Decreasing pH from 6.0 to 5.5 will reduce the number of species in lakes and streams. Among remaining species, significant alterations in the ability to withstand stress may occur. Reproduction of some salamander species is impaired.
5.5-5.0	Below pH 5.5, numbers and diversity of species will be reduced. Reproduction is impaired and many species will be eliminated. Crustaceans, zooplankton, phytoplankton, molluscs, amphipods, most mayfly species, and many stone-fly species will begin to be eliminated. In contrast, several invertebrate species tolerant to low pH will become abundant. Overall, invertebrate biomass will be greatly reduced. Certain higher aquatic plants will be eliminated.
5.0-4.5	Below pH 5.0, decomposition of organic detritus will be impaired severely. Most fish species will be eliminated.
4.5	In addition to exacerbation of the above changes, many forms of algae will not survive at a pH of less than 4.5

Source: Calvert et al. (1985), Hendrey and Wright (1976) and Leivestad et al. (1976)

As lakes become acidified the diversity of phytoplankton species decline due to stresses on acid-sensitive organisms. As a result the entire species composition changes. At low pH, the chrysophyta, cyanophyta and chlorophyta are reduced and Pyrrophyta become dominant. The number of species of zooplankton present in a water body were found to decrease as pH decreased in studies conducted in Sweden, Canada and Norway.

Molluscs, crustaceans, ephemeroptera and plecoptera appear to be highly sensitive to acidification (Roff and Kwiatkowski, 1977). Invertebrates in acidic lakes may accumulate

toxic trace elements that could then be passed on to vertebrates in the food web. The most dramatic effects of acidification on aquatic organisms have been on fish (Abbasi and Soni, 1985; Abbasi et al., 1989, 1998). The observed effects include mortality, reproductive failure and increased heavy metal uptake.

Acidification of aquatic habitats also affects some amphibians. Pough (1976) found that the salamander, *Ambystoma maculatum*, was sensitive to acid. Mortality of its embryos was high at pH < 6.0.

7.2 Soils and vegetation

Soils of different regions have differing ability to process and neutralise acidic inputs (Kopstik et al., 2001). Broadly, soils have been classified into four categories on the basis of their acid-neutralising abilities (Abbasi and Khan 2000b):

- Type 1 Low or no buffering capacity, overlying waters very sensitive to acidification (granite/syenite, granitic gneisses, quartz sandstones, or equivalents).
- Type 2 Medium to low buffering capacity, acidification restricted to first and second order streams and small lakes sandstones, shales, conglomerates, high grade metamorphic to intermediate volcanic rocks, intermediate igneous rocks, calc-silicate gneisses).
- Type 3 High to medium buffering capacity, no acidification except in cases of overland run off in areas of frozen ground (slightly calcareous, low grade intermediate to mafic volcanic, ultramafic, glassy volcanic rocks).
- Type 4 'Infinite' buffering capacity, no acid precipitation effect of any kind (highly fossiliferous sediments or metamorphic equivalents, limestones, dolostones).

The acid neutralising ability of soil of a given region influences, to a great degree, the extent of harm acid rain may cause in that region.

The principal pathways and mechanisms of plant growth response to atmospheric deposition and gaseous pollutants are illustrated in Figure 4.

The exchange between hydrogen ions and the nutrient cations like potassium and magnesium in the soil cause leaching of nutrients, making the soil infertile. This is accompanied by decreased respiration by soil organisms. Increase of ammonia in soil due to reduction in other nutrients decreases the rate of decomposition. The nitrate level of soil is also found to decrease. The impact of acid rain on soil is more obvious in the UK and other European countries (Tamn and Hallbacken, 1988; Watmough and Dillon, 2003) than in India; this is because Indian soils are mostly alkaline, with good buffering ability.

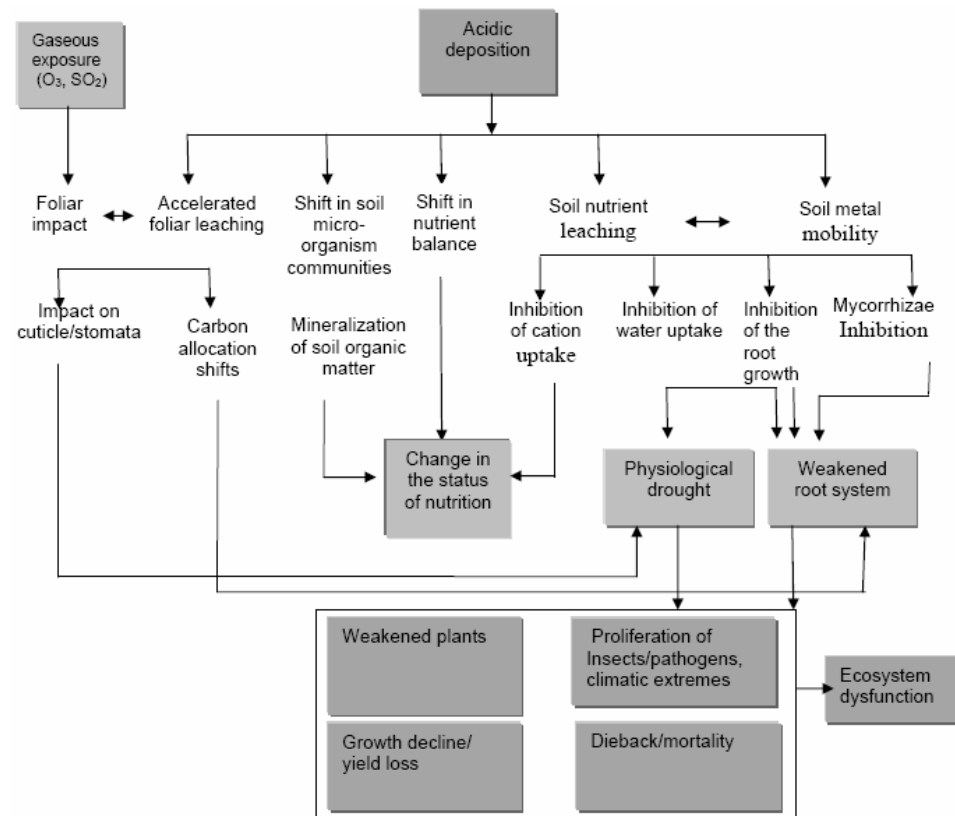
Acid rain affects trees and undergrowth in forests in several ways, causing reduced growth or abnormal growth (Crossley et al., 2001; Takanashi et al., 2001; Sant Anna-Santos et al., 2006).

The typical growth – decreasing symptoms are:

- a discoloration and loss of foliar biomass (yellowing and browning of needles and leaves)
- b loss of feeder-root biomass, especially in conifers
- c decreased annual increment (width of growth rings)

- d premature senescence (aging) of older needles in conifers
- e increased susceptibility to secondary root and foliar pathogens
- f death of herbaceous vegetation beneath affected trees (all within the drip line from the canopy)
- g prodigious production of lichens on affected trees
- h death of affected trees.

Figure 4 Impact of acid rain on ecosystems



The abnormal growth symptoms are:

- a active shedding of needles and leaves while still green, with no indication of disease
- b shedding of whole green shoots, especially in spruce
- c formation of stork's nest crown in young white fir
- d altered branching habit and greater than normal production of adventitious (out-of-place) shoots
- e excessive seed and cone production year after year
- f diseased trees show growth at top, not near bottom with very brittle branches.

In addition water-stress symptoms may also be caused:

- a altered water balance
- b increased incidence of wet wood disease.

Acid rain may cause a shift in the community structure of microorganisms (as explained in the following section); useful microorganisms in soil may be replaced by disease causing fungi and the population of beneficial earthworms (Gajalakshmi and Abbasi, 2002, 2004) may be reduced or eliminated.

7.3 *Microorganisms*

In an environment where nutrients are available in adequate quantities, it is the pH which determines whether any microbial species shall proliferate and the rate at which it can proliferate. Most bacteria and protozoa have pH optima near neutrality; most fungi prefer an acid environment, most blue-green bacteria prefer an alkaline environment. So after a long run of acid rain, microbial species in the soil and water shift from bacteria bound to fungi bound and cause an imbalance in microflora. The results are delay in the decomposition of soil organic material, and the increasing fungous disease to aquatic life and forests. There is also a latent burden on water supply treatment systems (Abbasi, 2001).

The effect of pH on the transport of material across the membrane of microorganisms is also a very important factor and perhaps the determining factor in influencing their growth. The ionisation of a required nutrient (such as iron, copper) may make it unavailable to the cell, whereas a toxic compound (such as cadmium) may become inhibitory only at a pH at which it is not ionised (Gajalakshmi et al., 2001a, 2001b).

7.4 *Wildlife*

The effects of acid rain on wildlife are not very apparent and are therefore, more difficult to document. Nevertheless, several direct and indirect effects of acid rain on the productivity and survival of wildlife populations have been reported (Abbasi 1998a, 1998b; Abbasi et al., 2000; Kitamura and Ikuta, 2001; Kawahara et al., 2001).

Acid rain can directly affect the eggs and tadpoles of frogs and salamanders that breed in small forest ponds (Abbasi, 1998a; Abbasi et al., 1989, 1998). The effects of acid rain are mostly unknown for wild life that do not depend so greatly on the aquatic medium as on total environment for their eggs or young.

It is postulated that acid rain can indirectly affect wildlife by allowing metals bound in soils and sediments to be released into the aquatic environment, where toxic substances may be ingested by wild life, like; birds; that feed in such environment. For example, an accumulation of toxic levels of aluminium in the food chain may explain the reproductive failure observed in flycatchers that feed on insects emerging from acidified lakes in Scandinavia (Whelpdale et al., 1996).

Other indirect effects of acid rain on wildlife are loss or alteration of food and habitat resources. The elimination of fish from a lake, for example, may mean that little use by loons or mergansers will occur during the breeding season, although an increase in emerging insect densities after fish elimination might benefit other water-bird species during their nesting or brood rearing state (Chari et al., 2003).

Degradation of plant communities from acid rain can include damage to leaves, loss of productivity and sometimes loss of sensitive plants. For example, foliar browning in natural stands of two species of birch (*Betula papyrifera* and *Betula cordifolia*) growing adjacent to the Bay of Fundy, Canada, have been correlated with fog acidity and frequency of fog episodes (Kouterick et al., 1998). Symptoms of this malady include brown leaf margins, brown spotting, and premature senescence. Because abundance and diversity of plants is directly related to that of wildlife, any effect on the former will also affect the latter.

7.5 Humans and buildings

A number of studies have brought out the deleterious effect acid rain exerts on building materials and objects of day-to-day use like kitchenware (Park, 1987; De Oliveira Loureiro et al., 2007). For example, Kaneko et al. (2006) report that architectural titanium sheets are discoloured by acid rain or acidic fog. When Tsujino et al. (1995) exposed different materials such as copper, bronze, and marble under indoor and outdoor conditions to acid rain, the resulting corrosion was directly correlated with the ratio of SO_2/NO_x and climate. The incremental effects of wet and dry deposition on carbonate stone erosion due to hydrogen ion, SO_2 and NO_x were quantified by Baedecker et al. (1992). The results indicate that approximately 30% of erosion by dissolution could be attributed to the wet deposition of hydrogen ion and the dry deposition of SO_2 and HNO_3 . Organic acids present in the acid rain were found to corrode copper specimens, the relative aggressiveness of the acids was acetic > formic > butyric/propionic (Bastidas and La Iglesia, 2007). Organic acids can also corrode several other metals.

Acid rain speeds up the natural chemical weathering and corrosion of exposed materials in a variety of ways. For example, ferrous metals are attacked by SO_2 and rusted more quickly than they otherwise would. Steel buildings, railway tracts and other structures built of iron are very seriously affected by acid rain with extensive economic losses (Anonymous, 1984). Acid rain has a particularly devastating effect on those buildings which are made of sand stone, limestone and marble. Calcium carbonate is the common constituent of these materials, which reacts with sulphuric acid present in acid rain to form calcium sulphate. This is granular and gets washed off in the subsequent rains, exposing the hitherto unaffected calcium carbonate to further acid attack.

Historical monuments such as The Taj Mahal in India have been affected by what has been termed 'stone-cancer'. Stone-cancer is yet another effect of acid rain – caused by its corrosive action on the building material. Numerous other materials are harmed by acid rain or the gases responsible for acid rain (Table 5). In China, acid rain has seriously corroded metal structures and concrete works in the cities of Chongging and Guiyan (Bashkin and Radojevic, 2003).

The repairs on building and monuments can be quite costly. In Westminster, England, up to ten million pounds had to be spent on repairs caused by acid rain damage. In 1990, the USA spent 35 billion dollars on paint damage. In 1985, the Cologne Cathedral cost the Germans approximately 20 million dollars in repairs. The restoration of acid-rain effected Roman monuments cost the Italian government about 200 million dollars.

Table 5 Acid rain damage to materials

<i>Material</i>	<i>Type of impact</i>	<i>Principal air pollutants</i>	<i>Other environmental factors</i>	<i>Mitigation measures</i>
Metals	Corrosion, tarnishing	Sulphur oxides and other acid gases	Moisture, air, salt, particulate matter	Surface plating or coating replacement with corrosion resistant material, removal to control environment
Building stone	Surface erosion, soiling, black crust formation	Sulphur oxides and other acid gases	Mechanical erosion, particulates, moisture, temperature fluctuations, salt, vibration, CO ₂ , micro-organisms	Clearing, impregnation with resins, removal to controlled environment
Ceramics and glass	Surface erosion, surface crust formation	Acid gases, especially fluoride-containing	Moisture	Protective coating, replacement with more resistant material, removal to controlled atmosphere
Paints and organic coatings	Surface erosion, discolouration, soiling	Sulphur dioxides, hydrogen sulphide	Moisture, sunlight, ozone particulate matter, mechanical erosion, micro-organisms	Repairing, replacement with more resistant material
Paper	Embrittlement, discolouration	Sulphur oxides	Moisture, physical wear, acidic materials introduced in manufacture	Synthetic coatings, storing in controlled atmosphere, deacidification, encapsulation, impregnation with organic polymers
Photographic materials	Micro-blemishes	Sulphur oxides	Particulate matter, moisture	Removal to controlled atmosphere
Textiles	Reduced tensile strength, soiling	Sulphur and nitrogen oxide	Particulate matter, moisture, light, physical wear, washing	Replacement, use of substitute materials, impregnation with polymers.
Textile dyes	Fading, colour change	Nitrogen oxides, ozone	Light, temperature	Replacements, use of substitute materials, removal to controlled environment
Leather	Weakening, powdered surface	Sulphur oxides	Physical wear, residual acids introduced during manufacture	Removal to controlled atmosphere, consolidated with polymers, or replacement
Rubber	Cracking	Ozone	Sunlight, physical wear	Add antioxidants to formulation, replace with more resistant materials

Source: Odan (1976); La Bastille (1981); Jeng-Peng and Bhargava (1996)

There is a wide range of effects on human health. The obvious ones are bad smells, reduced visibility, irritation of the skin, eyes and the respiratory tract (Abbasi, 1999). Some direct effects include chronic bronchitis, pulmonary emphysema and cancer. Some indirect effects include food poisoning vis-a-vis drinking water and food. Increase in levels of toxic heavy metals like manganese, copper, cadmium, aluminium and chromium (Abbasi and Abbasi, 2009) also contributes to the detrimental effects on human health. A report on the susceptibility of UK groundwaters to acid-deposition-induced acidification (Kinniburgh and Edmunds, 1984) has made the point that the most serious consequence of a significant fall in ground water pH was likely to be the increased solubility to metals in potable water and accelerated corrosion of the distribution network. The greatest threat was probably to small, untreated, local supplies from springs and shallow wells and boreholes. Acid groundwaters in shallow wells and at lake inflows have been reported in Sweden (Hultberg and Johansson, 1981; Bergman and Hill 2000).

There is much evidence to suggest that acid flushes may be associated with high storm-water concentrations of sulphate and nitrate (Abbasi and Abbasi, 2009, 2011a). This is particularly the case during snowmelt, when the processes which normally help to regulate the drainage to these species into streams and lakes may be substantially curtailed. For nitrate, the problem may be further exacerbated by the soil freeze/thaw effect, which may mobilise even more nitrate (Likens et al., 1987; Edwards et al., 1986). Ultimately, high nitrate levels could present more of a water quality problem than high hydrogen ion concentrations. There is strong historical evidence for a dramatic increase in the nitrate component of acid rain in Europe and North America. When high concentrations of sulphate pass through soils to drainage water, there is often an associated increase in concentrations of base element and other metal cationic species. Aluminium mobilised in this way may play a major role in the adverse effects of acidic freshwaters on fish and other aquatic life. Sulphate anion adsorption leads to base cation retention, as discussed later, but sulphate saturation of adsorption sites facilitates cation leaching.

As acid rain enhances the scavenging of toxic materials from atmosphere, mobilises natural or synthetic contaminants in catchment areas, and promotes corrosion of drinking water distribution systems, as indicated above, it would eventually lead to bioaccumulation of toxic chemicals in human body. In Sweden; groundwater; which is their main drinking water reserve has grown acidic in some areas. The average adult ingests two litres of water each day, including water used to prepare food and beverages. Children and infants consume a disproportionately greater amount with respect to body weight. Thus, the babies may be at risk even when the water they consume contains toxic materials within the permissible limit. In some remote areas where drinking water is obtained locally, trace contaminants mobilised by acid deposition could be an important route to human exposure. This problem is complicated by the fact that such people who live there may not even be aware of the dangers they face.

- **Mercury:** Methyl mercury and related short chain alkyl mercurial compounds are the environmental contaminants most dangerous to humans, primarily because they accumulate in edible fish tissue (Abbasi and Soni, 1983). Although acid deposition may not increase the production of methylmercury it may increase the partitioning of methylmercury into the water column. In some recent efforts to neutralise acidic lakes through the application of lime appear to have helped in reducing mercury levels in fish.

- **Aluminium:** Acidified waters are known to leach substantial amounts of aluminium from watersheds. Concentrations of aluminium in acidified well waters in the USA have been found as high as 1.7 mg/l that far exceeds its background level. Alum-treated water shows aluminium levels three times higher than in untreated waters. Even at relatively low levels, aluminium has been implicated in dialysis dementia, a disorder of the central nervous system and may be toxic to individuals with impaired kidney function.
- **Cadmium:** Cadmium can enter drinking water supply through corrosion of galvanised pipe or from copper-zinc solder used in the distribution systems. A decrease in water pH from 6.5 to 4.5 can result in a five-fold increase in cadmium and could cause renal tubular damage in 0.9% of the population (Abbasi and Soni, 1986; Abbasi et al., 1998).
- **Lead:** A survey has revealed that drinking water in 16.1% of 2,654 rural US households studied had lead levels in excess of the 50 µg/l maximum acceptable limits. Fetuses and infants are highly susceptible to drinking water contaminated with lead. Because lead can cross the placenta, fetuses can absorb up to 50% of ingested lead, whereas adults absorb only 8%. High blood lead levels in children (> 30 µg/ml) are believed to induce biochemical and neurophysiological dysfunction. However, even low blood levels of lead can result in mental deficiencies and behavioural problems.
- **Asbestos:** Asbestos from natural rock can be released by acidic waters with fibres up to 500 million/l. As many as 40 million persons in the USA may be exposed to asbestos in their drinking water. The human health effects of increased ingestion of asbestos fibres are not yet fully understood.

General impact of corrosion of distribution systems: When water of low (acidic) pH passes through water supply pipelines it corrodes the supply lines and solubilises metals (Abbasi and Abbasi, 2009). As much as 85% to 92% of the drinking water supplies in the acid-sensitive North-eastern USA were found to suffer from such corrosion. This problem is also serious in North Europe.

7.6 Agriculture and fisheries

The adverse impact of acid rain on farming and fishing may lead to a deterioration of life quality indices like gross national product (GNP) and per capita income, especially in the predominantly agricultural and developing countries like India (Khemani et al., 1989a, 1989b; Chandrawanshi and Patel, 1999; Das et al., 2005; Abbasi and Abbasi, 2011d; 2012).

Acid rain has been found to enhance the accumulation of heavy metals (Cd, Cu, Pb, and Zn) in crops by Chen et al. (1998). The authors have compared the ratios of relative concentrations of the four heavy metals in brown rice and leaves of vegetables sampled from an acid rain affected area and non-affected area. The ratios of relative concentrations of Cd, Cu, Zn in brown rice and 19 vegetable species growing in the acid rain area and growing in an area unaffected by acid rain were mostly higher than 1, in some cases even higher than 3. This indicates that acid rain may cause heavy metal accumulation in grains and vegetables which can be dangerous for humans and other

animals. Acid rain has been shown to adversely effect morphological characteristics of food crops, such as wheat (Singh and Agarwal, 2004).

8 Acid rain: socio-economic aspects

The most disputed aspect of acid rain is the 'cleaning-up' process. The cleanup programmes are not only very expensive but it is also very difficult to assess their success or failure (Jeffries et al., 2003; Fredric and Hans, 2004; Menz and Seip, 2004). Inevitably, the high costs involved must be met by the countries that export the pollution, whereas the benefits to be gained will be enjoyed mostly by the importer countries (Burtraw et al., 1997). Thus, arises the inevitable difference of opinion between countries over the best way of tackling the problem of acid rain. Those countries that are hardest hit by the problem (such as Canada and Nordic States) are convinced that something must be done, without further delay, to reduce emissions and thus save their forests and lakes. Twenty one governments had resolved to cut their own emissions of sulphur dioxide by at least 30% and have been trying to persuade the main producers of the culprit oxides to join them in a truly international attack on the problem.

Whereas the international scientific community regards acid rain as one of the most serious and significant environmental problems of our time, which requires immediate political initiatives both nationally and internationally, leading politicians and government officials argue that the problems are as yet too little understood and that links with possible source areas and likely sources such as coal-fired power stations are as yet too ill defined to justify wholesale political intervention. Such an intervention would require the introduction of emission controls and lead to electricity price rises for the consumer. The acid rain debate is thus as much a battle in politics as a struggle in science. Estimation of economic impacts and assessments of benefit-cost ratios of controlling acid rain has been a concern in both Europe and the USA ever since the issue rose to prominence in the 1970s. However, the initial understanding of the relationship between acid deposition and its effects was so full of uncertainties that for long the role of cost-benefit analysis remained limited (Menz and Seip, 2004).

Recently, there has been renewed interest in cost-benefit analysis to motivate policy makers in Europe and to some extent in the USA. It is still not easy to conduct such an analysis due to paucity of data as well as its imprecision, but attempts have made which clearly point out that reductions in harmful health effects are the major benefit in monetary terms if emissions of SO₂ and NO_x are reduced. It is now fairly clear that there are net cost savings from the use of economic incentives such as emissions trading for acid rain control (Menz and Seip, 2004).

Most recent and more comprehensive assessments indicate that the large reduction of sulphur emissions in both Europe and the USA have resulted in benefits that significantly outweigh the costs (Menz and Seip, 2004). Similar conclusions emerge from a study in China (Aunan et al., 2004).

Acidity in rain has declined by about 50% over the UK since 1986 and the decline is detectable even in the remote regions of the country, but the magnitude in both absolute and relative terms are smaller in the remote areas (Fowler et al., 2005). However, the decline in concentration and wet deposition of SO₄²⁻ is much smaller than expected from the decline in emissions of SO₂ over the UK and Europe. Many sites, especially on the

west and south coasts, are affected by an increase in emissions of sulphur from shipping, which has offset the decline in wet deposition of sulphur from terrestrial sources.

Concentrations of NO_3^- in rain have declined in UK but the trends are significant only in the English Midlands, where concentrations are 20% smaller than 1986, and, over this period, emissions declined by 40%. This important non-linearity in the emission-deposition relationship has important implications for control strategies, which assume linearity (Fowler et al., 2005).

From 1980 onwards, a major international conference *The Acid Rain Conference* is held once every five years to take stock of the situation. The last such conference was held at Prague, Czech Republic, in June 2005 and the next one is due at China in 2010. The Prague conference issued a statement of which relevant portions are reproduced below. The statement clearly brings out that even though some success has been achieved in reducing emissions of NO_x and SO_x by developed nations the problem of acid rain is far from being solved. Rather, the problem is heading to be more and more serious:

- a Emissions of sulphur and to a lesser extent nitrogen have declined as international and national measures have been implemented. Acidification of soil and surface water has also ceased in some areas, and ecosystems are beginning to recover. But there is still a long way to go, as recovery so far has been slow and erratic, and the path is strewn with confounding factors.
- b In fact the news is not all good. Even when the Gothenburg protocol and other pending legislation are implemented, the critical loads will still be exceeded in large areas of Europe and North America, and the future beyond the year 2020 is uncertain, especially with respect to nitrogen emissions and their effects.
- c In many other regions of the world acid rain and the whole complex mixture of air pollutants have emerged as a growing problem. S and N emissions have decreased in Europe and Eastern North America, but they are increasing rapidly everywhere else. Large regions such as China, Japan, and the Indian subcontinent are now at risk for damage to human health and to freshwater and terrestrial ecosystems. The prognosis is for growing fossil fuel use and agricultural activity with the accompanying growing emissions of S and N, particles, and other substances. There is an urgent need for more monitoring and research in these regions.
- d Acid rain research and the policy response must become bigger and wider in scope. Long-range transported air pollution includes a wide spectrum of potentially harmful substances; S and N gases and particles, fine particles, ozone, heavy metals, and POPs. The Gothenburg protocol for the first time dealt with multi-pollutants and multi-effects.
- e Long-range transport across oceans is of increasing importance, and for some substances even a global view is necessary. Recent initiatives to address the ever-widening range of transboundary air pollution include a EU-USE joint task force on hemispheric transport, and a NGO-led Global Atmospheric Pollution Forum. Such initiatives provide a highly valuable means by which scientists and policy makers from countries around the world can meet, compare experiences and undertake joint activities.

- f It has taken years of careful scientific sleuth work to unravel the complicated details of acid rain and its effects. Well-designed, harmonised, and quality-assured monitoring of air, rain, water, soil and forests has been a key component to this understanding. The work of the UN-ECE CLTRAP through the ICPs and EMEP has been particularly important, and similar such networks are of vital importance for other areas of the world. Indeed, the monitoring has provided the 'ground truth' that the implementation of the protocols has had the desired effect.
- g Although there has been great progress in the understanding of acid rain, it is becoming increasingly clear that there are many other factors that confound the picture of acidification and recovery. The role of climate and potential future climate change has become of increasing concern, as is the role of other types of ecosystem disturbance and the synergistic effects of several pollutants acting simultaneously. Intensive forestry has been also recognised as an important contribution to soil acidification. This problem had remained undetected during several years of frequent acid rains and is now a threat to the recovery of these ecosystems. This problem is particularly common and serious in the mountain regions of central Europe.

Acid rain will undoubtedly exacerbate the very serious global problem of ocean acidification (Abbasi and Abbasi, 2011a), but its role in global warming is not that clear (Martins and De Andrade, 2002; Cerceo, 2004). Liu et al. (2008) suggest that in peatlands, acid rain can simulate sulphate reducing bacteria into populations which can out-compete methanogens for substrates, thereby suppressing the emission of the greenhouse gas methane.

9 Control measures

Most effects of acid rain on fish and wild life resources cannot be directly countered without reducing or eliminating the sources of pollution. However, it is possible to take measures locally to counter acidification of streams, soil, and rest of the environment. Some of the measures which have shown good results in the past are (Stoddard et al., 1999, 2003; Evans et al., 2001):

- a Buffering: The practice of adding a neutralising agent to the acidified water to increase the pH is one of the important control measures. Usually, lime in the form of calcium oxide and calcium carbonate is used.
- b Breeding of hatchery fish in acidified water: this practice replenishes fish population that would otherwise decline, thus helping to maintain an ecological balance within acidified lakes.
- c Prevention of the emission of excess SO_x and NO_x from industries: Laws should be formulated by the governments to regulate the emission. Some of the measures are:
 - 1 decreasing emissions of SO₂ from power stations by burning less fossil fuel, using alternate energy sources like tidal, wind, hydropower, hydrogen, etc. (Abbasi and Abbasi, 2010b, 2011e, 2011f)
 - 2 using low sulphur fuel
 - 3 desulphurisation

- 4 decrease in emission of NO_x from power stations
- 5 modification in engines to make them more energy-efficient.

Emissions of SO_x can be controlled in various ways (Abbasi, 1999; Singh and Agrawal, 2008):

- a conversion to sulphuric acid
- b conversion to elemental sulphur
- c neutralisation and manufacture of other products.

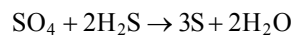
In all these processes, the gas mixture containing sulphur dioxide is first cleaned with water in order to eliminate impurities such as arsenic, selenium salts, mercury, chlorides, and sulphides. The gas stream is then passed through a succession of catalyst beds (usually V_2O_5) and then to absorption vessel (H_2SO_4 , single contact). The efficiency of conversion of SO_2 to SO_3 in this process is 97% to 98% provided the gas strength is greater than 3.5%. The conversion efficiency to SO_3 can be increased to 99.9% if the residual gas on first sequence of absorption through vessel is reheated and brought once again on the catalyst beds. In order to run this process successfully, the original air mixture leaving the smelter should have a SO_2 concentration higher than 6% and the final stack gas concentration below 500 ppm.

Table 6 Representative costs of strategies to reduce SO_x emissions

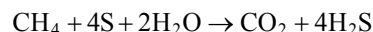
<i>Control strategies</i>	<i>Costs (in US dollars per ton SO_2)</i>
Coal cleaning	
North Appalachia and east Midwest coal	50–600
South Appalachia coal	700–1,000
Fuel switching	
Shift from high-to-low-sulphur coal	250–350
Shift from high-to-medium-sulphur coal	350–400
Shift from medium-to-low-sulphur coal	400–500
Shift from high-to-low-sulphur residual oil	300–400
Fuel gas desulphurisation	
Shift from unscrubbed to scrubbed high-sulphur coal	400–600
Shift from unscrubbed to scrubbed medium-sulphur coal	600–1,500
Shift from unscrubbed to scrubbed low-sulphur coal	1,800–3,000
Limestone injection multi-staged burns	
High-sulphur coal	200–350
Medium-sulphur coal	250–700
Low-sulphur coal	500–1,200

Elemental sulphur can be recovered from the smelter gases by any of the process described below (Abbasi, 1999; Abbasi and Abbasi, 2010c). The gas concentration should be brought to a lower level (up to 1% to 3% SO_2) and the sulphur produced should be dried, dedusted and cooled to 50°C.

- 1 Absorption of gas in buffered citric acid/sodium citrate at pH 3.8 (strictly) and removal of sulphur from the solution by filtration/thickening.
- 2 Liquid phase Claus conversion to sulphur.



H₂S required for this is generated from reaction shown below:



The typical costs of SO_x removal are given in Table 6.

Acid rain and its effects will not go away overnight. Increasing public awareness of the problem is the first step towards finding some of the solutions. The cost of control versus the cost of damage must be considered while evaluating the merit of any management alternative. Given the fact that past studies has indicated that the benefits of acid rain control easily outweigh the costs, it is a problem not without hope. A right strategy can help to improve the situation.

10 Really how big a threat is acid rain?

As is with other environmental issues, the phenomenon of acid rain has been enveloped in controversy. There have been two radical and conflicting sets of opinions – one believing that acid rain would cause catastrophic damage to the environment and the other playing down the acid rain hazard to something more or less inconsequential.

When one sifts through the literature available on acid rain one finds numerous original papers and reviews describing adverse impacts of acid rain in which the authors have used one or other body of the evidence to drive home their own belief on the extent of threat of acid rain. Lying between the two extremes are opinions of varying extents of moderation.

When we balance the available evidence the following pointers emerge:

- a Acid rain is a slow acting scourge – its impacts are not dramatically evident over a short time span unless, in exceptional cases, the acidification of the rain has taken place suddenly and sharply.
- b Some regions feel the impact of acid rain more easily than other regions and this essentially depends on the availability, or the lack of, acid-neutralising dust/soil/water in the region.
- c It is simplistic to believe that if in a particular region acidification of rain is not presently causing proportional acidification of receiving water and soil, this shall continue to be so indefinitely. If not checked acid rain would gradually wear down the acid-assimilative capacity of the receiving environments.

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References

- Abbasi, S.A. (1986) 'Binary and ternary complexes of interest to environmental systems', *Roczeniki Chemie*, Vol. 23, No. 3, pp.339–347.
- Abbasi, S.A. (1987) 'A new method for the microdetermination of molybdenum (VI) in steel, biological materials and waters', *Analytical Letters*, Vol. 20, No. 12, pp.2021–2034.
- Abbasi, S.A. (1988a) 'Atomic-absorption spectrometric and spectrophotometric trace analysis of germanium in environmental-samples with n-p-bromophenyl-2-furylacrylohydroxamic acid and phenylfluorone', *International Journal of Environmental Analytical Chemistry*, Vol. 33, No. 2, pp.149–160.
- Abbasi, S.A. (1988b) 'Environmental status of bismuth and its trace analysis in alloys plant-tissues, animal-tissues and waters as ternary complex with n-para-methoxyphenyl-2-furylacrylohydroxamic acid and a pyridylazo reagent', *Analytical Letters*, Vol. 21, No. 3, pp.461–476.
- Abbasi, S.A. (1988c) 'Environmental-analysis of cerium using n-para-chlorophenyl-2-furylacrylohydroxamic acid with or without 1-(2-pyridylazo)-2-naphthol', *International Journal of Environmental Analytical Chemistry*, Vol. 34, No. 3, pp.181–190, Elsevier.
- Abbasi, S.A. (1989a) 'Atomic-absorption spectrometric microdetermination of tungsten(vi) in alloys and environmental samples after extractive separation with a hydroxamic acid into mibk', *International Journal of Environmental Analytical Chemistry*, Vol. 35, No. 3, pp.139–147.
- Abbasi, S.A. (1989b) 'Atomic-absorption spectrometric and spectrophotometric trace analysis of uranium in environmental-samples with n-para-methoxyphenyl-2-furylacrylohydroxamic acid and 4-(2-pyridylazo) resorcinol', *International Journal of Environmental Analytical Chemistry*, Vol. 36, No. 3, pp.163–172.
- Abbasi, S.A. (1998a) *Environment Everyone: Bitter Sweet Essays on Environment*, Discovery Publishing House, New Delhi, VI+148pages.
- Abbasi, S.A. (1998b) *Water Quality – Sampling and Analysis*, Discovery Publishing House, New Delhi, viii+212pages.
- Abbasi, S.A. (1999) *Environmental Pollution and its Control Cogent International*, Philadelphia, Pondicherry, xi+439pages.
- Abbasi, S.A. (2001) *Water Resources Projects and their Environmental Impacts*, Discovery Publishing House, New Delhi, xvi+299pages.
- Abbasi, S.A. and Abbasi, N. (2000) 'The likely adverse environmental impacts of renewable energy sources', *Applied Energy*, Vol. 65, Nos. 1–4, pp.121–144.
- Abbasi, S.A. and Abbasi, N. (2008) *Renewable Energy Sources and their Environmental Impact*, PHI Learning, New Delhi, xii + 162pages.
- Abbasi, S.A. and Arya, D.S. (1995) *Urbanization and its Environmental Impacts*, Discovery Publishing House, New Delhi, iii+101pages.
- Abbasi, S.A. and Khan, F.I. (2000a) *Computer-Aided Environmental Management*, Discovery Publishing House, New Delhi, viii+424pages.
- Abbasi, S.A. and Khan, F.I. (2000b) *Greenbelts for Pollution Control: Concepts Design, Applications*, Discovery Publishing House, New Delhi, x+246pages.
- Abbasi, S.A. and Ramasamy, E.V. (1999) *Biotechnological Methods of Pollution Control*, Orient Longmans/UPII, viii+168pages.
- Abbasi, S.A. and Ramesh, N. (2003) *The Theory and the Practice of Environmental Impact Assessment*, Discovery Publishing House, New Delhi, xii+223pages.
- Abbasi, S.A. and Soni, R. (1983) 'Stress-induced enhancement of reproduction in earthworm *Octochaetus pattoni* exposed to chromium (VI) and mercury (II) – implications in environmental management', *International Journal of Environmental Studies*, Vol. 22, No. 1, pp.43–47.

- Abbasi, S.A. and Soni, R. (1984) 'Teratogenic effects of chromium (VI) in environment as evidenced by the impact on larvae of amphibian *Rana tigrina*: implications in the environmental management of chromium', *International Journal of Environmental Studies*, Vol. 23, No. 2, pp.131–137.
- Abbasi, S.A. and Soni, R. (1985) 'Environmental management and treatment levels of chromium with respect to impact on common Catfish', *Journal of the Institution of Engineers (India): Environmental Engineering Division*, Vol. 65, pp.113–116.
- Abbasi, S.A. and Soni, R. (1986) 'An examination of environmentally safe levels of zinc, cadmium, and lead with reference to impact on channelfish *Nuria denricus*', *Environmental Pollution*, Vol. A40, No. 1, pp.37–51.
- Abbasi, S.A. and Soni, R. (1993) 'Computer-aided studies on environmental impact assessment and management of seven heavy metals', *Journal of Institution of Public Health Engineers*, Vol. 1993, No. 2, pp.1–4.
- Abbasi, S.A. and Vinithan, S. (1997) *Environmental Impacts of Industries on Suburban Environments*, Discovery Publishing House, New Delhi, viii+145pages.
- Abbasi, S.A. and Vinithan, S. (1999) 'Water quality in and around an industrialized suburb of Pondicherry', *Indian Journal of Environmental Health*, Vol. 41, No. 4, pp.253–263.
- Abbasi, S.A., Abbasi, N. and Soni, R. (1998) *Heavy Metals in Environment*, Mittal Publications, New Delhi, xvii + 314pp.
- Abbasi, S.A., Baji, V. and Soni, R. (1989) 'Simulation of the impact of acid rain and alkaline wastewater inflow on pond biota', *International Journal of Environmental Studies*, Vol. 35, pp.97–103.
- Abbasi, S.A., Khan, F.I., Sentilvelan, K. and Shabudeen, A. (1999) 'Modelling of Buckingham canal water quality', *Indian Journal of Environmental Health*, Vol. 41, No. 3, pp.176–183.
- Abbasi, S.A., Khan, F.I., Sentilvelan, K. and Shabudeen, A. (2002) 'Modelling of Buckingham canal water quality', *Indian Journal of Environmental Health*, Vol. 44, No. 4, pp.290–297.
- Abbasi, S.A., Krishnakumary, P. and Khan, F.I. (2000) *HOT TOPICS: Everyday Environmental Concerns*, Oxford University Press, xviii+208pages.
- Abbasi, S.A., Nipanay, P.C. and Arya, D.S. (1994) 'Heavy metals in the sediments of a river impacted by pulp-and-paper effluents', *Journal of Institution of Public Health Engineers*, Vol. 1994, No. 2, pp.18–23.
- Abbasi, S.A., Nipanay, P.C. and Soni, R. (1988) 'Studies on environmental management of mercury, chromium, and zinc with respect to impact on some arthropods and protozoans', *International Journal of Environmental Studies*, Vol. 32, Nos. 2–3, pp.181–187.
- Abbasi, S.A., Nipanay, P.C., Soni, R. and Arya, D.S. (1992) 'Assessment of water quality for cobalt, nickel, and copper', *Journal of Institution of Public Health Engineers*, Vol. 1992, pp.8–16.
- Abbasi, T. and Abbasi, S.A. (2007a) 'The boiling liquid expanding vapour explosion (BLEVE): mechanism, consequence assessment, management', *Journal of Hazardous Materials*, Vol. 141, No. 3, pp.489–519.
- Abbasi, T. and Abbasi, S.A. (2009) 'Water quality management of rooftop rainwater harvesting systems', *Indian Journal of Environmental Science & Engineering*, Vol. 51, No. 4, pp.325–330.
- Abbasi, T. and Abbasi, S.A. (2010a) 'Biomass energy and the environmental impact of its production and utilization', *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 3, pp.919–937.
- Abbasi, T. and Abbasi, S.A. (2010b) 'Production of clean energy by anaerobic digestion of phytomass – new prospects, for a global warming amelioration technology', *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 6, pp.1653–1659.
- Abbasi, T. and Abbasi, S.A. (2011a) 'Ocean acidification: the newest threat to global environment', *Critical Reviews in Environmental Science and Technology*, Vol. 41, No. 18, pp.1601–1663.

- Abbasi, T. and Abbasi, S.A. (2011b) 'Sources of pollution in rooftop rainwater harvesting systems and their control', *Critical Reviews in Environmental Science and Technology*, Vol. 41, No. 23, pp.2097–2167.
- Abbasi, T. and Abbasi, S.A. (2011c) 'Decarbonization of fossil fuels as a strategy to control global warming', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 4, pp.1928–1834.
- Abbasi, T. and Abbasi, S.A. (2011d) 'Water quality indices based on bioassessment: the biotic indices', *Journal of Water and Health (IWA Publishing)*, Vol. 9, No. 2, pp.330–348.
- Abbasi, T. and Abbasi, S.A. (2011e) 'Renewable hydrogen: prospects and challenges', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 6, pp.3034–3040.
- Abbasi, T. and Abbasi, S.A. (2011f) 'Smallhydro and the environmental implications of its extensive utilization', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 4, pp.2134–2143.
- Abbasi, T. and Abbasi, S.A. (2012) *Water Quality Indices*, Elsevier, Oxford, xi + 384 pp.
- Abbasi, T., Kannadasan, T. and Abbasi, S.A. (2009) 'A study of the impact of acid rain on chromium toxicity', *International Journal of Environmental Studies*, Vol. 66, No. 6, pp.765–771.
- Abbasi, T., Premalatha, M. and Abbasi, S.A. (2011) 'The return to renewables: will it help in global warming control?', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 1, pp.891–894.
- Abbasi, T., Ramasamy, E.V., Khan, F.I. and Abbasi, S.A. (2012) *Regional EIA and Risk Assessment in a Fast Developing Country*, Nova Science, New York, vii + 430pp.
- Abbasi, T., Tauseef, S.M. and Abbasi, A.A. (2010) 'Risks of fire and explosion associated with the increasing use of liquefied petroleum gas', *Journal of Failure Analysis and Prevention*, Vol. 10, No. 4, pp.322–333.
- Abbasi, S.A., Abbasi, N., Nipanay, P.C. and Ramasamy, E.V. (1995) 'Environmental impact of non-conventional energy sources', *Journal of Scientific and Industrial Research*, Vol. 54, pp.285–293.
- Abbasi, T. and Abbasi, S.A. (2007b) 'Dust explosions – cases, causes, consequences, and control', *Journal of Hazardous Materials*, Vol. 140, Nos. 1–2, pp.7–44.
- Almer, A., Dickson, B.W., Ekstrom, E. and Hornstrom, E. (1987) 'Sulphur pollution and the aquatic ecosystem', in Nriagu, J. (Ed.): *Sulphur in the Environment, Part II. Ecological Impacts*, pp.273–311, John Wiley & Sons, New York.
- Andersson, G., Fleischer, S. and Granets, W. (1978) 'Influence of acidification on decomposition processes in lake sediments', *Verh. Int. Verein. Limnol.*, Vol. 20, pp.802–807.
- Anonymous (1984) 'Twelve power stations must be cleaned up', *Acid News*, pp.5–6.
- Aunan, K., Fang, J., Vennemo, H., Oye, K. and Seip, H.M. (2004) 'Co-benefits of climate policy – lessons learned from a study in Shanxi, China', *Energy Policy*, Vol. 32, No. 4, pp.567–581.
- Ayers, G., Gillett, R. and Hara, H. (1996) 'Acidic deposition in Asia and Oceania', in Whelpdale, D.M. and Kaiser, M.S. (Eds.): *Global Acid Deposition Assessment*, Global Atmospheric Watch Report No. 106, World Meteorological Organization, Geneva.
- Baedecker, P.A., Reddy, M.M., Reimann, K.J. and Sciammarella, C.A. (1992) 'Effects of acidic deposition on the erosion of carbonate stone experimental results from the United States national acid precipitation assessment program (NAPAP)', *Atmospheric Environment*, Vol. 26, No. 2, pp.147–158.
- Balasubramanian, R., Victor, R. and Begum, R. (1999) 'Impact of biomass burning on rainwater acidity and composition in Singapore', *Journal of Geophysical Research*, Vol. 104, No. D21, pp.26,881–26,890.
- Bartlett, P.W., Commoner, B., Couchot, K., Bush, B., Eisl, H. and Cooney, P. (2000) 'Modeling source-to-receptor atmospheric transport: Atrazine, PCBs and Dioxin in North America', *Organohalogen Compounds*, Vol. 5, pp.45–51.

- Bashkin, V.N. and Radojevic, M. (2003) 'Acid rain and its mitigation in Asia', *International Journal of Environmental Studies*, Vol. 60, No. 3, pp.205–214.
- Bastidas, D.M. and La Iglesia, V.M. (2007) 'Organic acid vapours and their effect on corrosion of copper: a review', *Corrosion Engineering Science and Technology*, Vol. 42, No. 3, pp.272–280.
- Berge, E., Bartnicki, J., Olendrzynski, K. and Tsyro, S.G. (1999) 'Long-term trends in emissions and transboundary transport of acidifying air pollution in Europe', *Journal of Environmental Management*, Vol. 57, No. 1, pp.31–50.
- Bergman, L. and Hill, M. (2000) 'Productivity and growth effects of acidification: a dynamic CGE modeling study of Sweden', Discussion paper, Stockholm School of Economics, Stockholm.
- Bhatti, N., Streets, D.G. and Foell, W.K. (1992) 'Acid rain in Asia', *Environmental Management*, Vol. 16, No. 4, pp.541–562.
- Bouwman, A.F., Van Vuuren, D.P., Derwent, R.G. and Posch, M. (2002) 'A global analysis of acidification and eutrophication of terrestrial ecosystem', *Water Air Soil Pollution*, Vol. 141, Nos. 1–4, pp.349–382.
- Burman, S. (1985) 'Environmental impact of acid rain', *Yojana*, Vol. 29, pp.15–18.
- Burtraw, D., Krupnick, A., Mansur, E., Austin, D. and Farrell, D. (1997) 'The costs and benefits of reducing acid rain', Discussion paper 97-31-REV, Resources for the Future, Washington, DC.
- Calvert, J.G., Lazrus, A., Kok, G.L., Heikes, B.G., Walega, J.G., Lind, J. and Cantrell, C.A. (1985) 'Chemical mechanisms of acid generation in the troposphere', *Nature*, Vol. 317, pp.27–35.
- Cerceo, E. (2004) 'Global warming and acid precipitation: some aspects of their effect on climate, part 1', *American Laboratory*, Vol. 36, No. 20, pp.26–32.
- Chandrawanshi, C.K. and Patel, K.S. (1999) 'Chemistry of rain in central India. Id. Ojars', *Quarterly Journal of the Hungarian Meteorological Service*, Vol. 103, No. 3, pp.189–213.
- Chari, K.B., Abbasi, S.A. and Ganapathy, S. (2003) 'Ecology, habitat and bird community structure at Oussudu lake: towards a strategy for conservation and management', *Aquatic Conservation: Marine and Freshwater Ecosystems*, Vol. 13, No. 5, pp.373–386.
- Chari, K.B., Richa, S. and Abbasi, S.A. (2005a) *Comprehensive Environmental Impact Assessment of Water Resources Projects*, Vol. 1, Discovery Publishing House, New Delhi, xvi+580pages.
- Chari, K.B., Richa, S. and Abbasi, S.A. (2005b) *Comprehensive Environmental Impact Assessment of Water Resources Projects*, Vol. 2, Discovery Publishing House, New Delhi, xvi+581–724pages.
- Charlson, R.O. and Rodhe, H. (1982) 'Factors controlling the acidity of natural rainwater', *Nature*, Vol. 295, No. 5851, pp.683–685.
- Chen, Z.S., Liu, J.C. and Cheng, C.Y. (1998) 'Acid deposition effects on the dynamic of heavy metals in soil sand their biological accumulation in the crops and vegetables in Taiwan', in Bashkin, V. and Park, S-U. (Eds.): *Acid Deposition and Eco system Sensitivity in East Asia*, pp.189–228, Nova Science Publishers, New York.
- Chester, P.F. (1986) 'Acid Lakes in Scandinavia – the evolution of understanding', Report PRD/L/PFC/010/R86, Central Electricity Research Laboratories, Leatherhead, Surrey, UK.
- Cronan, C.S. and Schofield, C.L. (1979) 'Aluminium leaching response to acid precipitation: effects on high elevation watersheds in the north east', *Science*, Vol. 204, No. 4390, pp.304–306.
- Crossley, A., Sheppard Lucy, J., Parrington, J.F., Harvey, J. and Neil Cape, J. (2001) 'Effects of simulated acid mist on a Sitka spruce forest approaching canopy nitrogen input', *Water Air and Soil Pollution*, Vol. 130, Nos. 1–4, pp.953–958.
- Cullis, C.F. and Hischler, M.M. (1980) 'Atmospheric sulphur: natural and manmade sources', *Atmospheric Environment*, Vol. 14, No. 11, pp.1263–1278.
- Das, R., Das, S.N. and Misra, V.N. (2005) 'Chemical composition of rainwater and dust fall at Bhubaneswar in the east coast of India', *Atmospheric Environment*, Vol. 39, No. 32, pp.5908–5916.

- De Costa, J. (1980) 'The zooplankton communities of acidic lakes', *International Conference on the Ecological Impact of Acid Precipitation*, San Deformed, Norway, p.116.
- De Oliveira Loureiro, C.R., De Carvalho, C.R., Cardoso, J.A. and Junqueira, R.M.R. (2007) 'Effect of acid rain in colored stainless steel [Efeito da chuva acida em acoos inoxidaveis coloridos]', *Revista Escola de Minas*, Vol. 60, No. 1, pp.45–48.
- Downing, R.J., Ramankutty, R. and Jitendra, J.S. (1997) *Rains-Asia: An Assessment Model for Acid Deposition in Asia*, The World Bank, Washington, DC.
- Driscoll, C.T., Lawrence, G.B., Bulger, A.J., Butler, T.J., Cronan, C.S., Eagar, C., Lambert, K.F., Likens, G.E., Stoddard, J.L. and Weathers, K.C. (2001) 'Acidic deposition in the Northeastern United States: sources and inputs, ecosystem effects, and management strategies', *BioScience*, Vol. 51, No. 3, pp.180–198.
- Edwards, A.C., Creasey, J. and Cresser, M.S. (1986) 'Soil freezing effects on upland stream solute chemistry', *Water Research*, Vol. 20, No. 7, pp.831–834.
- Evans, C.D., Cullen, J.M., Alewell, C., Kopáček, J., Marchetto, A., Moldan, F., Prechtel, A., Rogora, M., Veselý, J. and Wright, R.F. (2001) 'Recovery from acidification in European surface waters', *Hydrology Earth Systems Science*, Vol. 5, No. 3, pp.283–297.
- Fowler, D., Smith, R.I., Muller, J.B.A., Hayman, G. and Vincent, K.J. (2005) 'Changes in the atmospheric deposition of acidifying compounds in the UK between 1986 and 2001', *Environmental Pollution*, Vol. 137, No. 1, pp.15–25.
- Fredric, C.M. and Hans, M.S. (2004) 'Acid rain in Europe and the United States: an update', *Environmental Science & Policy*, Vol. 7, No. 4, pp.253–265.
- Gajalakshmi, S. and Abbasi, S.A. (2002) 'Effect of the application of water hyacinth compost/vermicompost on the growth and flowering of *Crossandra undulataefolia*, and on several vegetables', *Bioresource Technology*, Vol. 85, No. 2, pp.197–199.
- Gajalakshmi, S. and Abbasi, S.A. (2004) 'Neem leaves as a source of fertilizer-cum-pesticide vermicompost', *Bioresource Technology*, Vol. 92, No. 3, pp.291–296.
- Gajalakshmi, S., Ramasamy, E.V. and Abbasi, S.A. (2001a) 'Assessment of sustainable vermiconversion of water hyacinth at different reactor efficiencies employing *Eudrilus eugeniae* Kinberg', *Bioresource Technology*, Vol. 80, No. 2, pp.131–135.
- Gajalakshmi, S., Ramasamy, E.V. and Abbasi, S.A. (2001b) 'Towards maximising output from vermireactors fed with cowdung spiked paper waste', *Bioresource Technology*, Vol. 79, No. 1, pp.67–72.
- Galanter, M., Levy, H., II and Carmichael, G.R. (2000) 'Impact of biomass burning on tropospheric CO, NO_x and O₃', *Journal of Geophysical Research*, Vol. 105, No. D5, pp.6633–6653.
- Galloway, J.N. and Cowling, E.B. (2002) 'Reactive nitrogen and the world: 200 years of change', *Ambio*, Vol. 31, No. 2, pp.64–71.
- Gao, C., Yin, H., Ai, N. and Huang, Z. (2009) 'Historical analysis of SO₂ pollution control policies in China', *Environmental Management*, Vol. 43, No. 3, pp.447–457.
- Gilbert, J. (1987) 'History of acid rain', in Park, C. (Ed.): *Acid Rain – Rhetoric and Reality*, John Wiley & Sons, New York.
- Gjessing, E., Henriksem, A., Johannessen, M. and Wright, R. (1976) 'Effect of acid precipitation on fresh water chemistry', in Braekke, F. (Ed.): *Impacts of Acid Precipitation on Forest and Freshwater Ecosystems in Norway*, Research report, Vol. 6.
- Goodwin, J.W.L., Salway, A.G., Dore, C.J., Murrells, T.P., Passant, N.R., Watterson, J.D., Hobson, M.M., Haigh, K.E., King, K.R., Pye, S.T., Coleman, P.J. and Conolly, C.M. (2004) 'On the relation between pH and the chemical composition of atmospheric precipitation', *Tellus*, Vol. 24, p.550.
- Gorham, E. (1955) 'On the acidity and salinity of rain', *Geochim. Cosmochim. Acta*, Vol. 7, No. 5–6, pp.231–239.

- Granat, L., Das, S.N., Tharkur, R.S. and Rodhe, R. (2001) 'Atmospheric deposition in a rural area in India – net and potential acidity', *Water, Air, and Soil Pollution*, Vol. 130, Nos. 1–4, pp.469–474.
- Granat, N.E. (1972) 'Organization of specialized obstetrical care. [Organizatsiia spetsializirovannoi akusherskoï pomoshchi]', *Meditsinskaiia sestra*, Vol. 31, No. 10, pp.54–56.
- Harte, J. (1983) 'An investigation of acid precipitation in Qinghai Province, China', *Atmospheric Environment*, Vol. 17, No. 2, pp.403–408.
- Hendrey, G. and Wright, R. (1976) 'Acid precipitation in Norway, effects on aquatic fauna', *Journal of Great Lakes Research*, Vol. 2, No. 1, pp.192–207.
- Hidey, G. (1995) 'Acid rain', in *Encyclopedia of Environmental Biology*, pp.1–17, Academic Press.
- Hsiao, H-M., Lin, T-C., Hwong, J-L., Huang, C-C. and Lin, N-H. (2007) 'Precipitation chemistry at the Lienhuachi Experimental Forest in central Taiwan', *Taiwan Journal of Forest Science*, Vol. 22, No. 1, pp.1–13.
- Hu, G.P., Balasubramanian, R. and Wu, C.D. (2003) 'Chemical characterization of rainwater at Singapore', *Chemosphere*, Vol. 51, No. 8, pp.747–755.
- Hutlberg, H. and Johansson, S. (1981) 'Acid groundwater', *Nordic Hydrology*, Vol. 12, No. 1, pp.51–64.
- Jain, M., Kulshrestha, U.C., Sarkar, A.K. and Parashar, D.C. (2000) 'Influence of crustal aerosols on wet deposition at urban and rural sites in India', *Atmospheric Environment*, Vol. 34, Nos. 29–30, pp.5129–5137.
- Jeffries, D.S., Brydges, T.G., Dillon, P.J. and Keller, W. (2003) 'Monitoring the results of Canada/U.S.A. acid rain control programs: some lake responses', *Environmental Monitoring and Assessment*, Vol. 88, Nos. 1–3, pp.3–19.
- Jeng-Peng, L. and Bhargava, D.S. (1996) 'The menace of acid rain', *Ecology*, Vol. 10, pp.19–34.
- Jickells, T.A., Knap, A., Church, T., Galloway, J. and Miller, J. 1982) 'Acid rain in Bermuda', *Nature*, Vol. 297, pp.55–57.
- Kaiser, J. (2001) 'The other global pollutant, nitrogen proves tough to curb', *Science*, Vol. 294, No. 5545, pp.268–269.
- Kaneko, M., Takahashi, K., Hayashi, T., Tokuno, K. and Tamenari, J. (2006) 'Discoloration resistance of architectural titanium sheets in long-term atmospheric exposure tests', *Materials Performance*, Vol. 45, No. 2, pp.38–42.
- Kawahara, A., Motoyoshi, Y.T., Fumigation, I. and Nagae, M. (2001) 'Effect of acidification stress on endocrine and immune functions in *Cyprinus carpio*', *Water Air and Soil Pollution*, Vol. 130, Nos. 1–4 II, pp.893–898.
- Khan, F.I. and Abbasi, S.A. (1996) 'Simulation of accidents in a chemical industry using the software package MAXCRED', *Indian Journal of Chemical Technology*, Vol. 3, No. 6, pp.338–344.
- Khan, F.I. and Abbasi, S.A. (1997a) 'Risk analysis of a chloralkali industry situated in a populated area using the software package MAXCRED-II', *Process Safety Progress*, Vol. 16, No. 3, pp.172–184.
- Khan, F.I. and Abbasi, S.A. (1997b) 'Mathematical model for HAZOP study time estimation', *Journal of Loss Prevention in the Process Industries*, Vol. 10, No. 4, pp.249–257.
- Khan, F.I. and Abbasi, S.A. (1997c) 'Accident hazard index: a multi-attribute method for process industry hazard rating', *Process Safety and Environmental Protection*, Vol. 75, No. 4, pp.217–224.
- Khan, F.I. and Abbasi, S.A. (1998a) 'Multivariate hazard identification and ranking system', *Process Safety Progress*, Vol. 17, No. 3, pp.157–170.
- Khan, F.I. and Abbasi, S.A. (1998b) 'DOMIFFECT (DOMIno eFFECT): user-friendly software for domino effect analysis', *Environmental Modelling and Software*, Vol. 13, No. 2, pp.163–177.
- Khan, F.I. and Abbasi, S.A. (1998c) 'Inherently safer design based on rapid risk analysis', *Journal of Loss Prevention in the Process Industries*, Vol. 11, No. 6, pp.361–372.

- Khan, F.I. and Abbasi, S.A. (1999a) 'Modelling and control of the dispersion of hazardous heavy gases', *Journal of Loss Prevention in the Process Industries*, Vol. 12, No. 3, pp.235–244.
- Khan, F.I. and Abbasi, S.A. (1999b) 'HAZDIG: a new software package for assessing the risks of accidental release of toxic chemicals', *Journal of Loss Prevention in the Process Industries*, Vol. 12, No. 2, pp.167–181.
- Khan, F.I. and Abbasi, S.A. (1999c) 'Assessment of risks posed by chemical industries – application of a new computer automated tool MAXCRED-III', *Journal of Loss Prevention in the Process Industries*, Vol. 12, No. 6, pp.455–469.
- Khan, F.I. and Abbasi, S.A. (1999d) 'The world's worst industrial accident of the 1990s: what happened and what might have been – a quantitative study', *Process Safety Progress*, Vol. 18, No. 3, pp.135–145.
- Khan, F.I. and Abbasi, S.A. (2000a) 'Attenuation of gaseous pollutants by greenbelts', *Environmental Monitoring and Assessment*, Vol. 64, No. 2, pp.457–475.
- Khan, F.I. and Abbasi, S.A. (2000b) 'Analytical simulation and PROFAT II: a new methodology and a computer automated tool for fault tree analysis in chemical process industries', *Journal of Hazardous Materials*, Vol. 75, No. 1, pp.1–27.
- Khan, F.I. and Abbasi, S.A. (2001a) 'Effective design of greenbelts using mathematical models', *Journal of Hazardous Materials*, Vol. 81, Nos. 1–2, pp.33–65.
- Khan, F.I. and Abbasi, S.A. (2001b) 'An assessment of the likelihood of occurrence, and the damage potential of domino effect (chain of accidents) in a typical cluster of industries', *Journal of Loss Prevention in the Process Industries*, Vol. 14, No. 4, pp.283–306.
- Khemani, L.T. (1993) 'The role of alkaline particulates on pH of rain water and implications for control of acid rain', in Ellasesser, H.W. (Ed.): *Global 2000 Revisited*, p.87, Pargon House, New York.
- Khemani, L.T., Momin, G.A., Rao, P.S.P., Safai, P.D., Singh, G., Chatterjee, R.N. and Prakash, P. (1989a) 'Long term effects of pollutants on pH of rain water in North India', *Atmospheric Environment*, Vol. 23, No. 4, pp.753–756.
- Khemani, L.T., Momin, G.A., Rao, P.S.P., Safai, P.D., Singh, G. and Kapoor, R.K. (1989b) 'Spread of acid rain over India', *Atmospheric Environment*, Vol. 23, No. 4, pp.757–762.
- Kinniburgh, D.G. and Edmunds, W.M. (1984) 'The susceptibility of UK groundwaters to acid deposition. Report to the Department of the Environment', Hydrogeology Research Group, British Geological Survey, Wallingford.
- Kitamura, S. and Ikuta, K. (2001) 'Effects of acidification on Salmonid spawning behaviour', *Water Air and Soil Pollution*, Vol. 130, Nos. 1–4, pp.875–880.
- Kopstik, G.N., Kopstik, S.V. and Aamlid, D. (2001) 'Pine needle chemistry near a large point SO₂ sources in Northern Fennoscandia', *Water Air and Soil Pollution*, Vol. 130, Nos. 1–4, pp.929–934.
- Kouterick, K.B., Skelly, J.M., Pennypacker, S.P. and Cox, R.M. (1998) *Proceedings of the first International Conference on Fog and Fog Collection*, IDRC, Ottawa, pp.128–133.
- Krajick, K. (2001) 'Long-term data show lingering effects from acid rain', *Science*, Vol. 292, No. 5515, pp.195–196.
- Kulshrestha, U.C., Kulshrestha, M.J., Sekar, R., Sastry, G.S.R. and Vairamani, M. (2003) 'Chemical characteristics of rainwater at an urban site of South-central India', *Atmospheric Environment*, Vol. 37, No. 21, pp.3019–3026.
- Kulshrestha, U.C., Kulshrestha, M.J., Sekar, R., Vairamani, M., Sarkar, A.K. and Parashar, D.C. (2001) 'Investigation into alkaline nature of rain water in India', *Water, Air, and Soil Pollution*, Vol. 130, Nos. 1–4 III, pp.1685–1690.
- Kulshrestha, U.C., Sarkar, A.K., Srivastava, S.S. and Parashar, D.C. (1996) 'Investigation into atmospheric deposition through precipitation studies at New Delhi (India)', *Atmospheric Environment*, Vol. 30, No. 24, pp.4149–4154.

- Kulshrestha, U.C., Saxena, A., Kumar, N., Kumari, K.M. and Srivastava, S.S. (1998) 'Chemical composition and association of size differentiated aerosols at a suburban site in semiarid tract of India', *Journal of Atmospheric Chemistry*, Vol. 29, No. 2, pp.109–118.
- Kuylenstierna, J.C.I., Rodhe, H., Cinderby, S. and Hicks, K. (2001) 'Acidification in developing countries: Ecosystem sensitivity and the critical load approach on a global scale', *Ambio*, Vol. 30, No. 1, pp.20–28.
- La Bastille, A. (1981) 'Acid rain: how great a menace?', *National Geographic*, Vol. 160, No. 5, pp.652–679.
- Larssen, T., Lydersen, E., Tang, D., He, Y., Gao, J., Liu, H., Duan, L., Seip, H.M., Vogt, R.D., Mulder, J., Shao, M., Wang, Y., Shang, H., Zhang, X., Solberg, S., Aas, W., Okland, T., Eilertsen, O., Angell, V., Liu, Q., Zhao, D., Xiang, R., Xiao, J. and Luo, J. (2006) 'Acid rain in China', *Environmental Science and Technology*, Vol. 40, No. 2, pp.418–425.
- Last, F.T. and Nicholson, I.A. (1982) 'Acid rain', *Biologist*, Vol. 29, pp.250–252.
- Lee, D.S., Kohler, I., Grobler, E., Rohrer, F., Sausen, R., Gallardo-Klenner, L., Olivier, J.G.J., Dentener, F.J. and Bouwman, A.F. (1997) 'Estimations of global NO_x emissions and their uncertainties', *Atmospheric Environment*, Vol. 31, No. 12, pp.1735–1749.
- Leivestad, H., Hendrey, G., Muniz, I. and Snetki, E. (1976) 'Effect of acid precipitation of freshwater organisms', in Braekke, F. (Ed.): *Impact of Acid Precipitation on Forest and Fresh Water Ecosystems in Norway*, Research report, Vol. 6, pp.86–111.
- Li, W. and Gao, J. (2002) 'Acid deposition and integrated zoning control in China', *Environmental Management*, Vol. 30, No. 2, pp.169–182.
- Likens, G.E. and Bormann, F. (1974) 'Acid rain: a serious regional environmental problem', *Science*, Vol. 184, No. 4142, pp.1176–1179.
- Likens, G.E. (1985) 'An experimental approach for the study of ecosystem', *Journal of Ecology*, Vol. 73, No. 2, pp.381–396.
- Likens, G.E. and Butler, T.J. (1981) 'Recent acidification of precipitation in North America', *Atmospheric Environment*, Vol. 15, No. 7, pp.1103–1109.
- Likens, G.E., Keene, W.C., Miller, J.M. and Galloway, J.N. (1987) 'Chemistry of precipitation from a remote, terrestrial site in Australia', *Journal of Geophysical Research*, Vol. 92, No. 13, pp.299–314.
- Liu, Z-Z., Zeng, C-S., Zhong, C-Q. and Tong, C. (2008) 'Effects of acid deposition on methane emission and carbon cycling in peatland', *Chinese Journal of Ecology*, Vol. 27, No. 10, pp.1799–1805.
- Martins, C.R. and De Andrade, J.B. (2002) 'Atmospheric chemistry of sulfur (IV): emissions, aqueous phase reactions and environmental effects', *Quimica Nova*, Vol. 25, No. 2, pp.259–272.
- Meera, V. and Mansoor Ahammed, M. (2006) 'Water quality of rooftop rainwater harvesting systems: a review', *Journal of Water Supply Research and Technology*, Vol. 55, No. 4, pp.1–13.
- Menz, F.C. and Seip, H.M. (2004) 'Acid rain in Europe and the United States: an update', *Environmental Science and Policy*, Vol. 7, No. 4, pp.253–265.
- Moiseenko, T. (1994) 'Acidification and critical loads in surface waters: Kola, Northern Russia', *Ambio*, Vol. 23, No. 7, pp.418–434.
- Norman, M., Das, S.N., Pillai, A.G., Granat, L. and Rodhe, H. (2001) 'Influence of air mass trajectories on the chemical composition of precipitation in India', *Atmospheric Environment*, Vol. 35, No. 25, pp.4223–4235.
- Odan, S. (1976) 'The acidity problem – an outline of concepts', *Water Air and Soil Pollution*, Vol. 6, Nos. 2–4, pp.317–365.

- Parashar, D.C., Granat, L., Kulshrestha, U.C., Pillai, A.G., Naik, U.S., Momin, G.A., Prakasa Rao, P.S., Safai, P.D., Khemani, L.T., Naqvi, S.W.A., Narverkar, P.V., Thapa, K.B. and Rodhe, H. (1996) 'Chemical composition of precipitation in India and Nepal', A preliminary report on an Indo-Swedish Project on Atmospheric Chemistry, Report CM-90, Department of Meteorology, Stockholm University.
- Park, C. (1987) *Acid Rain – Rhetoric and Reality*, John Wiley & Sons, New York.
- Pough, F. (1976) 'Acid precipitation and embryonic mortality of spotted salamanders', *Science*, Vol. 192, No. 4234, pp.68–70.
- Radojevic, M. and Harrison, R.M. (1992) *Atmospheric Acidity: Sources, Consequences and Abatement*, Elsevier Applied Science, Amsterdam.
- Ramasamy, E.V., Gajalakshmi, S., Sanjeevi, R., Jithesh, M.N. and Abbasi, S.A. (2004) 'Feasibility studies on the treatment of dairy wastewaters with upflow anaerobic sludge blanket reactors', *Bioresource Technology*, Vol. 93, No. 2, pp.209–212.
- Ravichandran, C. and Padmanabhamurty, B. (1994) 'Acid precipitation in Delhi, India', *Atmospheric Environment*, Vol. 28, No. 14, pp.2291–2297.
- RGAR (1987) 'Acid deposition in the United Kingdom 1981–1985', A second report of the United Kingdom Review Group on acid rain, prepared at the request of the Department of the Environment, Warren Spring Laboratory, Stevenage, p.104.
- Rodhe, H., Dentener, F. and Schulz, M. (2002) 'The global distribution of acidifying wet deposition', *Environment Science and Technology*, Vol. 36, No. 20, pp.4382–4388.
- Rodhe, H., Langner, J., Gallardo, L. and Kjellstrom, E. (1995) 'Global scale transport of acidifying pollutants', *Water, Air, and Soil Pollution*, Vol. 85, No. 1, pp.37–50.
- Roff, J. and Kwiatkowski, R. (1977) 'Zooplankton and zoobenthos communities of selected Northern Ontario lakes of different acidities', *Canadian Journal of Zoology*, Vol. 55, No. 6, pp.899–911.
- Sanhueza, E., Ferrer, Z., Romero, J. and Santana, M. (1991) 'HCHO and HCOOH in tropical rains', *Ambio*, Vol. 20, Nos. 3–4, pp.115–117.
- Sant Anna-Santos, F.B., da Silva, L.C., Azevedo, A.A., de Aranjó, J.M., Feguedo Alves, E., da Silva E.A.M. and Aguiar, R. (2006) 'Effects of simulated acid rain on the foliar micromorphology and anatomy of tree tropical species', *Environment Experimental Botany*, Vol. 58, Nos. 1–3, pp.158–168.
- Schofield, C.L. (1976) 'Acid precipitation: effects on fish', *Ambio*, Vol. 5, Nos. 5–6, pp.228–230.
- SEPA (2004) 'Report on the state of the environment in China 2003', available at <http://www.zhb.gov.cn/english/SOE/soechina2003>.
- Singh, A. and Agrawal, M. (2008) 'Acid rain and its ecological consequences', *Journal of Environmental Biology*, Vol. 29, No. 1, pp.15–24.
- Singh, R. and Agarwal, S.K. (2004) 'Effect of organic manuring and nitrogen fertilization on productivity, nutrient-use efficiency and economics of wheat (*Triticum aestivum*)', *Indian Journal of Agronomy*, Vol. 49, No. 1, pp.49–52.
- Smith, R.A. (1872) *Air and Rain: the Beginnings of a Chemical Climatology*, p.600, Longmans, Green and Co., London.
- Soni, R. (1991) 'Impact of pollutants on aquatic organisms', PhD thesis, p.359, University of Calicut.
- Stoddard, J.L., Jeffries, D.S., Lükewille, A., Clair, T.A., Dillon, P.J., Driscoll, C.T., Forsius, M., Johannessen, M., Kahl, J.S., Kellogg, J.H., Kemp, A., Mannio, J., Monteith, D.T., Murdoch, P.S., Patrick, S., Rebsdorf, A., Skjelkvåle, B.L., Stainton, M.P., Traaen, T., vanDam, H., Webster, K.E., Wieting, J. and Wilander, A. (1999) 'Regional trends in aquatic recovery from acidification in North America and Europe', *Nature*, Vol. 401, No. 6753, pp.575–578.

- Stoddard, J.L., Kahl, J.S., Deviney, F.A., De Walle, D.R., Dr, C.T., Herlihy, A.T., Kellogg, J.H., Murdoch, P.S., Webb, J.R. and Webster, K.E. (2003) *Response of Surface Water Chemistry Clean Air Act Amendments of 1990*, EPA620/R-03/001, Environmental Protection Agency, Research Triangle Park, NC.
- Streets, D.G., Tsai, N.Y., Akimoto, H. and Oka, K. (2000) 'Sulfur dioxide emissions in Asia in the period 1985–1997', *Atmospheric Environment*, Vol. 34, No. 26, pp.4413–4424.
- Takanashi, A., Takanashi, W., Kazuo, S. and Fujita, S.I. (2001) 'Atmospheric deposition of acidifying components to a Japanese cedar forests', *Water Air and Soil Pollution*, Vol. 130, Nos. 1–4, pp.559–564.
- Tamn, C.O. and Hallbacken, L. (1988) 'Changes in soil acidity in two forest areas with different acid deposition 1920 to 1980', *Ambio*, Vol. 17, pp.56–61.
- Tanner, P.A. and Law, P.T. (2003) 'Organic acids in the atmosphere and bulk deposition of Hong Kong', *Water, Air, and Soil Pollution*, Vol. 142, Nos. 1–4, pp.279–297.
- Tsujino, Y., Matsumoto, M., Komeji, T., Tanio, K., Kitamura, M., Hao, Z., Chen, S.L., Maeda, Y. and Bandow, H. (1995) 'Acid deposition and material damage in Eastern Asia', *Pure and Applied Chemistry*, Vol. 67, pp.1429–1433.
- UN (2000) State of the Environment in Asia and Pacific, ESCAP.
- van Aardenne, J.A., Carmichael, G.R., Levy, I.H., Streets, D. and Hordijk, L. (1999). 'Anthropogenic NO_x emissions in Asia in the period 1990–2020', *Atmospheric Environment*, Vol. 33, pp.633–646.
- Wagh, N.D., Poonam, V., Sarika, S., Tambe, B. and Ingle, S.T. (2006) 'Biological monitoring of roadside plants exposed to vehicular pollution in Jalgaon City', *Journal of Environmental Biology*, Vol. 27, No. 2, pp.419–421.
- Wang, J., Yang, J., Ge, C., Cao, D. and Schreifels, J. (2004) 'Controlling sulfur dioxide in China: will emission trading work?', *Environment*, Vol. 46, No. 5, pp.28–39.
- Wang, W. and Wang, T. (1995) 'On the origin and trend of acid precipitation in China', *Water, Air, and Soil Pollution*, Vol. 85, No. 4, pp.2295–2300.
- Watmough, S.A. and Dillon, P.J. (2003) 'Base cation and nitrogen budgets for a mixed hardwood catchment's in South-central Ontario', *Ecosystems*, Vol. 6, No. 7, pp.675–693.
- Watt, W.D., Scott, C.D. and White, W.J. (1983) 'Evidence of acidification of some Nova Scotia rivers and its impact on Atlantic Salmons, *Salmosalar*', *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 40, No. 1981, pp.462–473.
- Watt, W.D., Scott, C.D., Zamora, P.J. and White, W.J. (2000) 'Acid toxicity levels in Nova Scotian rivers have not declined in synchrony with the decline in sulfate levels', *Water, Air, and Soil Pollution*, Vol. 118, Nos. 3–4, pp.203–229.
- Whelpdale, D.M., Ayers, G., Dovland, H., Galloway, J.N., Miller, J.M. and Summers, P.W. (1996) 'Global acid deposition assessment', in Whelpdale, D.M. and Kaiser, M.S. (Eds.): *Global Atmospheric Watch Report No. 106*, World Meteorology Organization, Geneva.
- Wilkening, K.E., Barrie, L.A. and Engle, M. (2000) 'Trans-Pacific air pollution', *Science*, Vol. 290, No. 5489, pp.65–67.
- Wright, R.F. and Gjessing, E.T. (1976) 'Acid precipitation: changes in the chemical composition of lakes', *Ambio*, Vol. 5, Nos. 5–6, pp.219–223.
- Xie, Y., Ye, S., Kitagawa, K. and Wang, K. (2004) 'The acid rain issues and its countermeasures in China', *Journal of the Japan Institute of Energy*, Vol. 83, No. 11, pp.902–907.
- Zhao, D. and Sun, B. (1986) 'Air pollution and acid rain in China', *Ambio*, Vol. 15, No. 1, pp.2–5.
- Zhao, D. et al. (1988) 'Acid rain in Southwestern China', *Atmospheric Environment*, Vol. 22, No. 2, pp.349–358.