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Acid Rain Formation and Its Direct Impacts on Plants: Wheat and Rice

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Abstract

Acid rain is a serious environmental problem that occurs in many places around the world. Acid deposition can form as a result of the oxidation of sulfur dioxide and nitrogen oxide gases that are released into the atmosphere. These gases (SO2, NOx) are the primary causes of acid rain, and physically and chemically react with water, oxygen, and other chemicals to form other acidic compounds such as sulfuric acid (H2SO4) and nitric acid (HNO3). Acid rain can form in the presence of ozone and carbon dioxide as well. Sulfuric acid (H2SO4) and nitric acid (HNO3) affect biological systems like plants directly. This paper provides information about acid formation and the direct impacts of acid rain on plants. Through a survey of the literature, we assessed the direct effects of acid rain on leaf chlorophyll, growth, and yield parameters on crops that have the highest economic importance in Afghanistan. (e.g., wheat, rice). For the analysis of the data, linear regression was applied. The results showed that plant parameters (dependent variables) such as leaf length, leaf area, chlorophyll content, leaf dry weight, and weight of 1000 seeds of wheat; leaf area; net-photosynthetic rate; and leaf dry weight of rice can be significantly affected by pH treatments (pH 5.5–2.5) (independent variables). The trends of the analysis determined significant negative effects of acid rain on plant parameters. To reduce the impacts of acid rain on plants, it is necessary to apply adaptation and mitigation strategies.

Keywords: *Acid Rain; Acid Rain Formation; Direct Effect of Acid Rain; Wheat and Rice Crops*

Introduction

Acid rain is any precipitation with a very low pH, whereas normal rainwater is slightly acidic with a pH range of 5–6, but the pH level of rainwater falls below pH 5.6, becoming acid rain. It happens as a result of the wet and dry deposition from the atmosphere by chemical pollutants emitted by natural sources such as biological processes and various human activities such as the burning of fossil fuels, combustible waste, vehicle exhausts, thermal power projects, the combustion of vegetation, and the wastes of war (Singh and Agrawal, 2007; Naeem and Ansari, 2020). Dry deposition is more frequent and effective than wet deposition. The major reasons for acid rain formation entail the occurrence of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and ozone in the air (Singh and Agrawal, 2007), and they form sulfuric, nitric, and carbonic acids (Ramadan, 2004; Debnath and Ahmed, 2020). Although the contribution of NO_x to acid rain formation is lesser compared to SO_2, its volume is increasing day by day (Debnath and Ahammed, 2020). Acid rains are a serious environmental problem that affects all parts of ecosystems, such as plants (forests, agricultural crops, grasses, and trees), animals, soil, buildings, and aquatic organisms, as well as human health (Ramadan, 2004; Alrawi, 2022).

The effects of acid rain at different levels, or pH units, have been reported by many researchers around the world. It has been concluded that acid rain can directly reduce leaf chlorophyll, growth, and yield parameters. Leaf chlorophyll content was studied by Du et al., (2017) in 67 species, of which 48 showed significant reductions in response to acid rain within the pH range from 2.0 to 5.6, while 19 species showed insignificant responses (Du et al., 2017). The effects of acid rain on deciduous species, evergreens, angiosperm species, gymnosperm species, fodder crops, and cereal crops have been reported by 8.67%, 4.06%, 6.84%, 3.93%, 16.67%, and 4.29% per pH unit, respectively. Moreover, herbs, woody species, and vegetables have been affected by acid rain by 10.7%, 11.6%, and 13.23%, respectively (Sirohi and Khan, 2006; Lal, 2016; Dang et al., 2017; Du et al., 2017).

Previous studies have indicated that acid rain affects plant growth directly and indirectly. The direct damage of acid rain to plant foliage includes physiological and morphological damages (Singh and Agrawal, 2007; Matsumura and Izuta, 2017; Kohno, 2017; Du et al., 2017). Different studies have shown different indicators of plant to exposure at pH treatment. Lee et al., (1980) studied the effect of simulated acid rain on some crops and reported yield reduction for radish, carrot, beet, mustard green, and broccoli at lower pH and stimulation for tomato, green pepper, strawberry, alfalfa, and orchard grass. Acid rain at pH 4.5 decreased the net photosynthetic rate, plant height, the number of pods, chlorophyll content, dry weight (gr), and leaf area (cm2) (Eguagie et al., 2016; Li and Liang, 2019). Zabawi et al., (2008) used several levels of pH on rice seeds. They observed that the percentage of seed germination decreased as the pH level decreased, at pH 3.5 by 3–5% (Kohno, 2017). All the seeds of the plants were musty at pH 1.0 (Lal, 2016). Leaf chlorophyll of wheat at pH 5.5 and 4.5 increased, while leaf chlorophyll decreased at pH 3.5 and 2.5 (Ezzati and Rabbani, 2015).

Wheat and rice are most important and popular crops that most people in Afghanistan are dependent on for their nutrition. This study was conducted to show the impact of acid rain on wheat and rice. Plant parameters such as leaf area, leaf length, dry weight of leaf, chlorophyll content, pigment change, photosynthesis rate, weight of 1000 seeds, and seed germination were considered dependent variables, while pH levels (2.0 up to 5.5) were considered independent variables. Moreover, pH 5.6–7 was considered a control. We synthesized data from published literature about acid rain formation and its direct impacts on species at different levels of acidity. The impacts of acid rain on plants were categorized based on growth and development, photosynthesis, and yield parameters. Linear regression was applied to analyze the data.

Materials and Methods

We conducted a literature survey by using the keywords "acid rain" and "effects of acid rain on plants." The data were collected from published literature that indicated the direct effects of acid rain on plants. Based on the topic, a literature search was conducted in the scientific data sets. The following key words were used to select and find the literature as a topic search:

Topic search = (acid formation, or acidrain, or acid precipitation, or acid deposition) (effect of acidrain on crops, physiology, morphology, or photosynthesis, or chlorophyll contents, or yield, or production).

The following criteria were used for the selection of literature as well:

Acid formation or the chemical reaction of materials to form acids should be reported;

The pH levels in the range of 2.0–5.0 and 6, 7 (as control) should be reported;

Effects of acids on plant growth and development (biomass, leaf area, stem height, etc.) should be reported;

Impacts of acids on photosynthesis, chlorophyll contents, or pigments should be indicated;

Impacts of acids on yields or production of crops should be reported;

The effects on plants were categorized by chlorophyll content, yield and growth parameters. Plant indicators are dependent variables, and pH treatments are independent variables. The pH treatments were selected across ranges from 2.0 to 5.6, and the above 5.6 was considered the control treatment.

Data Analysis

The results from different measurement methods and the values of plant parameters for each plant were assessed. A linear regression model was applied to explore the relationship between the plant parameters and the level of pH treatment according to the following equation:

PP (y) = C pH + a

Where pp is the value of plant parameters, C and a are parameters, and pH is the pH level of the acid treatment. A coefficient determination was performed to examine the model by Ms. Excel.

Results

1. Acid Rain Formation

The emission of chemical pollutants such as SO_2, NO_x, CO, CO_2, and O_3 to the atmosphere from various sources and their interaction with other materials (e.g., sunlight, water) are forming acids such as H_2SO_4, HNO_3, and HCO_3.

2. Direct Impact of Acid Rain on Plants

A. Impacts of Acid Rain on Growth Parameters

Overall, growth and development parameters of plants such as plant height, leaf area, leaf length, shoot and root fresh weight, leaf number, germination rate, and the number of branches under acid rain treatment were significantly affected. The pH 5.5 decreases leaf area significantly and leaf length insignificantly on wheat, whereas the pH 4.5 increases leaf area on rice (Fig. 1 a-c).

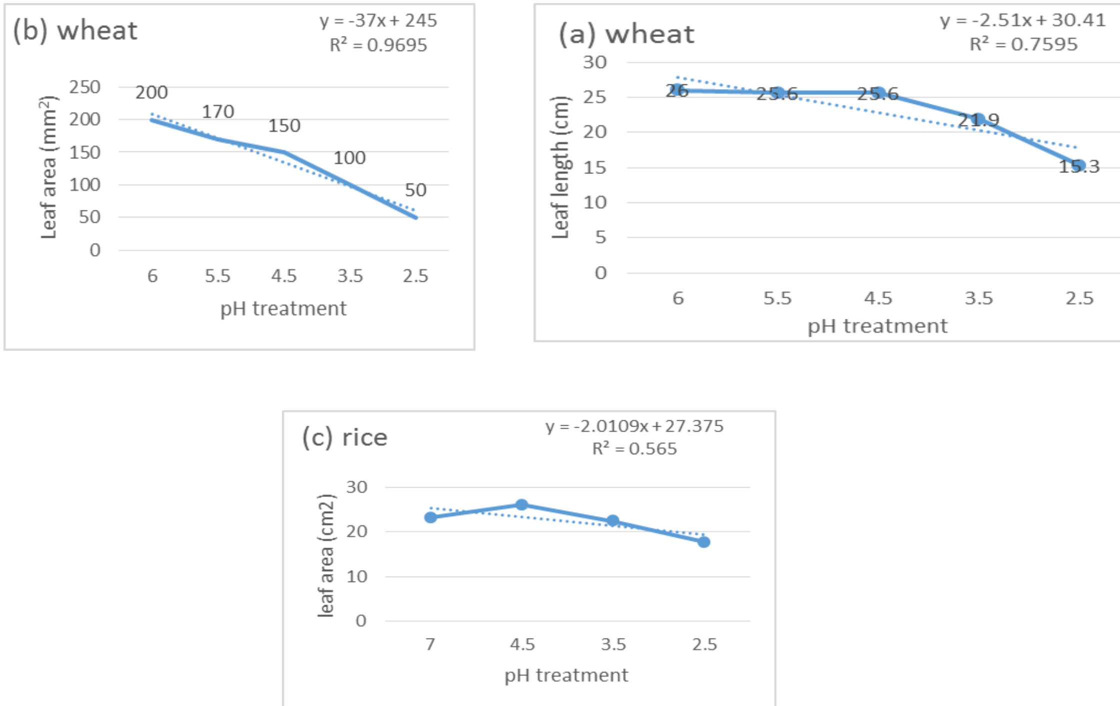

Figure 1: (a) Effect of acid rain on the leaf length (cm) of wheat. The trend shows the negative effect of acid rain on plants. R^2 indicated that the plant parameter (leaf length) can be affected by pH treatment by 75.95%. (b) Effect of acid rain on leaf area (mm^2) of wheat.The trend indicates a negative impact of acid rain on the parameter. R^2 illustrated that the leaf area of wheat can be affected by pH treatment by 96.95%. (c) Effect of pH treatment on leaf area (cm^2) on rice. It shows the negative effect of pH treatment on rice. R^2 showed that the leaf area of rice can be affected by pH treatment by 56.5%.

B. Impacts of Acid Rain on Leaf Chlorphyll

Leaf chlorophyll content and net photosynthetic rate were significantly affected by acid rain treatments (Fig. 1). Chlorophyll content of wheat increased at pH 5.5 signifcantly, while increase on rice insignificantly. Chlorophyll content was decreased at pH 4.5 and below on both crops. There is a significant increase at pH 5.5 on wheat, and a slight increase at pH 4.5 on rice as well (Fig. 2 (a), (b)).

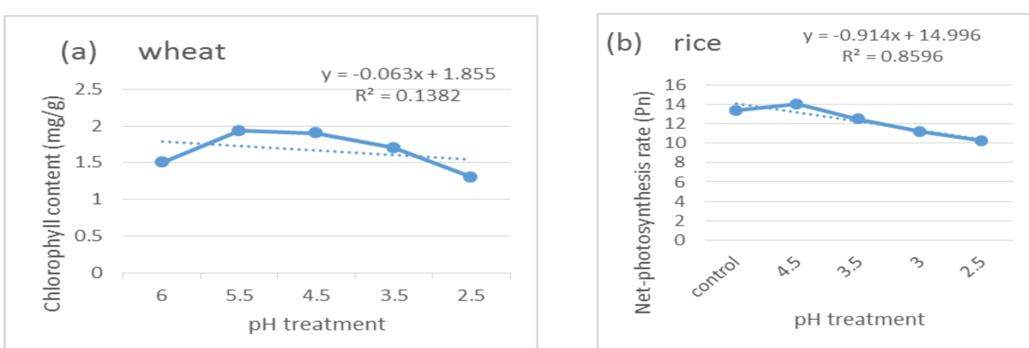

Figure 2. (a) Effects of pH treatment on the chlorophyll content of wheat. The trend shows that the impact of acid rain on wheat is negative. R^2 showed that chl. Content can be affected by pH treatment by 13.82%. (b) Effects of acid rain on the leaf photosynthetic rate of rice.The trend shows the negative effect of acid rain on rice. R^2 determined the effect of acid rian on net-photo. rate by 85.96%.

C. Impact of Acid Rain on Yield Parameters

Yield parameters are reduced significantly by acid rain. Figure 3 shows the trend impact of acid rain on both crops. The pH 4.5 treatment affected leaf dry weight (gr) on rice by 0.012 (gr) and on wheat by -0.4 (gr) to compare with the control treatment.

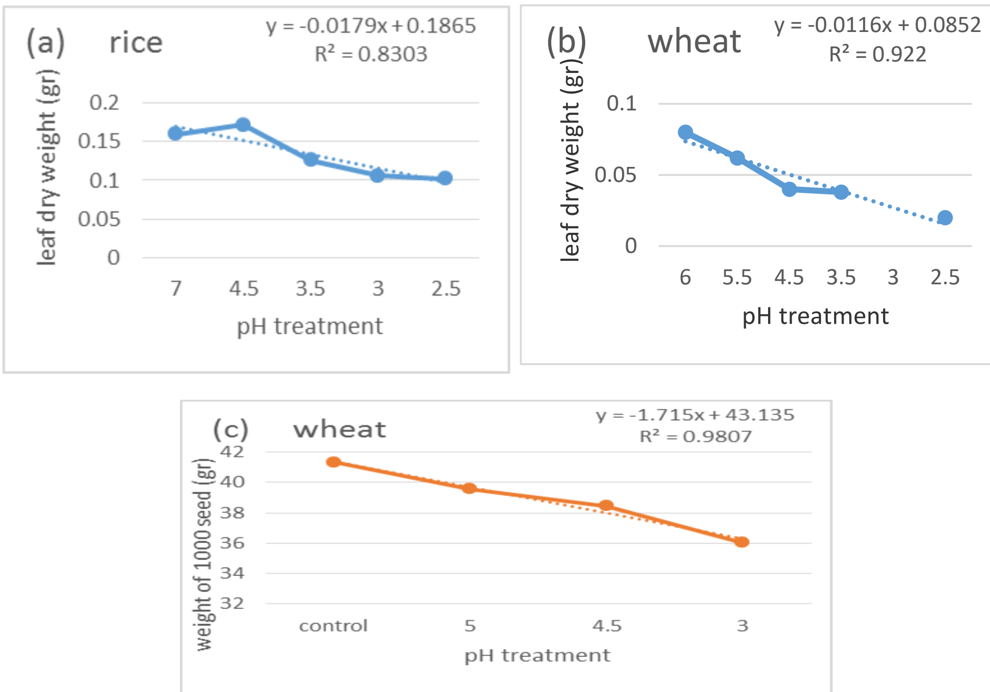

Figure 3. (a) Impacts of pH treatment on leaf dry weight (gr) on rice (b) Effects of pH treatment on leaf dry weight (gr) in wheat (c) change the yield parameter of wheat in response to pH treatment. The trends show the negative impacts of acid rain on both crops.

Discussion

1. Acid Rain Formation

1- Acid Formation in the Presence of Sulfur

A. Chemical reaction in the gas phase for SO_2

a: Sulfur in coal burns with oxygen to form sulfur dioxide

$$S \text{ (coal) (g)} + O_2 \text{ (g)} \longrightarrow SO_2 \text{ (g1)}$$

b: Sulfur reacts with oxygen in the atmosphere to form sulfur tri-oxide

$$nSO_2 \text{ (g)} + O_2 \text{ (g)} \longrightarrow nSO_3 \text{ (g)}$$

c: Sulfur dioxide reacts with hydroxide in the presence of sunlight to form sulfuric acid;

[1] Gas

SO_2 (g) + 2(OH) (g) ⟶ H_2SO_4(g) (Ramadan, 2004)

SO_2 + H_2O ⟶ H_2SO_3 (Debnath and Ahmmed, 2020)

B. Chemcal reaction in liquid phase for SO_2

a: Sulfur trioxide react with moisture in the atmosphere to form sulfuric acid

SO_3 (gas) + H_2O(L[2]) ⟶ H_2SO_4 (L) (Ramadan, 2004; Debnath and Ahmmed, 2020)

2- Acid Formation in the Presence of Nitrogen

A. Chemical Reaction in Gas Phase for No_x

a: Combustion engines mix oxygen and nitrogen together

nN_2(g) + nO_2 (g) + energy ⟶ nNO(g)

b: Nitrous oxide reacts with diatomic oxygen to form nitrous dioxide

nNO(g) + O_2 (g) ⟶ nNO_2(g)

c: Nitrogen dioxide react with hydroxide radicals in sunlight to produce nitric acid

NO_2 (g) + OH (g) ⟶ HNO_3 (g)

B. Chemical reaction in liquid phase for NO_x
A: Nitrogen dioxide reacts with atmospheric moisture to form nitric acid

NO_2 (g) + H_2O (L) ⟶ HNO_3 (L)

O_3 ⟶ O_2 + (O)

(O) + H_2O ⟶ 2(OH) (hr[3])

OH + SO_2 ⟶ HSO_3^{-1}

HSO_3^- + OH ⟶ H_2SO_4

2(OH) + 2 NO_2 ⟶ 2HNO_3

3- Acid Formation In The Presence of Ozone (O_3)

$2HSO_3^{-1}$ + 1/2 O_2 ⟶ $2SO_3^{2-}$ + H_2O (pr[4]) (Debnath and Ahmmed, 2020)

4- Acid Formation In The Presence Of Other Gases

A: There are other gasses to form acid, such as carbon dioxide

CO_2 + H_2O ⟶ H_2CO_3 (L) (Ramadan, 2004)

CO_2 + H_2O ⟶ H_2CO_3 (Debnath and Ahmmed, 2020)

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[2] Liquid
[3] Hydroxy radical
[4] Peroxy radical

$H_2CO_3 \longrightarrow H^+ + HCO_3^{-1}$ (Ramadan, 2004)

2. Direct Impacts of Acid Rain on Plants

A. Negative Impact of Acid Rain on Plant Growth

Acid rain is an abiotic stress factor that impacts a wide range of physiological and metabolic processes, leading to a significant reduction in the normal growth and development of plants. Our analysis determined that acid rains have negative impacts on key plant growth parameters such as leaf height, leaf area (Fig. 1), shoot and root fresh weight, germination rate, the number of branches, and leaf chlorophyll contents (Pham et al., 2021; Liu et al., 2007, 2011b; Dolatabadian et al., 2013). Kausar et al., (2010) reported that simulated acid rain had an adverse effect on morphological, biochemical, and leaf epidermal parameters (the number of stomata, stomatal aperture, and length of trichomes) in wheat. Acid rain first destroys the wax and cuticle of leaf surfaces, damages theepidermal structure of leaves, and then diffuses into the cortex through stomata and epidermis (Liang, 2020). Due to the reduction of leaf area in response to acid rain, the growth of roots and shoots would be directly affected (Lal and Singh, 2012; Lal, 2016). A significant reduction of leaf area of plants such as wheat and rice at different levels of pH (below pH 4.5) has been reported by Ezzati and Rabbani (2015), Sun et al., (2016), and Singh and Agrawal (1996).

Acid rain has a negative effect on pollen germination and pollen tube growth (CO_X, 1984). A significant fall in the germination rate was observed with increasing levels of acidity. The germination rate of soybean at pH 3.0 and 3.5 was 78% and 83%, respectively (Pham et al., 2021). The impacts of SAR pointed out by Zabawi et al., (2008) on rice seeds between pH 3.5 and 5.6 (as a control treatment) were negative. pH 3.5 caused a reduction in germination by 3–5% and a relatively slower germination rate (Kohno, 2017). The germination rates on wheat at pH 3.0 and 2.5 have been reported by 60% and 50%, respectively (Ezzati and Rabbani, 2015) (table 1).

Table 1 shows the effects of acid rain on some important plants.

effect of acid rain on leaf area (cm2) of wheat and rice

		Wheat		Rice
pH	Leaf area(cm2)	Leaf length (cm)	Seed germination	Leaf area(cm2)
7	20	26	80	23.219
5.5	17	25.6	70	na
5	na		na	na
4.5	15	25.6	70	26.015
4	na		Na	Na
3.5	10	21.9	60	22.451
3	na		na	na
2.5	5	15.3	50	17.704
Ref.		Ezzati and Rabbani, 2015		Sun et al., 2016

na. not available

The table (2) indicated a significant reduction in the germination of plants.

Acid rain caused marked symptoms of phytotoxicity, such as chlorosis, necrosis, less leaf production, leaf curling, leaf withering, leaf abscission, and stubby plants becoming stunted and brittle in stress conditions (Debnath et al., 2018c).

B. Impact of Acid Rain on Photosynthesis in Plants

Acid rain exerted significant effects on leaf photosynthesis over the pH range below 5.6 (Dang et al., 2017). Chlorophyll is essential in photosynthesis to support plant growth and can be a sensitive indicatore of the damaging effects of environmental stresses on leaf function (Liang, 2020). Damage of leaf chlorophyll content can directly reflect by symptoms on foliage and inhibition on plant productivity by acid rain. Our analysis showed that the effect of acid rain at pH 4.5 was positive but it was negative at pH 3.5 and 3.0 on chlorophyll content and photosynthesis rate on wheat and rice(Fig. 2). The amount of chlorophyll is reduced by acid rain with a pH of 3.0 (Jafarian et al., 2015). Morrison (1984) reported that chlorophyll formation may be decreased by acid rain due to the leaching of nutrient elements such as magnesium (Mg). A linear reduction of leaf chlorophyll content was shown in response to acid rain exposure (across pH ranges from 2.0 to 5.6) (Liang, 2020). Leaf chlorophyll content was substantially reduced by acid rain at 6.71% per pH unit on plant species that were studied by Du et al., (2017). Moreover, Sensor et al., (1990) pointed out that plant pigments are very sensitive to air pollutants and identified them as indicators of the physiological states of plants stressed by acid rain, among the plant metabolites (Lal, 2016). Chen et al., (2013); Kovacik et al., (2011) pointed out that acid rain hampers photosynthetic activity; nonetheless, differences in plant species and rian acidity may partially respond to a variation range(Liang, 2020; Debnath and Ahammed, 2020).

Chloroplast is the major site that is affected by acid rain. The granum thylakoids were thinned at pH 4.5, 3.5, and 3.0, and the lamellar structure of the thylakoids became loose (Wen et al., 2011; Sun et al., 2012; Liang, 2020). Kausar et al., (2010) reported that acid rian decreased photosynthetic pigments (Chl a, Chl b, total Chl, and carotenoids) on wheat leaves significantly (Lal, 2016). Acid rain deposition affects the ultrastructures of the chloroplast and plasma membrane of leaves; thus, chlorophyll degradation and lower photosynthetic activity occur. The destruction of the structure of chloroplasts led to a decrease in the content of chlorophyll. Moreover, acid rain decreases leaf water content and chloroplast ATP synthase activity, inhibates the rate of the Calvin cycle, the Krebs cycle, glycolysis, and the pentose phosphate pathway under acid rain conditions as well (Liang, 2020; Sun et al., 2016; Debnath and Ahmed, 2020).

The studies showed a significant reduction of chlorophyll in Afghanistan's economic plants, such as wheat and rice at various pH levels (below 4.5) (Ezzati and Rabbani, 2015; Sun et al., 2016) table3. The impacts of acid rain on the chloroplasts of rice were studied by Sun et al., (2016). They showed the net photosynthetic rate (Pn) at pH 7.0–2.5 at different values. Net photosynthetic rate (Pn) observed 14.03 at pH 4.5, 12.47 at pH 3.5, and 10.23 at pH 2.5 (Sun et al., 2016) (table 3).

Table 3 shows the impact of acid rian (SAR) on the photosynthesis process.

	Wheat	Rice
PH	Chlorophyll content (mg g-1 fw)	net photosy. Rate(Pn)
7	1.5	13.37
5.5	1.93	
4.5	1.9	14.03
4		
3.5	1.7	12.47
3		11.17
2.5	1.3	10.23
Sources	Ezzati and Rabbani, 2015	Sun et al., 2016

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C. Impact of Acid Rain on Crop Yield Parameters

Researchers have studied the impacts of simulated acid rain on different crops, and they reported the yield reduction of several crops treated at low acidity of rainfall (Singh and Agrawal, 2004). This study showed that acid rain at pH below 5.5 reduced yield parameters on wheat and rice (Fig 3). The average production loss due to acid rain ranges from 3.28 to 14.24% per pH unit across all economic use types (Du et al., 2017). Singh and Agrawal (1996) reported that Indian wheat cultivars showed marked sensitivity to acid rain, particularly at pH ranges of 3.0–5.0 under field conditions. Kausar et al., (2010) showed the negative effect of acid rain on yield parameters (ear length, number of grains, and weight of 100 grains) of wheat at pH 3.0 to 5.0. The yield of wheat decreased significantly at pH 3.0 and 4.0 due to a decline in the weight of 1000 seeds and the number of grains per plant (Singh and Agrawal, 2004) (table 4). Significant reductions were also observed in total biomass at lower pH in simulated acid rain by Evans and Lewin (1981); Johnston et al., (1982); Singh et al. (1992); and Singh and Agrawal (1996). Seed carbohydrate (soluble and insoluble), seed protein (soluble and insoluble) also decreased significantly with the increase of acidity (Kausar et al., 2010).

Table 4 shows the effects of acid rain (SAR) on plant yields.

	Wheat			Rice
pH	Leaf dry weight(gr)	yield (gr/m^2)	Weightt of 1000 seeds (gr)	Leaf dry weight(gr)
7	0.08	372.75	41.36	0.159
5.5	0.062	na	na	
5		358.5	39.57	
4.5	0.04	324.75	38.44	0.71
3.5	0.038			0.126
3		389.5	36.02	0.106
2.5	0.02			0.102
Ref.	Ezzati and Rabbani 2015	Singh and Agrawal, 2004		Sun et al., 2016

na: not available

Conclusion

Low pH of sulfuric and nitric acids damage ecosystems by acid deposition (dry or wet). Damage to biological systems like plants, animals, humans, and microorganisms increases with increasing acidity due to human activities. The above review of literature demonstrates that natural and simulated acid rains with pH values of 5.0 and below have a negative effect on plants. The physiological, biochemical, and morphological systems of plants, particularly wheat and rice, are affected by acid rain. This effect causes a decline in yield parameters and a reduction in photosynthesis as a result of leaf abscission, leaf curl, chlorosis, necrosis, decreased biomass, budding behavior, metabolic processes, enzyme activities, cytoplasmic properties, seed germination, and pollen behavior in a range of plant species. It is necessary to reduce the impacts of acid rain on plants by using several strategies, such as policy implementation, advanced technology, reducing the emission of primary acids, and raising public awareness. There is a need to conduct more studies on crops, and find their sensitivities and resistances to acidic deposition.

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