INTERACTIVE EFFECTS OF ZINC AND NICKEL ON GROWTH AND NUTRITION OF RICE (*Oryza sativa* L)

Thesis

Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE
in
SOIL SCIENCE
(Minor Subject:Chemistry)

By

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(L-2016-A-138-M)

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CERTIFICATE I

This is to certify that the thesis entitled, **"Interactive effects of zinc and nickel on growth and nutrition of rice (*Oryza sativa* L)"** submitted for the degree of **M.Sc.**, in the subject of **Soil Science** (Minor subject: **Chemistry**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Ms. Diksha Goyal (L-2016-A-138-M)** under my supervision and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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Dr J S Manchanda
Senior Soil Chemist
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CERTIFICATE II

This is to certify that the thesis entitled, **"Interactive effects of zinc and nickel on growth and nutrition of rice (*Oryza sativa* L)"** submitted by **Ms. Diksha Goyal (L-2016-A-138-M)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of **M.Sc.**, in the subject of **Soil Science** (Minor subject: **Chemistry**) has been approved by the student's Advisory Committee after an oral examination on the same.

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ABSTRACT

A pot experiment was conducted to study the interactive effects of Zn and Ni on growth and nutrition of rice. The soils used in the study were i) loamy sand (ls) Typic Ustipssament (pH 7.9, EC 0.25 dS m^{-1}, OC 0.15%, $CaCO_3$ 0.13%, DTPA-Zn 1.00 and DTPA-Ni 0.19 mg kg^{-1} soil) and ii) sandy loam (sl) Typic Haplustept (pH 8.1, EC 0.35 dS m^{-1}, OC 0.32%, DTPA-Zn 1.20 and DTPA-Ni 0.46 mg kg^{-1} soil). Seven levels of Zn (0, 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil) as zinc sulfate heptahydrate and six levels of Ni (0, 2.5, 5, 10, 20 and 40) as nickel chloride were applied in all possible combinations to eight kg of soil per pot with three replications. Rice (cv PR-126) was grown till maturity and soil, root, grain and straw samples were collected. Soil and plant samples were processed and analysed for DTPA-Zn, DTPA-Ni, various pools of Zn and Ni (exchangeable, specifically adsorbed, manganese oxide bound, amorphous Fe and Al oxides bound, crystalline Fe and Al oxides bound, organically bound and residual mineral fraction) and Zn and Ni concentration in root, grain and straw . The activity of urease enzyme in soil was estimated at maximum tillering and harvesting stage. Mean DTPA-Zn in both the soils decreased with increasing levels of applied Ni, while mean DTPA- Ni in both the soils remained unaffected up to a level of Zn application @ 20 mg kg^{-1} soil, but significant decrease over control was observed with an application of 40 and 80 mg Zn kg^{-1} soil. The interaction effect of Zn and Ni levels on DTPA-Zn was also significant. It was observed that DTPA-Zn decreased significantly by 45 and 34 per cent when 40 mg Ni kg^{-1} soil was applied along with 80 mg Zn kg^{-1} soil as compared to when only 80 mg Zn kg^{-1} soil was applied in loamy sand and sandy loam soil, respectively. Nickel and Zn application decreased exchangeable and specifically adsorbed Zn in both the soils. However, applied Zn increased Ni in manganese-oxides and amorphous oxides bound pools. The quadratic response of relative root dry matter yield (RRDMY), grain and straw yield to DTPA-Zn indicated that RRDMY, grain and straw yield increased up to level of 5 mg DTPA-Zn kg^{-1} soil and thereafter it declined in both the soils. The quadratic response of RRDMY to DTPA-Ni in both the soils indicated that maximum RDMY was produced when soil contained 2 mg DTPA-Ni kg^{-1} soil. However, quadratic response of relative grain and straw yield to DTPA-Ni indicated that grain and straw yield increased up to level of 3 mg DTPA-Ni kg^{-1} soil and thereafter yield declined in both the soils. Irrespective of the soil used, about 12.0, 16.5 and 14.5 mg DTPA-Zn kg^{-1} soil and 5.37, 7.45 and 7.10 mg DTPA-Ni kg^{-1} soil produced 50 per cent reduction from maximum yield of root, grain and straw, respectively, which may be considered as the upper critical values for rice. Irrespective of the soils, the concentration of Ni in root, grain and straw decreased as the concentration of Zn increased. Thus indicating their antagonism with each other. Nickel uptake by each plant part decreased with increase in DTPA-Zn. With increase in level of applied Zn, activity of urease enzyme significantly decreased at both the stages (Maximum tillering and harvesting stage). Application of Ni significantly increased urease activity up to a level of 10 mg Ni kg^{-1} soil and thereafter it was reduced in both the soils at both the stages. The results also indicated that antagonistic effect of Zn on activity of urease was more pronounced in loamy sand as compared to sandy loam soil. The farmers should apply Zn to the soils only, if the soil test value is below the critical deficiency level to avoid Zn induced Ni deficiency due to build up of Zn in the soils.

Keywords: Rice, Zn pools, Ni pools, urease

Signature of Major Advisor

Signature of the Student

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ਸਾਰ ਅੰਸ਼

ਝੋਨੇ ਦੇ ਵਿਕਾਸ ਅਤੇ ਪੋਸ਼ਣ ਲਈ ਜਿੰਕ ਅਤੇ ਨਿੱਕਲ ਦੇ ਪਰਸਪਰ ਪ੍ਰਭਾਵ ਦਾ ਮੁਲਾਂਕਣ ਕਰਨ ਲਈ ਇੱਕ ਪੋਟ ਤਜ਼ਰਬਾ ਕੀਤਾ ਗਿਆ। ਅਧਿਐਨ ਲਈ ਦੋ ਮਿੱਟੀਆਂ ਰੇਤਲੀ ਮੈਰਾ (ਐਲ.ਐਸ.) ਟਿਪਿਕ ਓਸਟੀਸਾਮੈਂਟ (ਪੀ.ਐਚ.7.9, ਈ.ਸੀ. 0.25 ਡੈਸੀਸੀਮੇਨ ਪ੍ਰਤੀ ਮੀਟਰ ,ਓ.ਸੀ. 0.15 ਪ੍ਰਤੀਸ਼ਤ, ਕੈਲਸ਼ੀਅਮ ਕਾਰਬੋਨੇਟ 0.13 ਪ੍ਰਤੀਸ਼ਤ, ਡੀ.ਟੀ.ਪੀ.ਏ. ਨਿੱਕਲ 0.19 ਮਿਲੀਗ੍ਰਾਮ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ) ਅਤੇ (2) ਮੈਰਾ ਰੇਤਲੀ (ਐਸ.ਐਲ.) ਟਿਪਿਕ ਹੈਪਲ ਉਸਟੈਪਟ (ਪੀ.ਐਚ. 8.1, ਈ.ਸੀ. 0.35 ਡੈਸੀਸੀਮੇਨ ਪ੍ਰਤੀ ਮੀਟਰ, ਓ.ਸੀ. 0.32 ਪ੍ਰਤੀਸ਼ਤ ਡੀ.ਟੀ.ਪੀ.ਏ ਜ਼ਿੰਕ 1.20 ਅਤੇ ਡੀ.ਟੀ.ਪੀ.ਏ ਨਿੱਕਲ 0.46 ਮਿਲੀਗ੍ਰਾਮ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ) ਦੀ ਵਰਤੋਂ ਕੀਤੀ ਗਈ। ਜ਼ਿੰਕ ਸਲਫੇਟ ਹੈਪਟਾਹਾਈਡ੍ਰੇਟ ਰੂਪ ਵਿੱਚ ਜ਼ਿੰਕ ਦੇ ਸੱਤ ਪੱਧਰਾਂ (0, 2.5,5, 10,20, 40 ਅਤੇ 80 ਮਿਲੀਗ੍ਰਾਮ ਜ਼ਿੰਕ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ) ਨੂੰ ਸਾਰੇ ਬਦਲਵੇਂ ਸੰਯੋਜਕਾਂ ਦੇ ਰੂਪ ਵਿੱਚ ਪੋਟ ਤਜ਼ਰਬੇ ਦੌਰਾਨ ਵਰਤਿਆ ਗਿਆ ਅਤੇ ਇਹ ਤਜ਼ਰਬਾ ਤਿੰਨ ਵਾਰ ਦੁਹਰਾਇਆ ਗਿਆ। ਝੋਨੇ ਦਿ ਕਿਸਮ ਪੀ.ਆਰ. 126) ਉਗਾਈ ਗਈ ਅਤੇ ਫ਼ਸਲ ਦੇ ਪੱਕਣ ਤੇ ਮਿੱਟੀ ਜੜ੍ਹਾਂ ਦਾਇਆਂ ਅਤੇ ਪਰਾਲੀ ਦੇ ਨਮੂਨੇ ਇਕੱਠੇ ਕੀਤੇ ਗਏ। ਮਿੱਟੀ ਦੇ ਨਮੂਨਿਆਂ ਦਾ, ਡੀ.ਟੀ.ਪੀ.ਏ ਜ਼ਿੰਕ ਡੀ.ਟੀ.ਪੀ.ਏ ਨਿੱਕਲ, ਵੱਖ –ਵੱਖ ਜ਼ਿੰਕ ਤੇ ਨਿੱਕਲ ਦੇ ਪੂਲ (ਐਕਸੇਂਚਏਬਲ, ਐਡਸੋਰਬਡ, ਮੈਨਗਨੀਜ਼ ਆਕਸਾਈਡ ਬਾਂਡ, ਐਮੋਰਫਸ-ਆਇਰਨ ਅਤੇ ਐਲੂਮੀਨੀਅਮ ਆਕਸਾਇਡ ਬਾਂਡ ਕਰਿਸਟੇਲਾਇਨ-ਆਇਰਨ ਅਤੇ ਐਲੂਮੀਨੀਅਮ ਆਕਸਾਈਡ ਬਾਂਡ, ਜੈਵਿਕ ਬਾਂਡ ਤੇ ਰੈਸੀਡਿਊਲ ਖਣਿਜ ਫਰੈਕਸ਼ਨ ਦਾ ਵਿਸ਼ਲੇਸ਼ਣ ਕੀਤਾ ਗਿਆ। ਪਰਾਲੀ ਵਿੱਚੋਂ ਜ਼ਿੰਕ ਅਤੇ ਨਿ4ਕਲ ਦੀ ਮਾਤਰਾ ਦਾ ਮੁਲਾਂਕਣ ਕੀਤਾ ਗਿਆ। ਮਿੱਟੀ ਵਿੱਚ ਯੂਰੀਏਜ਼ ਐਨਜ਼ਾਇਮ ਦੀ ਗਤੀ ਵੱਧ ਤੋਂ ਵੱਧ ਟਿਲਰਿੰਗ ਅਤੇ ਕਟਾਈ ਵਾਲੇ ਪੜ੍ਹਾਅ ਤੇ ਅਨੁਮਾਨਿਤ ਕੀਤੀ ਗਈ। ਦੋਵਾਂ ਮਿੱਟੀਆਂ ਵਿੱਚ ਔਸਤਨ ਡੀ.ਟੀ.ਪੀ.ਏ. ਨਿੱਕਲ ਘਟ ਗਿਆ ਨਾਲ ਘੱਟ ਰਿਹਾ ਹੈ। ਜਦਕਿ ਦੋਵਾਂ ਮਿੱਟੀਆਂ ਵਿੱਚ 20 ਕਿਲੋਗ੍ਰਾਮ ਜ਼ਿੰਕ ਪ੍ਰਤੀ ਕਿਲੋ ਪਾਉਣ ਨਾਲ ਡੀ.ਟੀ.ਪੀ.ਏ. ਨਿੱਕਲ ਦਾ ਪੱਧਰ ਪ੍ਰਭਾਵਿਤ ਨਹੀਂ ਹੋਇਆ, ਪਰੰਤੂ 40 ਅਤੇ 80 ਮਿਲੀਗ੍ਰਾਮ ਜ਼ਿੰਕ ਪ੍ਰਤੀ ਕਿਲੋ, ਪਾਉਣ ਨਾਲ ਡੀ.ਟੀ.ਪੀ.ਏ ਨਿੱਕਲ ਵਿੱਚ ਕਮੀ ਦੇਖੀ ਗਈ। ਡੀ.ਟੀ.ਪੀ.ਏ. ਜ਼ਿੰਕ ਅਤੇ ਨਿੱਕਲ ਦੇ ਪੱਧਰ ਦਾ ਪ੍ਰਭਾਵ ਵੀ ਮਹੱਤਵਪੂਰਨ ਸੀ, ਇਹ ਦੇਖਿਆ ਗਿਆ ਕਿ ਰੇਤਲੀ ਮੈਰਾ ਅਤੇ ਮੈਰਾ ਰੇਤਲੀ ਮਿੱਟੀ ਵਿੱਚ 40 ਕਿਲੋਗ੍ਰਾਮ ਨਿੱਕਲ ਪ੍ਰਤੀ ਕਿਲੋ ਦੇ ਨਾਲ 80 ਕਿਲੋਗ੍ਰਾਮ ਜਿੰਕ ਪਾਉਣ ਨਾਲ ਐਕਸਚੇਂਜ਼ੇਬਲ ਅਤੇ ਖਾਸ ਤੌਰ ਤੇ ਐਡਜ਼ੋਰਬਡ-ਜ਼ਿੰਕ ਵਿੱਚ ਗਿਰਾਵਟ ਦੇਖੀ ਗਈ। ਹਾਲਾਂਕਿ ਜ਼ਿੰਕ ਪਾਉਣ ਨਾਲ ਮੈਗਨੀਜ ਆਕਸਾਇਡ ਅਤੇ ਐਮੋਰਫਸ ਆਕਸਾਇਡ ਬਾਂਡ ਨਿੱਕਲ ਦੇ ਪੂਲ ਵਿੱਚ ਵਾਧਾ ਹੋਇਆ। ਜੜਾ ਦਾਇਆ ਅਤੇ ਪਰਾਲੀ ਦਾ ਝਾੜ ਪੰਜ ਮਿਲੀਗ੍ਰਾਮ ਡੀ.ਟੀ.ਪੀ.ਏ ਜਿੰਕ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ ਦੇ ਪੱਧਰ ਤੱਖ ਦਾ ਵਾਧਾ ਹੋਇ ਅਤੇ ਬਾਅਦ ਵਿੱਚ ਦੋਵਾਂ ਮਿੱਟੀਆਆਂ ਵਿੱਚ ਗਿਰਾਵਟ ਦੇਖੀ ਗਈ। ਜੜਾ ਦਾ ਝਾੜ ਸਿਰਫ ਦੋ ਮਿਲੀਗ੍ਰਾਮ ਪ੍ਰਤੀ ਕਿਲੋ ਨਿਕਲ ਤੱਕ ਹੀ ਵਧਿਆ ਅਤੇ ਉਸ ਤੋ ਬਾਅਦ ਘੱਟ ਗਿਆ। ਹਾਲਾਂਕਿ ਡੀ.ਟੀ.ਪੀ. ਏ ਨਿੱਕਲ ਨਾਲ ਦਾਇਆਂ ਅਤੇ ਪਰਾਲੀ ਦੀ ਕੁਆਰਡਰੇਟਿਕ ਪ੍ਰਤੀ ਕਿਰਿਆ ਨੇ ਸੰਕੇਤ ਦਿੱਤਾ ਕਿ ਦਾਇਆਂ ਅਤੇ ਪਰਾਲੀ ਦੀ ਉਪਜ 3 ਮਿਲੀਗ੍ਰਾਮ ਡੀ.ਟੀ.ਪੀ.ਏ ਨਿੱਕਲ ਪ੍ਰਤੀ ਕਿਲੋ ਦੇ ਪੱਧਰ ਤੱਕ ਵਧੀ ਅਤੇ ਇਸ ਤੋਂ ਬਾਅਦ ਦੋਵਾਂ ਵਿੱਚ ਗਿਰਾਵਟ ਦੇਖੀ ਗਈ। ਦੋਵਾਂ ਮਿੱਟੀਆਂ ਦੀ ਵਰਤੋਂ ਨਾਲ 12.0, 16.5 ਅਤੇ 14.5 ਮਿਲੀਗ੍ਰਾਮ ਡੀ.ਟੀ.ਪੀ.ਏ ਜਿੰਕ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ ਅਤੇ 5.37,7.45 ਅਤੇ 7.10 ਮਿਲੀਗ੍ਰਾਮ ਡੀ.ਟੀ.ਪੀ.ਏ ਨਿੱਕਲ ਪ੍ਰਤੀ ਕਿਲੋ ਮਿੱਟੀ ਜੜ੍ਹ ਦਾਇਆਂ ਅਤੇ ਪਰਾਲੀ ਦੀ ਕੁੱਲ ਪੈਦਾਵਾਰ ਵਿੱਚ 50 ਫੀਸਦੀ ਤੱਕ ਕਮੀ ਆਈ, ਜਿਸ ਨੂੰ ਝੋਨੇ ਦੀ ਫਸਲ ਲਈ ਉਚਤਮ ਕ੍ਰਿਟੀਕਲ ਅੰਕ ਮੰਨਿਆ ਜਾ ਸਕਦਾ ਹੈ। ਜਿੰਕ ਦੇ ਪੱਧਰ ਵਿੱਚ ਵਾਧੇ ਦੇ ਨਾਲ ਯੂਰੀਏਜ ਐਨਜ਼ਾਇਮ ਦੀ ਗਤੀ ਦੋਨਾਂ ਪੜਾਵਾਂ (ਵੱਧ ਤੋਂ ਵੱਧ ਟਿਲਰਿੰਗ ਅਤੇ ਕਟਾਈ ਪੜਾਅ) ਤੇ ਘਟ ਗਈ ਹਾਲਾਂਕਿ 10 ਮਿਲੀਗ੍ਰਾਮ ਦੇ ਨਾਲ ਪ੍ਰਤੀ ਕਿੱਲੋ ਨਿੱਕਲ ਪਾਉਣ ਨਾਲ ਯੂਰੀਏਜ ਐਨਜਾਇਮ ਦੀ ਗਤੀ ਵਿੱਚ ਵਾਧਾ ਦੇਖਿਆ ਗਿਆ। ਨਤੀਜਿਆਂ ਵਿੱਚ ਇਹ ਵੀ ਸੰਕੇਤ ਮਿਲਦਾ ਹੈ ਕਿ ਰੇਤਲੀ ਮਿੱਟੀ ਦੀ ਤੁਲਨਾ ਵਿੱਚ ਰੇਤੇ ਵਿੱਚ ਯੂਰੀਏਜ ਦੀ ਗਤੀ ਤੇ ਜਿੰਕ ਦੇ ਵਿਰੋਧਾਤਮਕ ਪ੍ਰਭਾਵ ਨੂੰ ਵਧੇਰੇ ਉਚਾਰਣ ਕੀਤਾ ਗਿਆ, ਕਿਸਾਨਾਂ ਨੂੰ ਖੇਤੀਬਾੜੀ ਲਈ ਜ਼ਿੰਕ ਸਿਰਫ ਤਾਂ ਹੀ ਵਰਤੋਂ ਵਿੱਚ ਲਿਆਉਣਾ ਚਾਹੀਦਾ ਹੈ, ਜੇਕਰ ਮਿੱਟੀ ਟੈਸਟ ਵਿੱਚ ਜਿੰਕ ਦਾ ਘਾਟ ਹੋਵੇ ਨਹੀਂ ਤਾਂ ਜ਼ਿਆਦਾ ਮਾਤਰਾ ਵਿੱਚ ਜ਼ਿੰਕ ਮਿੱਟੀ ਵਿੱਚ ਨਿੱਕਲ ਦਾ ਮਾਤਰਾ ਨੂੰ ਘਟਾ ਸਕਦਾ ਹੈ।

ਮੁੱਖ ਸ਼ਬਦ: ਝੋਨਾ, ਜਿੰਕ ਪੂਲ, ਨਿੱਕਲ ਪੂਲ, ਯੂਰੀਏਜ

ਮੁੱਖ ਸਲਾਹਕਾਰ ਦੇ ਹਸਤਾਖਰ | **ਵਿਦਿਆਰਥੀ ਦੇ ਹਸਤਾਖਰ**

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CHAPTER I

INTRODUCTION

Soil is a major source of food production. It plays a pivotal role in formative the crop productivity of an agro-ecosystem (Ladha *et al* 2000). As the agriculture is becoming intensive day by day, the soil toxicities and deficiencies of various kinds threaten the sustainability of crop production. India is one of the leading producers of rice. Rice is the basic food crop and being a tropical plant, it flourishes comfortably in hot and humid climate. In Punjab, the cropping intensity has increased from 134% in 1995 to 189.4% at present and rice-wheat is the major cropping system of state. Rice occupied an area of 28.94 lakh hectares with a total production of 166.61 lakh tonnes of paddy during 2016-17(Anonymous 2017).

Zinc (Zn) is the 24^{th} most abundant element in the earth and is present in almost all soils. On an average total content of Zn in soils of different groups, range between 60 and 89 mg kg^{-1} soil. It is required for basic metabolic processes of the plants and is involved in many physiological and biochemical processes such as antioxidative defense, protein synthesis, carbohydrate and auxin metabolism. It is also needed for stability of membranes. Zinc is mainly required in synthesis of tryptophan, which is precursor of a growth hormone indol acetic acid (IAA). Zinc also facilitates gene expressions, enzymes structure, energy production and krebs cycle. Zinc also play important role in pollination by facilitating pollen tube formation. Availability of Zn in Punjab soils varies from as low as 0.08 to as high as 7.06 mg kg^{-1} soil (Anonymous 2008). A field scale deficiency of zinc was first observed during 1969-70 with the introduction of high yielding varieties. Since then the farmers of the Punjab are applying Zn regularly to their crops especially in paddy during *kharif* season. As a result its deficiency has decreased from about 47% in 1990 to 21% at present (Sadana *et al* 2012). Build up of Zn in agricultural soils through prolonged use of Zn fertilizers may cause an imbalance in the use of other nutrients by plants including nickel.

Nickel (Ni) is the recent nutrient which has been added in the list of essential nutrients, required for plants (Brown *et al* 1987, Eskew *et al* 1984, Welch 1981). It is a transition metal of group 8^{th} of the periodic table and occurs in a number of oxidation states, but divalent nickel cation is most stable state found in soil environment. It is a component of nine metalloenzymes, including urease which catalyzes the hydrolysis of urea and involved in nitrogen metabolism because it act as a cofactor which enables urease to catalyse the conversion of urea into ammonium ions which the plants can use as a source of nitrogen. It is also involved in symbiotic nitrogen fixation. It also acts both as a plant growth stimulant and retardant and has also been shown to stimulate seed germination. Most of the soils contain small quantity of nickel which is below the level at which toxicity occurs but serpentine soils derived from ultrabasic igneous rocks contain 5000 mg kg^{-1}. Nickel content of soils vary from

13-37 mg kg^{-1} soil. Nickel content of 0.5 to 1.4 mg kg^{-1} in soil is considered to be low. Nickel deficiency was first reported in orchard trees of pecan in the southeast USA and it was concluded that this deficiency was due to Zn fertilization-induced reduction in the physiological availability of Ni due to competitive inhibition. Interaction of Zn and Ni is antagonistic in soils. Nickel and Zn are chemically similar. Nickel concentration in plants vary from 0.1-0.5 mg kg^{-1} dry matter (Mishra and Kar 1974). It is essential for higher plants at low concentration only. At higher level it may prove to be toxic to plants. More concentration of this element in growing medium exert adverse effects on plants such as chlorosis, weak plant growth, yield depression and disorder in plant metabolism (Molas and Baran 2004). Gad *et al* (2007) observed that the tomato fruit quality improved up to a level of 30 mg Ni kg^{-1} soil. But an adverse effect was caused by increasing level from 30 to 45 and 60 mg kg^{-1} soil. Also Ni deficiency adversely affects plant growth and metabolism as well as uptake of some micronutrients. At low concentration, stimulatory effect of nickel has been reported in some species through its role in urea utilization in N metabolism during the reproductive phase of plant growth (Brown *et al* 1987). Deficiency of Ni also results in delayed nodulation and reduced efficiency of N fixation. Hence both these elements compete for binding sites of low selectivity. If Ni is present in high concentration, it induces Zn deficiency and Zn induced Ni deficiency affects the urease activity adversely. Due to impaired activity of urease hydrolysis of urea is also effected which causes accumulation of urea in soil. Hence sometime Ni fertilization might be needed for those soils with high concentration of Zn. Keeping this in view the present study was designed with the following objectives:

1. To study the interactive effects of Zn and Ni on growth and nutrition of rice.
2. To study the effect of applied Zn and Ni on their transformation into various chemical pools.

CHAPTER II

REVIEW OF LITERATURE

The literature pertinent to the present investigation entitled "Interactive effects of zinc and nickel on growth and nutrition of rice (*Oryza sativa* L)" has been reviewed under following headings:

2.1 Importance of zinc and nickel in plant nutrition

2.2 Interaction between zinc and nickel

2.3 Transformation of zinc and nickel in various chemical pools in soils

2.4 Activity of urease in soils as influenced by zinc and nickel fertilization

2.1.1. Zinc

Zinc as an essential element for higher plants was first recognized by Sommer and Lipman (1926). It is involved in a number of physiological processes of plant growth and metabolism like enzyme activation, protein synthesis, metabolism of carbohydrates, lipids, auxins and nucleic acids, gene expression and regulation and reproductive development (Marschner 1995, Cakmak 2000, Mengel and Kirkby 2001).

Rice (*Oryza sativa* L.) is one of highly sensitive crops to zinc deficiency. It is the most important micronutrient limiting rice growth and yield. Symptoms of Zn deficiency in rice for the first time were observed in calcareous soils of northern India (Nene 1966, Yoshida and Tanaka 1969) which usually appear 2 to 3 weeks after transplanting of rice seedlings. The deficiency symptoms include development of rusty brown blotches and streaks that may fuse to cover older leaves entirely, plants remain stunted and in severe cases may die (Nene and Lantin 1994).

Zinc deficiency causes a decrease in plant growth and yield (Ishimaru *et al* 2011). As Zn plays multiple roles in plant biochemical and physiological processes, even slight deficiency causes a decrease in growth, yield, and Zn content of edible plant parts. Zn deficiency is a serious agricultural problem as around one half of the cereal-growing soils in the world contains low Zn in the soil (Graham and Welch 1996, Cakmak *et al* 1999).

Zinc deficiency is mostly corrected by application of zinc sulphate heptahydrate (21% Zn). The response of paddy to Zn application has been reported by many workers (Takkar and Singh 1978, Kausar *et al* 2001). An increase of about 4.9 and 6.1% in paddy yield with application of 5 and 10 mg Zn kg^{-1} soil, respectively over control was observed by Kausar *et al* (2001). In a pot experiment, Gangwar *et al* (1989) reported higher dry matter and grain yields of rice with 10 mg Zn kg^{-1} soil compared to control. A significant impact on growth and yield of rice due to zinc application was observed by Malik *et al* (2011), however the fresh and dry matter production of rice was adversely affected when supplied with 200 ppm Zn.

Telong and Zhao (1997) studied that Zn in rice has been recognized to have a stimulating effect on number of productive tillers, leaf area index (LAI) and dry matter accumulation with increase in level of Zn. Increase in the level of Zn significantly increased plant growth parameters such as LAI, crop growth rate, dry matter accumulation and plant height (Grewal *et al* 1997).

Nathan *et al* (2005) observed that dry matter accumulation in rice significantly increased with the application of 13.5 kg Zn ha^{-1}. Dry matter yield of rice was higher (13.6%) with the application of Zn as compared to the control (9.4%). Fageria (2001) and Ghatak *et al* (2005) concluded that application of zinc fertilizers (zinc sulphate heptahydrate or zinc oxide) significantly increased the effective tillers, panicle length, plant height, grain/panicle, grain and straw yield. Application of 30 kg zinc sulphate ha^{-1} recorded highest values of yield attributes.

Khan *et al* (2007) conducted a field experiment to study the response of Zn application in rice-wheat system. Yield of paddy (IRRI 6) was significantly increased by Zn application. Highest yield was obtained from 10 kg Zn ha^{-1}. Zn application also significantly affected the yield parameters of rice like the spike length, plant height and 1000 grain weight over control.

Sharma *et al* (1999) observed that grain and straw yield increased with increasing rates of Zn application, the highest yield recorded with 36 kg zinc ha^{-1} followed by two spray of zinc sulphate heptahydrate. Shivay *et al* (2008) reported that 1.0% coating of urea either with zinc sulphate or zinc oxide increased Zn concentration, uptake by rice grain and productivity. Dry matter accumulation of rice was increased by application of 13.5 kg Zn ha^{-1} and dry matter accumulation increased linearly with increase in rate of application Zn and which was not affected by source (Slaton *et al* 2005). Singh *et al* (1987) studied that grain and straw yield of rice progressively increased with increasing rates of Zn from 10-30 kg zinc sulphate ha^{-1}.

. Yilmez *et al* (1997) studied that Zn application irrespective of methods of its application significantly increased grain yield. This was endorsed to dilution of Zn in plant tissue because of enhanced dry matter production (Rengel and Graham 1995). Zinc application @ 25-30 kg ha^{-1} was sufficient to correct Zn deficiency for 4-7 years and the residual effect was best with soil application on long range basis. Shivay *et al* (2010) and Obrador *et al* (2003) suggested that Zn fertilization significantly increased the growth and yield parameters of rice and maize over control (no Zn). Zn deficiency resulted in a marked decrease shoot and root dry weight in rice after 28-days of growth in control treatments over Zn fertilized treatments at Beijing, China (Gao *et al* 2005).

Alam and Kumar (2015) observed that Zn fertilization significantly increased yield attributes such as grain and straw yield, effective tillers, grain per panicle, filled grains per panicle, test weight. Levels of Zn were 0, 5, 10 and 20 kg Zn ha^{-1} and the highest values were recorded with 10 kg Zn through $ZnSO_4$. All the growth parameters increased up to 10 kg Zn ha^{-1} and then decreased with further application of Zn.

Saraswat and Bansal (1991) observed linear and significant response of grain and straw yield of rice up to 40 kg $ZnSO_4$ ha^{-1}. The results were further confirmed by Prasad and Umar (1993) and Singh *et al* (1996). Kumar *et al* (2002) studied that 10 mg Zn kg^{-1} soil gave the highest grain yield grain (3.0 t ha^{-1}**)** and straw (4.8 t ha^{-1}) yield. Zn application had greatest influence on grain yield.

Muthukumararaja and Sriramachandrasekharan (2012) conducted a pot house experiment and observed that dry matter production significantly increased with increase in rate of application of Zn over control. Maximum dry matter production of 40.93 g pot^{-1} at panicle initiation and 2.98 g pot^{-1} at tillering was obtained with application of 5 mg Zn kg^{-1} and it was about 44 to 60% more as compared to control. Mandal *et al* (2009) recorded significantly higher dry matter accumulation, plant height and tiller numbers with the application of 10 kg Zn in three splits.

Jana *et al* (2009) conducted a field experiment to study the effect of zinc application on transplanted rice and observed that application of 30 to 40 kg $ZnSO_4$ ha^{-1} produced significantly higher growth attributes of rice. Maximum straw and grain yield was obtained when 10 kg Zn-EDTA ha^{-1} was applied in soil (Rana and Kashif 2014). Muamba and Ambara (2013) conducted experiment with three zinc doses (zero, 20 kg/ha, 30 kg/ha ZnSO4) and observed that grain yield was maximum when 30 kg $ZnSO_4$ ha^{-1} was applied. Significant increase in grain yield, straw and grain Zn content with foliar application of Zn as Zn-EDTA and $ZnSO_4$, but highest increase was observed with Zn-EDTA application (Rehman *et al* 2012).

Shivay *et al* (2012) conducted an experiment on the effect of Zn fertilization on yield attributes of rice. 2% Zn-coating with zinc sulfate ($ZnSO_4.7H_2O$) significantly increase partial factor productivity of applied Zn varied from 984-3387 kg grain kg Zn^{-1}, agronomic efficiency varied from 212-311 kg grain kg^{-1} Zn (applied) and physiological efficiency of Zn varied from 6,384-17, 077 kg grain kg^{-1} Zn (absorbed). Thus, adequate Zn fertilization of basmati rice can lead to higher grain yield and Zn-denser grains. Fageria *et al* (2011) conducted a pot house experiment with a objective of determining Zn requirements of rice and levels of Zn were 0, 5, 10, 20, 40, 80 and 120 mg Zn kg^{-1}. Maximum yield of grain was observed at 20 mg Zn kg^{-1} of soil. Tripathi and Tripathi (2004) observed significantly higher grain yield, straw yield, higher seed weight per panicle, panicle length, panicle weight, test weight and harvest index with the application of 30 kg $ZnSO_4$ ha^{-1}. Das *et al* (2004) reported a significant positive correlation (r=0.82**) between grain yield and Zn content in grain, suggesting an important role of Zn contributing towards yield of rice.

Islam *et al* (1989) studied the response of rice to Zn and observed significantly increased in dry matter yield of rice due to Zn application. Tiwari and Pathak (1976), Sakal *et al* (1993), Chaphale and Badole (1999) indicated that 1000-grain weight and highest grain per panicle was recorded with 15 kg Zn ha^{-1} ($ZnSO_4$) + recommended NPK dose (100:50:50) over absolute control and NPK dose alone.

Shanmugam and Veeraputhran (2000) studied that an application of 25 kg $ZnSO_4$ ha^{-1}, recorded significantly higher filled grains per panicle as compared to control. Tiwari (1996) studied the effect of zinc application on 8 winter season *rabi* crops viz, wheat, barley, chickpea, pea, lentil, oats, mustard and linseed and observed that zinc application at the rate of 15 kg $ZnSO_4$ ha^{-1}significantly increased grain yield of all the crops over control treatment. Mehla (1999) recorded highest grain and straw yield of rice by applying 5 kg Zn ha^{-1} to alternate crop of rice.

Increase in grain yield with Zn application has also been reported by Nambiar (1992), Agarwal and Bhan (1997) in rice-wheat cropping system. Singh *et al* (2002) reported that application of Zn at the rate of 5 kg ha^{-1} increased the grain yield to the extent of 40 per cent. Malavolta *et al* (2002) found that application of zinc at 0.065, 0.130 and 0.325 mg/l caused significantly differences in rice yield. The highest grain yield was obtained with treatment 0.065 mg Zn/l.

Zinc deficiency severely affects growth and yield of oilseed crop. Zn deficiency is common in semi-arid soils where sunflower cultivation is in practice by the farmers (Murthy 2011, Suresh *et al* 2013). Low solubility of Zn in soils rather than low total amount of Zn is the major reason for the widespread occurrence of Zn deficiency problem in crop plants. Shanmugasundaram and Savithri (2006) reported that the highest total dry matter yield of 66.7 t ha^{-1}in maize-sunflower cropping system produced with soil application of zinc sulphate @ 37.5 kg ha^{-1} to the first crop followed by 12.5 kg $ha^{-1}$$ZnSO_4$ to the second crop (sunflower) over control.

2.1.2 Nickel

Nickel is the latest element to be established as an essential nutrient for higher plants and plays a vital role in wide range of morphological and physiological functions including urea hydrolysis, nitrogen metabolism, nodulation and disease control. Most prevalent oxidation state of nickel is Ni^{+2}. In soils, its concentration varies from 3-1000 mg kg^{-1} soil (Kabata-Pendias 2000). Kansal *et al* (1996) reported that normal soils of Punjab contained 0.20 mg kg^{-1} DTPA-Ni which increased to 1.65 mg kg^{-1}in soils receiving industrial effluents. Normally its concentration in plants varies from 0.1 to 10 mg kg^{-1} dry matter (Mishra and Kar 1974). It is a component of urease enzyme which catalyses the hydrolysis of urea in soils. Nickel deficient plants accumulate toxic levels of urea (Wells 2005) and nickel deficiency results in chlorotic leaves followed by leaf tip necrosis. Nickel is essential micronutrient for legumes and possibly for higher plants. In leguminous plants its deficiency results in delayed nodulation and reduced efficiency of nitrogen fixation.

Ni was found to stimulate the growth of rice, soybean and tobacco in tissue cultures (Polacco 1977). Mishra and Kar (1974) studied that nickel is ubiquitous element in plant tissues and its concentration in plants vary from 0.1 to 5 mg kg^{-1} Dry weight. In some cases, low concentration of Ni has a beneficial effect on growth of species such as wheat, tomatoes, potatoes, cotton and paprika.

Singh (1994) reported that up to a level of 120 µg g^{-1} seed germination was normal but length of wheat coleoptile decreased with increasing Ni levels. On sandy soil chlorotic symptoms appeared first on 7^{th} day, while on clay loam soil symptoms surfaced on 14^{th} day. In sandy soils necrosis occurred and tillering was reduced at higher Ni levels. Maturity was delayed with increasing levels of Ni in both soils. He further reported that initial rate of Ni up to 5 and 10µg g^{-1}soil in sandy and clay loam soil respectively, had slight beneficial effect on wheat grain and straw yield. There was marginal depression in yield at 10 and 20 µg Ni, which reached to level of significance at 40 and 80 µg Ni g^{-1} of sandy and clay loam soil respectively. Singh *et al* (1990) reported that nitrogen in the form of urea increased toxic Ni influence by decreased content of Zn, Cu, Mn and Fe in shoots of wheat.

Total chlorophyll content and super oxide dismutase activity (SOD) in shoots of wheat did not change significantly after treatment with 10 µM Ni but when plants were exposed to 200 µM Ni, total chlorophyll was reduced due to toxic effect of Ni on enzyme activities (Gajewska *et al* 2006).

Wheat, fababeans and sorghum were grown on loamy soil treated with different levels of Ni in greenhouse experiment. Different levels of Ni were 15, 30, 45, 60 ppm, led to an obvious accumulation of Ni in plants and to a slight increase in dry matter production (Rabie *et al* 1992).

Narwal *et al* (1991) studied that dry matter yield of corn shoot decreased as the application of Ni to soil exceeded 50 mg kg^{-1} in clay loam soil and 25 mg kg^{-1} in sandy soils under green house conditions. Kumar (1992) observed that mean dry matter yield of maize shoot increased significantly initially from 18.33 g pot^{-1} in control to 19.86 g pot^{-1}, when Ni was added at a rate of 20 µg Ni g^{-1} to soils. But when rate of application of Ni was increased to 100 µg Ni g^{-1} soil, dry matter yield of root and shoot significantly decreased.

Narwal *et al* (1996) found that application of Ni up to 25 µg g^{-1} in sandy soil and 5 µg g^{-1} in clay soil caused increase in dry matter yield of corn. Gheibi *et al* (2011) studied both beneficial and adverse effects of various Ni level supplements on growth and chlorophyll content of corn plants. Various level of Ni were 0, 0.01, 0.05 and 0.1 mg l^{-1}. Leaf chlorophyll content and shoot and root fresh and dry weight of plants were determined. Both plant growth and chlorophyll content of plants increased significantly with increase in Ni content up to 0.1 mg l^{-1}. But with further increase in Ni level reduced the growth of plants.

Khurana *et al* (2011) conducted a pot experiment on a sandy loam soil. Ten levels of Ni (0, 5, 10, 20, 40, 80, 120, 160, 240, 320 mg kg^{-1} soil) were applied in a completely factorial randomized design. The dry matter yield of maize decreased with increasing levels of Ni but a significant decline in dry matter yield was observed beyond 20 mg kg^{-1} Ni.

Yang *et al* (1996) observed that dry matter of Maize and white clover plants increased slightly when grown at Ni level less than 60 µM, whereas dry matter of ryegrass and cabbage decreased significantly when plants were grown at similar Ni level. White clover had high dry matter at high Ni levels because of its low intake and translocation of Ni. At Ni levels <60 µM, maize had high dry matter because of its low translocation even though it had high intake of Ni. Ryegrass and cabbage was highly sensitive to Ni toxicity because of its high intake and translocation of Ni.

Nickel deficiency results in delayed nodulation and reduced efficiency of N fixation. Leguminous plants have a requirement for Ni. Ni fertilization might be needed particularly for leguminous crops such as grean bean and cowpea. Nickel may also stimulate plant disease resistance mechanisms, application of Ni to roots of cowpea, which contained only 0.03 mg kg^{-1} Ni dry weight, effectively reduced leaf-fungal infection by 50% (Brown 2006). In solution culture study, Eskew *et al* (1984) observed that 51.6% of leaflets of cowpea showed leaf tip necrosis in plants grown without nickel which was reduced to only 2.6% when 1µM Ni EDTA was present. Metawally and Rabie (1989) observed insignificant increase in dry matter yield of faba beans with 10-30ppm Ni application in calcareous soils.

Eskew *et al* (1984) studied Ni in higher plants by growing soybean in Ni deficient nutrient solution. Due to Ni deficiency there is accumulation of urea up to toxic concentration and due to accumulation of urea leaflet become necrotic. They further observed that seeds which contained 160 nanograms Ni had no leaflet tip necrosis symptoms.

Adrino (1986) suggested the possibility of stimulation of some metabolic rates at lower rates of Ni application. Insignificant dry matter yield increase in faba beans with 10-30 ppm Ni application in calcareous soils (Metwally and Rabie 1989). Narwal *et al* (1991), Kumar (1992), Wadhawan (1995) also observed similar beneficial effects of Ni rates below 50 mg kg^{-1} soil in maize.

Singh and Nayyar (1998) reported differential tolerance of the forage species to Ni toxicity and observed that forage crops belonging to gramineae family should not be grown in Ni contaminated soils. Brown *et al* (1987) observed critical concentration of 0.10 µg Ni g^{-1} for barley crop below which they seemed to be suffering from Ni deficiency in solution culture and observed that toxic concentration of crop vary from 25 to 50 µg g^{-1}. Brown *et al* (1987) reported that in barley grains containing less than 30 nanograms of Ni g^{-1} dry matter germination rate were reduced up to 50 per cent less than control and seedling vigour of viable grains was greatly depressed establishing essentiality of Ni in cereals.

Dry weight was highest in barley plants grown in 10 µM Ni, with a corresponding increase in the chlorophyll index of plants, suggesting that 10 µM Ni needs to be added to the nutrient solution for optimum growth of barley plants. Concentration of Zn in shoots and roots of plants decreased with increasing Ni supply in nutrient solution (Rahman *et al* 2005).

Paulik (1997) studied that when oats were grown at 0, 14, 28, 56, 84 and 168 µg Ni g^{-1} soil in green house experiment, grain yield increased significantly with 14-56 µg Ni g^{-1}, while 168 µg Ni g^{-1} soil resulted in plant mortality. Nickel has been reported as a growth stimulant as well as retardant for wide variety of plants. In some cases Nickel stimulates growth of plants but at lower concentration, whereas at higher concentration it has retarding effect.

Parida *et al* (2003) studied that leafy vegetables accumulate higher amount of Ni due to their more leafy vegetative growth. Therefore they applied different levels of Ni to assess the Ni accumulation pattern and its influence on growth and micronutrient distribution in fenugreek plants. Both green and dry matter yield of fenugreek increased slightly up to 20 g Ni kg^{-1} soil but it was decreased significantly with the application >40 mg Ni kg^{-1} soil. Growth and development of the crops grown with 10 and 20 mg Ni kg^{-1} soil was normal and slightly better than that grown in pots without Ni. However, growth of crops decreased above 40 mg Ni kg^{-1} soil.

The presence of Ni may stimulate the production of vegetables. A pot culture experiment was conducted at Department of Agricultural Chemistry and Soil Science, Agriculture College, Pune, during *rabi* season by Murthy (2004), with view to study heavy metals uptake and its effect on yield of carrot by using cadmium, lead, nickel and chromium levels @ 0, 2.5, 5, 7.5,10 and 12.5 mg kg^{-1}. The results indicated that the application of cadmium, nickel and chromium at higher levels (> 7.5 mg kg^{-1}) showed significant influence in the dry matter yield. The least shoot dry matter yield of carrot was observed in cadmium followed by chromium and nickel. However, highest reduction in root dry matter yield was recorded in chromium followed by nickel and cadmium. Effect of heavy metals on root growth revealed that application of cadmium at greater than 5 mg kg^{-1} decreased root length. However, nickel and chromium decreased the same at higher concentration (>7.5 mg kg^{-1}). Root girth was increased at higher concentrations (> 10 mg kg^{-1}) of heavy metals. Application of heavy metals had significantly influenced its uptake and nutrients. Nickel increased nitrogen content in carrot, chromium and nickel increased phosphorus uptake in plants. Chekai *et al* (1986) observed chlorosis of the youngest leaves and necrosis of meristems in Ni deficient tomatoes. The growth of lettuce and tomatoes was not affected adversely even when soil had 168 mg Ni kg^{-1} soil (Poulik 1999).

Nickel sufficient sunflower plants accumulated appreciable amounts of arginine, citrulline and orthine, which were not detectable in nickel deficient plants (Gerendas and Sattelmacher 1997). Gupta *et al* (2002) conducted a pot experiment using two soils i.e. sandy loam and clay loam and reported that increasing levels of nickel in both the soils decreased grain yield of raya (*Brassica juncea* L) except at 5 mg Ni kg^{-1}soil where increase in yield was recorded in sandy loam soil and in clay loam soil the increase in yield was observed up to 10 mg Ni kg^{-1} soil.

2.2 Interaction between zinc and nickel

Sarkunan *et al* (1989) have reported significant interaction effects of Zn-Cu-Ni on metal contents in rice. High levels of Ni may induce Zn or Cu deficiency because of cation competition. Singh *et al* (1990) observed that Ni had an antagonistic effect on N, Cu, Mn, Zn concentration of wheat. Singh (1994) observed that Ni had an antagonistic effect on the concentration and uptake of Zn by wheat and straw. This is due to antagonistic effect of Ni and Zn absorption due to competition at absorption sites on plant roots. Both Ni^{+2} and Zn^{+2} have similar ionic charge and possibly same carrier sites, and hence antagonistic effect of Ni on Zn in plants.

Antagonistic relationship between Ni and Zn and synergistic relationship between Ni and Fe in maize crop had been reported by Narwal *et al* (1991). Abdel-Sabour (1991) reported that Ni had synergistic effect on Zn, Cu and N uptake and antagonistic effect on Co uptake. Kumar (1992) observed a significant increase in the content of Ni, Fe and Mn and a significant decrease in Zn content of maize shoot and root with application of Ni. Copper content of shoot and root, however remained unaffected with Ni application. Naseem. *et al* (1986) reported that concentration of minerals (Na, K, Mg, Zn, Mn, Fe, Cu, Al, Mo, Pb) in cotton plants decreased in response to rising Ni rates in soil.

Khalid and Tinsely (1980), in glass house experiment by using non-calcareous acid soils, found that Ni concentration of ryegrass increased but Zn concentration was decreased with increasing level of Ni from 0 to 270 µg g^{-1}soil. The uptake of Mn and Zn decreased at all levels of applied Ni. Cataldo *et al* (1978) observed that the absorption of Ni by soybean was inhibited by Zn.

Palacious *et al* (1998) observed that high concentration of Ni significantly decreased the uptake of other divalent cations such as Mg^{+2}, Fe^{+2}, Mn^{+2}, Cu^{+2} and Zn^{+2}. Adsorption of Ni by soybean intact plant and its transfer from root to shoots was inhibited by presence of Zn due to competition kinetics. It was studied that presence of Zn inhibit Ni absorption competitively, suggesting that Ni and Zn are adsorbed using the same carrier sites.

Rahman *et al* (2005) reported that concentration of Zn and Mn in shoots and roots of barley decreased with increasing supply of Ni in the nutrient solution. Parida *et al* (2003) reported that excess of Ni in soil reduced the content of Cu and Zn in fenugreek.

Jain *et al* (2000) reported that application of 50 and 100 ppm Ni in soil decreased the micronutrient concentrations (Fe, Mn, Zn and Cu) of sugarcane, as compared to control. They concluded that this might be due to the inhibitory effect of nickel on sugarcane root growth and destruction of the integrity of the root meristems which led to alterations in mineral nutrition.

Wood *et al* (2004) observed Ni deficiency in soil due to an excessive amount of Zn in soil because Zn has inhibition effect on Ni. Nickel deficiency could be either due to low levels of available Ni in soils or due to high contents of Ca, Mg, Cu or Zn (Wells 2005). Elements can interact either synergistically or antagonistically in plant nutrition (Mishra and Kar 1974).

2.3 Transformation of zinc and nickel in various chemical pools in soils

Sequential extraction or fractionation of zinc from soils is a useful technique for determining chemical forms of zinc in soil system. Such information is potentially valuable in predicting bio availability, leaching and transformation between chemical forms in agricultural soils (Lake *et al* 1984). Several sequential extraction methods have been proposed to partition zinc in to fractions defined as soluble, exchangeable, adsorbed, organically bound, precipitated, oxide bound, occluded and residual, and to correlate zinc in these fractions with plant concentration or uptake (Iyengar *et al* 1981, Mandal and Mandal 1986, Murthy 1982, Murthy and Shoen 1987). Sposito *et al* (1982) while indicating the chemical specification of metals in soils, placed emphasis on identification of extractable forms that could be consistently correlated with metal uptake or plant growth. The availability of zinc to plants has been observed to vary with different zinc fractions. About five or less than 5 per cent of total zinc present in soil is available to the plants at any given time.

The knowledge regarding distribution of zinc fractions in soils helps in understanding the contribution of individual zinc fraction to plant availability (Iyenger *et al* 1981). Since the available zinc is in dynamic equilibrium with the zinc present in different pools in soils, the knowledge of distribution of zinc fraction in soils helps in understanding the contribution of individual zinc to plant availability.

Murthy (1982) distinguished four zinc fractions in wetland rice soils and observed that zinc in soluble organic complexes and exchange positions was of major importance in maintaining a zinc level sufficient for wetland rice. Studies by Mandal and Mandal (1986) revealed that in rice soils more than 90 per cent of the total zinc was in clay lattice bound form which was relatively inactive and only small fraction of total zinc was in water-soluble + exchangeable (0.26%), organically complexed (0.74%) amorphous sesquioxide bound (1.58%), crystalline sesquioxide bound (0.71%) forms.

Zn application increased the concentration of different fraction of Zn in the order : exchangeable < complexed < crystalline sesquioxide bound Zn < amorphous sesquioxide bound Zn fraction, as the exchangeable and amorphous sesquioxide bound Zn fraction contribute significantly towards the uptake of Zn by rice than other fractions (Singh and Abrol 1986). Edward Raja and Iyenger (1986) observed that about 86.90 per cent of native Zn was present in the residual fraction. The amount of Zn in other fractions was in the order: Sparingly soluble > Acid soluble > organically bound > complexed > exchangeable + water soluble.

Prasad *et al* (1990) conducted a field experiment to study transformation and availability of applied Zn in calcareous soil treated with organic material. Most of the Zn existed as residual Zn (41%) of total Zn and organically complexed Zn fractions (3%) in calcareous soil treated with organic materials. Agbenin (2003) studied the size of Zn pools in a Savanna soil. Total Zn ranged from 38 to 63 mg kg^{-1} in the natural site and from 28 to 57 mg kg^{-1} in the cultivated fields. For the natural site, residual zinc accounted for 48 per cent of total Zn, whereas, Mn-oxide bound Zn accounted for between 40 per cent and 61 per cent of the total zinc in the cultivated fields.

The distribution of soil Zn into different fractions indicated that most of the total Zn remains in residual form and the quantity in plant usable forms like water soluble + exchangeable Zn (0.41 to 0.64 mg kg^{-1}), Complexed Zn (2.31 to 2.72 mg kg^{-1}) and organic form (0.87 to 1.52 mg kg^{-1}) was very low. The order of dominancy of different fractions in soil was residual Zn > crystalline sesquioxide Zn > inorganic complexed Zn > amorphous sesquioxide bound Zn > organically bound Zn > water soluble + exchangeable Zn (Umesh 2004).

The distribution of native and applied Zn into different fraction indicated that most of the total Zn remains in residual form and the quantity in plant usable form like water soluble + exchangeable, complexed and organic form was very low which were about 0.27 to 0.69, 1.21 to 1.51 and 0.54 to 0.92 per cent, respectively. The order of dominancy of different fractions in soil was: residual Zn > crystalline sesquioxide bound Zn > inorganic complexed Zn > organically bound Zn > water soluble plus exchangeable Zn > amorphous sesquioxide bound Zn. Mutual transformation of water soluble plus exchangeable Zn, organically bound Zn, crystalline sesquioxide bound Zn and residual Zn seem to be dominant for maintaining Zn equilibria in soil (Kumari 2003).

Xiaorong *et al* (2005) studied the fractions and availability of zinc in the loess plateau, China using sequential extraction. Result revealed Zn accumulation in soil. The mineral bound Zn accounted for 95.57- 99.11 per cent of the total Zn while organic matter loosely bounded Zn accounted for 0.82-3.58 per cent of the total Zn. Results indicated that most Zn in the soil were considered as minerals, while few were included into the soil solution or combined with soil organic matter, carbonate or manganese oxides.

Laboratory and greenhouse experiments were conducted by Mandal *et al* (1986) with two soils viz., laterite and alluvial to study the transformation of applied Zn in soil fractions under submerged condition. The transformation of applied Zn in different fractions in soils showed that a major portion (53.6–72.6%) of it found its way to mineral fractions leaving only 1.0–3.3, 6.6–18.9, 11.0–21.6 and 2.3–8.8% of the applied amounts in water soluble plus exchangeable, organic complexed, amorphous sesquioxides and crystalline sesquioxides bound fractions respectively.

Hazra *et al* (1987) studied the distribution of different forms of zinc in 16 acidic alluvial rice growing soils in terai region of West Bengal, India. The results showed that more than 84 per cent of total zinc occurred in the relative inactive clay lattice-bound form while a smaller fraction viz., 1.1, 1.6, 11.1 and 2.0 % of the total occurred as water – soluble plus exchangeable, organic complexed, amorphous sesquioxide-bound and crystalline sesquioxide bound forms, respectively.

Pal *et al* (1997) reported from rice-growing areas of Orissa that total zinc ranged from 157 to 237 mg kg^{-1} soil was fractioned into water soluble plus exchangeable (WSEX-Zn), organic complexed (OC-Zn), amorphous sesquioxide (AMOX-Zn), crystalline sesquioxide (CRYOX-Zn) and residual zinc. The last fraction constituted highest percentage (94.0%) of the total Zn.

Singh *et al* (1999) conducted a laboratory incubation and green house experiment to study the transformation of zinc in wetland rice soils in different locations of wetland rice soils viz., Bhoilymbong (S-1), Lawbah (S-2), Upper Shillong (S-3), Summer (S-4), Umshing (S-5) and Mukhal (S-6) in the state of Meghalaya in relation to nutrition of rice crop and the study reported that the distribution of zinc fraction in soils showed that 65.6 to 76.6 per cent of total zinc remains in residual forms. While 1.12 to 2.73, 2.17 to 3.93, 3.08 to 5.31, 4.07 to 6.64 and 12.30 to 19.50 per cent remain in water soluble plus exchangeable, organically complexed, manganese oxide, amorphous sesquioxides and crystalline sesquioxide bound form, respectively.

.Singhal and Rattan (1995) studied the distribution of various fractions of soil zinc in ten alluvial soils from Haryana and Delhi. Fractions of soil samples showed that zinc in water soluble and exchangeable pools (Zn-CA) was virtually non-existent, major portion of the total zinc in the soils existed in the form of zinc specifically adsorbed to clays (Zn- AAC), organically bound (Zn-PYR), occluded by free oxides (Zn-OX) and residual zinc (Zn-RES) fractions. The last fractions constitutes higher percentage of total zinc.

Elsokkary (1979) chemically fractionated the Zn contents of alluvial soils from Egypt into water soluble + exchangeable, weakly bound to inorganic sites, organically bound, occluded as free oxide material, and residual materials in the mineral structure. On an average these fractions constituted about 0.01, 1.20, 28.6, 21.5 and 45.5 % of the total Zn respectively which averaged 76.25 ppm.

Dhane and Shukla (1995) studied the distribution of different forms of zinc in benchmark and other established soil series of Maharashtra. On an average, water soluble, exchangeable, specifically adsorbed, acid soluble, Mn-occluded, organic matter-occluded, amorphous Fe-occluded, crystalline Fe-occluded fractions of zinc contributed very little whereas the residual fraction of zinc was a dominant constituent (95.9%) in these soils.

Wei *et al* (2005) studied and found that from a 17-year study indicated that most of the fertilizer Zn applied to a calcareous soil at wheat sowing was bound to soil minerals at harvest. Only a small fraction of the fertilizer Zn was in the soil solution or bound to organic matter, carbonates, or Mn oxides.

Chirwa and Yerokun (2012) defined five mechanistic Zn pools in 11 cultivated agricultural soils of Zambian and their uncultivated pairs. A batch extraction scheme was used to estimate exchangeable (Ex-Zn), carbonate (CO3-Zn), organic (Org-Zn), sesquioxide (Ox-Zn) and residual (Res-Zn) Zn pools in each soil. Total Zn was calculated as a sum of the pools and it ranged from 13.11 to 108.02 mg kg^{-1} with an average of 52.26 mg kg^{-1}. The distribution of Zn in the soils on the basis of average concentrations was in the order 22.99 mg kg^{-1} Ox-Zn (44%)>14.97 mg kg^{-1} Res-Zn (29%)>7.51 mg kg^{-1} CO_3- Zn (14%)>4.81 mg kg^{-1} Org-Zn (9%)>1.98 mg kg^{-1} Ex-Zn (4%). Cultivation depressed Tot-Zn and Ex-Zn concentrations in several of the soils.

Zhenbin Li *et al* (1996) conducted a green house experiment, soil samples were fractionated into exchangeable (EXC), organic matter (OM), Mn oxide (MNO), amorphous Fe oxide (AFEO), crystalline Fe oxide (CFEO), and residual (RES) fractions. The added Zn was distributed among all fraction in soils, but added Cd and Ni were found predominantly in the EXC and OM fractions and also some of the added Ni occur in RES fraction

A pot experiment was conducted by Barman *et al* (2015) to assess the contribution of soil Ni fraction to plant uptake using soybean as a test crop. Fifteen bulk surface (0-15) soil samples were collected from cultivated fields of north western Indo-Gangetic alluvial plains. Results showed that residual Ni was the most dominant fraction in soil constituting 3.19–63.6% of total Ni. The water soluble plus exchangeable Ni accounted for only 0.70–4.04% of total soil Ni. Organically bound Ni varied from 1.60–6.85% of total Ni; these values are relatively lower as compared to those reported for temperate soils.

Narwal and Singh (1998) studied that Ni was present in small quantities in exchangeable fraction and nickel and Zn mainly found in residual fraction. Wang and Qu (1992) reported the distribution of chemical forms of Ni in manured loessial soil. Results showed that Ni was mainly in residual form, second dominant form Fe oxide bound third organic matter or carbonates and exchangeable was very less.

Ma and Rao (1997) reported that residual fraction was the most abundant pool for Cd, Cu, Ni and Zn in nine contaminated soils. With the increase of total Ni concentration in soils, a decreasing trend in exchangeable and increasing trend in residual fraction was observed.

2.4 Activity of urease in soils as influenced by zinc and nickel fertilization

Barcelos *et al* (2017) studied that Ni is a cofactor of urease enzyme and play a critical role in germination of seeds and assess the effect of foliar Ni application on mineral nutrition status, urease activity and the physiological quality of soybean seeds. The study was conducted by using many levels of Ni (0, 10, 20, 40, 60, 80 and 100 g ha^{-1}) and observed that Urease activity increased proportionally up to 20 g ha^{-1}, with peak activity between 20 and 40 g ha^{-1} of Ni. Also Seed germination and emergence rate increased proportionally with Ni application.

Oleivera *et al* (2013) studied that nickel is a micronutrient involved in nitrogen metabolism and a component of the urease molecule. Plant growth and urease activity were estimated in lettuce (*Lactuca sativa* L.) grown in soil-filled pots in a 2 x 8 factorial design with two nitrogen (N) sources and eight Ni rates, with five replications. Nitrogen was applied at 200 mg/l using the sources NH_4NO_3 (AN) and $CO(NH_2)_2$ (Ur). The Ni treatments (0, 2, 4, 8, 12, 16, 24 and 32 mg kg^{-1}) were applied as $NiCl_2$. Leaf urease activity was determined. Regardless of the N source leaf urease activity increased with Ni application.

Gerendas and Sattelmacher (1998) studied that Nickel is considered to be an essential micronutrient in plants because of its role in the metalloenzyme urease. In order to illustrate the metabolic con-sequences of Ni deficiency, the importance of Ni supply was evaluated for growth and N metabolism of rice plants. Results showed that urease activity was not measureable in leaves of Ni deprived plants, which in conjunction with arginase led to the accumulation of urea in plants due to the lack of urease activity.

Gerendas and Sattelmacher (1997) studied the effect of Ni supply on growth, N metabolism and leaf urease activity of six plant species (wheat, soybean, sunflower, rye, rape, zucchini). Urease activity is activated by Ni. Ni deficient plants accumulated considerable amount of urea which showed reduced dry matter production and reduced nitrogen concentration. Inadequate Ni supply reduced the soluble amino acid concentration.

Alibakhshi and Khoshgoftarmanesh (2014) examined the effects of Ni on urea metabolism and growth of two onion cultivars (Allium cepa L., cvs. Dorrcheh and Cebolla Valenciana) supplied with urea as nitrogen source. Three levels of Ni (0, 25, and 50 µM) were used in the form of $NiCl_2$. Addition of Ni positively affected nitrogen metabolism in onion plants fed with urea and thus was correlated with increase of the bulb yield. Irrespective of the plant cultivar an increase in urease activity and reduction in bulb urea concentration was observed by Ni nutrition.

Effect of heavy metal pollution on enzymatic activity of soils was investigated by Ofoegbu *et al* (2013). Activity of urease, hydrogen peroxidase, polyphenyl oxidase, soil dehydrogenase, alkaline and acid phosphatases was measured. Results indicated that the activities of urease, hydrogen peroxidase polyphenyl oxidase, soil dehydrogenase, alkaline and acid phosphatases showed significant negative correlation ($P<0.05$) with increase in heavy metal contents. This showed that analysis of activity of enzyme could be used as a indicator of heavy metal contamination.

Vaisvalavicius *et al* (2006) conducted an experiment in order to measure the functional diversity changes of soil microbial populations and enzymatic activity under the conditions of critical heavy metals (Pb, Zn and Cu) accumulation. High concentration of heavy metals was detected, total content of Pb, Cu and Zn reached up to 839,773 and 844 mg kg^{-1} respectively. This high contamination level of heavy metals reduced the counts of all investigated microbial groups and significantly lowered enzymatic activity when compared to uncontaminated soil. Decrease of enzyme activity was found to be in this descending order: Dehydrogense (95-98%), Urease (65-97%), Saccharase (57-77%) as compared with natural soil.

Balyaeva *et al* (2005) studied the effect of increasing rates of Pb, Zn and Cu on the activities of urease, catalase, acid phosphatase and invertase in two soils in a two-year greenhouse experiment. Increasing rates of all these metals caused a decrease in basal respiration rate. In second year, degree of inhibition was generally more than the first year. After first year of incubation, enzyme activities were reduced with increasing rates of addition of metals. But after two year, the pattern of response was more complicated because enzyme activities were increased at lower rate of addition of metals. Results showed that invertase and urease activities were greatly inhibited by heavy metal contamination than those of catalase and phosphatases. Evans *et al* (1991) reported that urease function and production depend upon availability of Ni.

Sethi and Gupta (2015) studied the effects of heavy metals pollution on soil enzymes such as urease, cellulose, protease, invertase, dehydrogenase, alkaline phosphatases, beta glucosidase and amylase. Results showed that urease and catalase activities were mostly inhibited by Zn application. Kumar *et al* (2016) conducted a pot house experiment to study the response of urease to soil application of Ni. There were ten treatments of Ni (0, 2.5, 5, 10, 15, 20, 30, 40, 50 and 60 mg kg^{-1}) and maximum urease activity was noticed with application of 40 mg Ni kg^{-1} soil. Tabatabai (1976) studied the effect of trace element on urease activity in soil and found that all the trace element such as Zn^{+2}, Cu^{+2}, Hg^{+2}, Ni^{+2}, Al^{+3} etc. inhibit the activity of urease in soil

Effron *et al* (2004) found that heavy metals inhibited the activities of urease, acid phosphatase, protease and arylsulfatase. Hemida *et al* (1997) found that urease activity completely extinct at 2000 mg heavy metals (Cu^{+2} and Zn^{+2}) g^{-1} soil. Wyszkowska *et al* (2007) concluded that concentration of 50 mg kg^{-1} of metals (Cu, Zn, Ni, Pb, Cd and Cr) inhibited soil enzyme activities (those of urease, dehydrogenase, acid phosphatase and alkaline phosphatase). Mikanova (2006) studied the effects of heavy metals on the enzyme activities (urease, arylsulfatase, invertase and dehydrogenase) of heavy metal polluted alluvial soils. Increasing the heavy metal concentration inhibited all of the soil enzymes studied.

Yang *et al* (2006) investigated the combined effects of cadmium (Cd), zinc (Zn) and lead (Pb) on activities of four enzymes in soil, including catalase, urease, invertase and alkaline phosphatase. HM content in tops of canola and four enzymes activities in soil were analysed at two months after the metal additions to the soil. Zn only inhibited urease and catalase activities. The inhibiting effect of Cd and Zn on urease and catalase activities can be intensified significantly by the additions of Zn and Cd. The urease activity was inhibited more by the HM combinations than by the metals alone and reduced approximately 20%-40% of urease activity. It is concluded that the soil urease activity may be a sensitive tool for assessing additive toxic combination effect on soil biochemical parameters.

CHAPTER III

MATERIAL AND METHODS

To achieve the objectives of this investigation following studies were undertaken

3.1 Pot culture studies

3.2 Laboratory studies

3.1 Pot culture studies

To study the interactive effects of Zinc and Nickel on growth and nutrition of rice

3.1.1 Collection of soil samples

Two bulk surface (0-15 cm) soil samples were used for the conduct of the pot experiment. One of the soil samples was collected from Krishi Vigyan Kendra, Bahowal, District Hoshiarpur and the other was collected from the farm area of Department of Soil Science, Punjab Agricultural University, Ludhiana. The soil samples were classified as Typic Ustipssaments and Typic Haplustept, respectively. The important physico-chemical characteristics of soils used in the study is given in Table 3.1.

3.1.2 Pot culture experiment was conducted with the following treatments

Zinc levels	:	0, 2.5, 5, 10, 20, 40 and 80 ppm Zn
Nickel levels	:	0, 2.5, 5, 10, 20 and 40 ppm Ni
Replications	:	3
Soils	:	2
Total number of pots	:	7x 6 x 3 x 2 = 252
Experimental design	:	Completely randomised design

3.1.2 Preparation of soil sample

The bulk soil samples were air dried under shade and ground by using a wooden pestle and mortar to pass through 2 mm sieve. A pot culture experiment was conducted in a screen house by growing rice as a test crop. Each polyethylene lined plastic pot of 10 kg capacity was filled with 8 kg of soil. Zinc was applied @ 0, 2.5, 5, 10, 20,40 and 80 mg Zn kg^{-1} soil through AR grade zinc sulfate and Ni was applied @ 0, 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil through AR grade nickel chloride in solution form in 42 possible combinations. The treatments were replicated thrice and in all there were 252 pots. Treatments were randomized in a Complete Randomized Design. Basal application of 25 mg N kg^{-1} soil was made through AR grade Urea. Five seedlings of rice (cv PR126) were sown on 2nd July, 2017. Besides a pre sowing irrigation, pots were regularly watered with water as and when required.

Table 3.1: Physico-chemical characteristics of experimental soils

Soil characteristic	Soil I (KVK Bahowal)					Soil II (PAU Farm)				
pH (1:2)	7.9					8.1				
EC (1:2) (dS m^{-1})	0.25					0.35				
Particle size distribution										
Sand (%)	82.00					73.5				
Silt (%)	4.5					13.5				
Clay (%)	13.5					13.0				
Textural class	Loamy sand					Sandy loam				
Calcium carbonate (%)	0.13					nil				
Organic carbon (%)	0.15					0.32				
Available P (kg ha^{-1})	9.74					13.35				
Available K_2O (kg ha^{-1})	205					213				
Micronutrients	Zn	Ni	Cu	Fe	Mn	Zn	Ni	Cu	Fe	Mn
DTPA-extractable (mg kg^{-1}soil)	1.1	0.19	0.18	3.20	2.65	1.20	0.46	1.05	51.6	4.15

Chemical pools of Zn (mg kg^{-1}soil)

	EXCH	SAD	MnOX	AMPOX	CRYOX	OM	RESIDUAL
Loamy sand (KVK Bahowal)	0.05	0.16	0.77	3.41	16.6	3.67	30.3
Sandy loam (PAU Farm)	0.08	0.23	0.82	3.75	17.1	4.12	28.8

Chemical pools of Ni (mg kg^{-1}soil)

	EXCH	SAD	MnOX	AMPOX	CRYOX	OM	RESIDUAL
Loamy sand (KVK Bahowal)	0.05	0.10	0.28	1.48	1.56	1.69	6.04
Sandy loam (PAU Farm)	0.09	0.15	0.30	1.75	1.70	1.97	6.84

EXCH = Exchangeable; SAD = Specifically adsorbed; MnOX= Manganese oxides bound; AMPOX = Amorphous iron and aluminum oxides bound; CRYOX = Crystalline iron and aluminum oxides bound; OM = Organically bound.

3.1.3 Harvesting

The crop was harvested at maturity. The data on grain and straw yield per pot was recorded. After harvesting soil samples were collected from each pot and also roots were extracted. The plant samples were washed thoroughly in succession with tap water, 0.01 N HCl and deionized water followed by air drying and oven drying at 65^{o}C to constant weight. The dried root and straw samples were ground in a willey mill having stainless steel blades to pass through 40 mesh sieve. Ground samples were stored in paper bags for chemical analysis. The soil samples collected after the harvest of crop were air dried, processed and stored in polyethylene bags for chemical analysis.

Table 3.2: Sequential extraction procedure for micronutrients cations in soil samples

Fraction	**Reagent**	**Soil: Extractant ratio**	**Conditions**	**Reference**
WS+ Exchangeable	0.005M Pb $(NO_3)_2$ (pH 6.8)	5: 20	Shake 15 minutes	Manchanda *et al* (2006)
Specifically adsorbed	0.05M $Pb(NO_3)_2$ (pH 6.0)	5: 20	Shake 2 hrs.	Iwasaki *et al* (1993)
Manganese oxides bound	0.1M $NH_2OH.HCl$ in 0.01 M HNO_3 (pH 2.2)	5: 20	Shake 30 minutes	Chao (1972)
Amorphous Fe and Al oxides bound	0.25 M NH2OH.HCl + 0.25 M HCl (pH 1.3)	5: 20	Shake 30 minutes at 50^{o} C	Chao and Zhou (1983)
Crystalline Fe and Al oxides bound	0.25 M $NH_2OH.HCl$ + 0.25 M HCl + 0.1 M Ascorbic acid (pH 1.21)	5: 20	Heating with boiling water (100^{o} C) in a beaker paced on hot plate for 30 minutes	Manchanda *et al* (2006)
Organically bound	1 % $Na_4P_2O_7$	5 : 20	Shake 1 hr	Raja and Iyengar (1986)
Residual	Total minus sum of all fractions			
Total	HNO_3: $HClO_4$ digestion			Hesse (1971)

3.2 Laboratory studies

To study the effect of applied Ni and Zn on various chemical pools Soil samples collected after the harvest of crop at maturity in the above pot experiment were analysed for various chemical pools of zinc and nickel as per details given in Table 3.2.

3.2.1 Sequential fractionation of soils for various pools of micronutrients

3.2.1.1 Exchangeable fraction (EXCH)

5 g of each soil sample was weighed in 50 ml centrifuge tube and 20 ml 0.005M $Pb(NO_3)_2$ (pH 6.8) was added, stoppered and shaken for 15 minutes. After shaking, centrifugation was done at 10000 g and the extract was filtered.

3.2.1.2 Specifically Adsorbed (SAD)

The soil left in the centrifuge tube after extraction of EXCH fraction was stirred with glass rod and 20 ml of 0.05M $Pb(NO_3)_2$ (pH 6.0) was added and shaken for 2 hours, centrifuged and filtered.

3.2.1.3 Manganese oxide bound fraction (MnOX)

The soil left in the centrifuge tube after the extraction of SAD fraction was stirred with glass rod and was added 20ml 0.1M $NH_2OH.HCI$ in 0.01M HNO_3 (pH 2.2) and shaken for 30 minutes, centrifuged and filtered.

3.2.1.4 Amorphous Fe & Al oxides bound (AMPOX)

The soil left in the centrifuge tube after extraction of MnOX fraction was stirred with glass rod and was added 20 ml 0.25M $NH_2OH.HCl$ + 0.25M HCl (pH 1.3) and shaken for 30 minutes at 50°C, centrifuged and filtered

3.2.1.5 Crystalline Fe & Al oxides bound (CRYOX)

The soil left in the centrifuge tube after extraction of AMPOX fraction was stirred with glass rod and was added 20ml 0.25M $NH_2OH.HCl$ + 0.25M HCl + 0.1M ascorbic acid (pH 1.21) and heated for 30 minutes in boiling water (100^o C) in a beaker placed on hot plate, centrifuged and filtered.

3.2.1.6 Organically bound fraction (OM)

The soil left in the centrifuge tube after extraction of CRYOX fraction was stirred with glass rod and was added 20 ml 1% $Na_4P_2O_7$ and shaken for 1 hour, centrifuged and filtered. The extracts were digested in diacid, made to known volume and filtered before feeding to atomic absorption spectrophotometer.

3.2.1.7 Residual mineral fraction (RES)

Residual mineral fraction was obtained by subtracting the sum total of all the above fractions from the total fraction.

3.2.1.8 Total fraction

Total fraction was determined by digesting 0.5 g soil with diacid $HClO_4$: HNO_3 (1:3) mixture as described by Hesse (1971). Zinc and nickel in all the above extracts were determined by atomic absorption spectrophotometer.

3.3 Analytical Methods

3.3.1 Soil analysis

3.3.1.1 Soil reaction

1:2 soil water suspension was used to determine soil pH by using digital pH mater.

3.3.1.2 Electrical Conductivity

Electrical conductivity of 1:2 soil water supernatant solution was measured by digital conductivity meter after keeping soil samples overnight for settling soil particles.

3.3.1.3 Available Zn, Ni, Fe, Mn, Cu

Available Zn, Ni, Fe, Mn, Cu in soils was determined by using 0.005M DTPA-CaCl2 (pH 7.3) following the procedure given by Lindsay and Norvell (1978).

3.3.1.4 Available P

Available P in soil was determined by the method of Olsen *et al* (1954).

3.3.1.5 Organic Carbon

Organic Carbon was determined by Walkley and Black's rapid titration method (1934).

3.3.1.6 Calcium carbonate

Calcium carbonate was determined by Puri's rapid titration method (1950).

3.3.1.7 Soil texture

Soil texture was determined by using International Pipette method as described by Piper (1950).

3.4 Plant analysis

Half g of the ground root/straw and 1.0 g of rice grain sample was digested in a di-acid mixture of distilled HNO_3: $HClO_4$ (3:1). The digested plant material was transferred to 25 ml volumetric flask and volume was made with deionized water, filtered through Whatman No.1 filter paper.

3.4.1 Determination of micronutrients in plant extracts

Micronutrients in plant extracts were determined by atomic absorption spectrophotometer.

3.4.2 Enzyme analysis

3.4.2.1 Reagents

i. Urea solution (2000 µg/ml): Add 2 g of urea (AR grade) in 1000 ml of distilled water.
ii. Phenylmercuric acetate (PMA) solution: Dissolve 50 mg of PMA in one litre of distilled water.
iii. Potassium chloride PMA solution (2M KCl-PMA):Dissolve 150 g KCl (Reagent grade) in 900 ml of distilled water, and then add 100 ml of PMA to make one litre.
iv. Diacetyl Monoxime solution (DAM): Dissolve 2.5 g of DAM in 100 ml of distilled water and make the volume to half litre with distilled water.

v. Acid reagent: Add 300 ml of 85% phosphoric acid and 10 ml of concentrated H_2SO_4 to 100 ml of distilled water and make volume to half litre with distilled water.

vi. Thiosemicarbazide (TSC): Dissolve 0.25 g TSC in 100 ml of distilled water.

vii. Coloring reagent: It is prepared immediately before use by adding 12.5 ml of DAM solution and 5 ml of TSC solution to 250 ml of acid reagent.

viii. Standard urea solution (for preparation of standard curve): Dissolve 250 g of urea in about 700 ml 2M KCl-PMA solution and dilute to one litre.

3.4.2.2 Determination of urease activity

Urease activity (EC 3.5.1.5) was assayed by the method of Douglas and Bremner (1970). 2.5 g soil was placed in 150 ml volumetric flask to which 2.5 ml of 2000 ppm urea solution was added and incubated at 37^0C for 5 hours. After 5 hours 25 ml of 2 M KCl-PMA solution was added to the flask and shaken for 1 hour in an electrical shaker. The soil suspension is then filtered. 1 ml of this filtrate was taken in a 25 ml volumetric flask. Then 5 ml of extracting reagent and 15 ml of colouring reagent were added to the volumetric flask and placed it in a boiling water bath for 30 minutes. After cooling down to room temperature final volume is made to 25 ml and intensity of red colour developed was determined at 527 nm on spectrophotometer.

3.5 Statistical analysis

The experimental data of pot experiment was analysed as per Completely Randomized Design by using SPSS software. The data was also subjected to linear correlations analysis to establish the relationship between soil and plant parameters.

Relative yield was calculated by using the formula $Y_0Y_t^{-1}$ *100 in which Y_0 is yield from untreated plot and Y_t is the yield from treated plot.

Relative yield (Y) and DTPA-Zn/Ni in soil or concentration of Zn/Ni in plant parts (X) was employed for evaluation of quadratic and Mitscherlich equation for estimation of upper and lower critical concentration of Zn/Ni in soils and plant parts, respectively, as under:

Quadratic $Y= b_0 + b_1X + b_2X^2$

Where 'Y' is the relative yield and 'X' is the Zn/Ni content in soil or plant parts.

Concentration of Zn/Ni in soil and plant parts were calculated by solving Mitscherlich equation $Y= \beta(1-\gamma e^{-\alpha x})$ where 'β' is the asymptotic maximum yield as 'x' approaches infinity, 'γ' is equal to $(\beta-y_0)\beta^{-1}$ in which y_0 is the yield when 'x' is zero and 'α' is the proportionality constant.

Critical levels (x) of Zn/Ni in soils/plants for 90 per cent of maximum yield were calculated by using following equation as suggested by Ware *et al* (1982)

$x = -\ln(0.1/\gamma)/\alpha$

α, β and γ were estimated from the observed data

CHAPTER IV

RESULTS AND DISCUSSION

The results of present investigation are presented and discussed under the following headings:

4.1 Interactive effects of Zn and Ni application on their availability and transformation in soils.

4.2 Interactive effects of Zn and Ni application on root dry matter, grain and straw yield.

4.3 Interactive effects of Zn and Ni application on their concentration in root, grain and straw

4.4 Interactive effects Zn and Ni application on their uptake by root, grain and straw.

4.5 Interactive effects of Zn and Ni application on activity of urease in soil at maximum tillering and harvesting stage.

4.1 Interactive effects of Zn and Ni application on their availability and transformation in soils

The data on the effect of Zn and Ni application on transformation and availability of Zn in soils is presented in Table 4.1 to 4.10 and figures 4.1 and 4.2.

4.1.1 DTPA-Zn

Table 4.1: Effect of Zn and Ni on DTPA-extractable Zn

Levels of Zn (mg kg^{-1} soil)	DTPA-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	1.00	0.96	0.84	0.69	0.67	0.51	0.78
2.5	1.52	1.33	1.07	0.83	0.71	0.63	1.01
5	1.99	1.79	1.61	1.59	1.46	1.05	1.58
10	2.75	2.62	2.38	2.25	2.29	1.92	2.37
20	3.67	3.33	2.56	2.45	2.30	2.03	2.72
40	5.23	4.18	4.00	3.48	2.97	2.95	3.80
80	8.67	6.37	5.52	5.13	4.85	4.77	5.88
Mean	3.55	2.94	2.57	2.35	2.18	1.98	
CD (5%)	Zn- 0.14			Ni- 0.13		Zn x Ni- 0.35	
Sandy loam							
0	1.20	1.15	1.19	1.00	0.85	0.79	1.03
2.5	1.86	1.39	1.33	1.28	1.20	1.16	1.37
5	2.13	2.05	2.02	1.77	1.76	1.40	1.85
10	3.06	2.60	2.28	2.16	2.07	1.47	2.27
20	4.23	4.20	3.76	3.51	3.21	2.15	3.51
40	8.35	7.72	7.11	6.10	4.40	3.54	6.20
80	12.46	12.41	11.53	11.10	10.89	8.24	11.10
Mean	4.76	4.50	4.17	3.84	3.48	2.68	
CD (5%)	Zn- 0.05			Ni- 0.04		Zn x Ni- 0.12	

Application of zinc significantly increased mean DTPA-Zn from 0.78 mg kg^{-1} soil in control to 5.88 mg kg^{-1} soil in loamy sand and from 1.03 mg kg^{-1} soil in control to 11.10 mg kg^{-1} soil in sandy loam with the highest level of applied zinc (Table 4.1, Fig. 4.1a, b). The extractability of Zn increased by 0.29, 1.02, 2.03, 2.48, 3.87 and 6.53 times that of control in loamy sand and by 0.33, 0.79, 1.20, 2.41, 5.02 and 9.77 times only in sandy loam when 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil was applied, respectively. A positive linear relationship of applied Zn with DTPA-Zn in loamy sand (Fig.4.1a, R^2=0.96) indicated that DTPA-Zn increased with increasing levels of applied Zn. Similar trend was observed in sandy loam (Fig.4.1b, R^2=0.99).

Mean DTPA-Zn in both the soils decreased with increasing levels of applied nickel (Table 4.1, Fig. 4.1c, d). In loamy sand, DTPA-Zn decreased significantly from 3.55 mg kg^{-1} soil in control to 1.98 mg kg^{-1} soil thus resulting in a decrease of 44.2 per cent over control with the application of 40 mg Ni kg^{-1} soil. In sandy loam soil, DTPA-Zn decreased significantly from 4.76 mg kg^{-1} soil in control to 2.68 mg kg^{-1} soil which represented a decrease of 43.7 per cent over control when nickel was applied @ 40 mg kg^{-1} soil. In loamy sand soil the negative linear relationship of applied Ni with DTPA-Zn (Fig.4.1 c, R^2=0.64) indicated that DTPA-Zn decreased with increasing levels of applied Ni. Same trend was observed in sandy loam soil (Fig.4.1 d, R^2=0.95). Reduction in available zinc with increasing nickel content might be due to competition at adsorption sites, where zinc is preferentially adsorbed over nickel thus decreasing its availability (Brummer *et al* 1986). Parida *et al* (2003) have reported that concentration of zinc in soil decreased with increasing levels of applied nickel. It was due to an antagonistic effect of nickel on zinc. Singh (1994) observed that both Ni^{+2} and Zn^{+2} have similar ionic charge and possibly same carrier sites, and hence antagonistic effect of Ni on Zn in soil. Sarkunan *et al* (1989) have reported significant interaction effects of Zn and Ni. High levels of Ni may induce Zn or Cu deficiency because of cation competition in soil. The interaction effect of Zn and Ni levels on DTPA-Zn was also significant. It was observed that DTPA-Zn decreased significantly by 45 and 34 per cent when 40 mg Ni kg^{-1} soil was applied along with 80 mg Zn kg^{-1} soil as compared to when only 80 mg Zn kg^{-1} soil was applied in loamy sand and sandy loam soil, respectively. It was further observed that at any level of applied Zn, DTPA-Zn decreased with increasing levels of applied Ni, in both the soils.

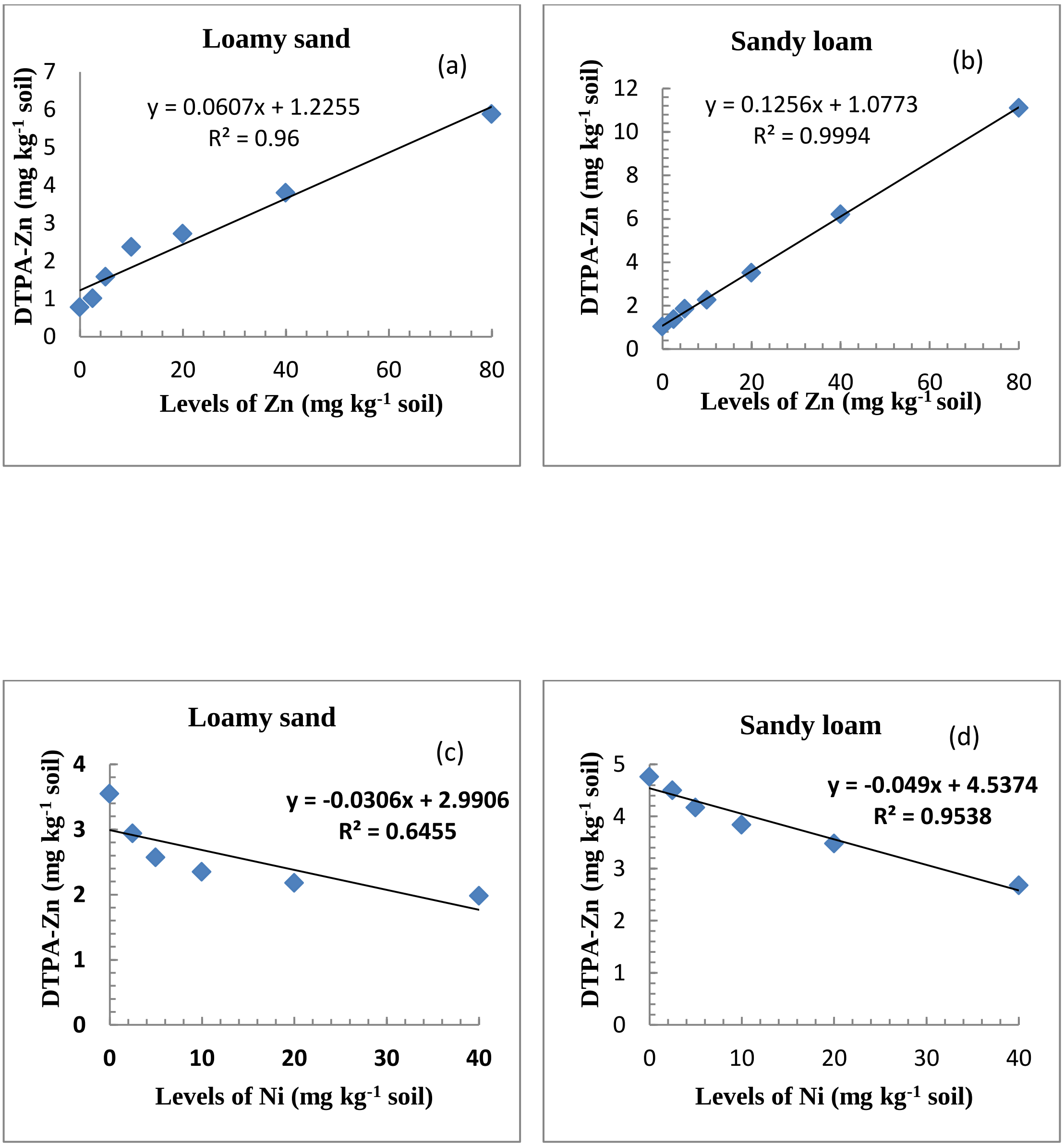


Fig.4.1: Relationship of levels of Zn and Ni on DTPA-Zn after harvest of rice

4.1.2 Exchangeable zinc (EXCH-Zn)

Table 4.2: Effect of Zn and Ni on exchangeable zinc

Levels of Zn (mg kg^{-1} soil)	EXCH-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.05	0.09	0.08	0.07	0.07	0.06	0.07
2.5	0.11	0.12	0.10	0.08	0.09	0.06	0.09
5	0.17	0.18	0.13	0.11	0.13	0.07	0.13
10	0.22	0.26	0.16	0.14	0.15	0.10	0.17
20	0.41	0.41	0.37	0.32	0.29	0.17	0.33
40	0.87	0.74	0.68	0.60	0.66	0.41	0.66
80	1.26	1.15	0.94	0.99	0.96	0.44	0.96
Mean	0.44	0.42	0.35	0.33	0.34	0.19	
CD (5%)	Zn- 0.05		Ni- 0.04		Zn x Ni- 0.12		
Sandy loam							
0	0.08	0.05	0.06	0.05	0.06	0.05	0.06
2.5	0.12	0.08	0.08	0.08	0.07	0.05	0.08
5	0.15	0.11	0.10	0.06	0.10	0.07	0.10
10	0.28	0.25	0.23	0.16	0.18	0.09	0.20
20	0.32	0.26	0.32	0.19	0.18	0.12	0.23
40	0.59	0.49	0.40	0.27	0.19	0.16	0.35
80	1.10	0.93	0.94	0.65	0.38	0.27	0.71
Mean	0.38	0.31	0.30	0.21	0.17	0.11	
CD (5%)	Zn- 0.03		Ni- 0.02		Zn x Ni- 0.07		

Zinc application resulted in a significant increase in exchangeable zinc in both the soils (Table 4.2, Fig. 4.2 a, b). It increased significantly from 0.07 mg kg^{-1} soil in control to 0.13, 0.17, 0.33, 0.66 and 0.96 mg kg^{-1} soil in loamy sand soil and from 0.06 mg kg^{-1} soil in control to 0.10, 0.20, 0.23, 0.35 and 0.71 mg kg^{-1} soil in sandy loam soil with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.2). A non-significant increase in exchangeable Zn was observed in both the soils when Zn was applied @ 2.5 mg kg^{-1} soil over control. Exchangeable Zn increased by 0.85, 1.42, 3.71, 8.42 and 12.71 times in loamy sand soil, and by 0.66, 2.33, 2.83, 4.83 and 10.83 times in sandy loam soil over control with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively.

Exchangeable zinc in both the soils decreased significantly over control with increasing levels of applied Ni (Table 4.2). In loamy sand soil, it decreased from 0.44 mg kg^{-1} soil in control to 0.35, 0.33, 0.34 and 0.19 mg kg^{-1} soil, with the application of 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. In sandy loam soil, the exchangeable Zn decreased from 0.38

mg kg^{-1} soil in control to 0.31, 0.30, 0.21, 0.17 and 0.11 mg kg^{-1} soil, with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Exchangeable Zn decreased by 20.4, 25, 22.7 and 56.8 per cent in loamy sand soil, and by 18.4, 21.0, 44.7, 55.3 and 71.0 per cent over control in sandy loam soil with increasing levels of applied Ni, respectively. A non-significant decrease in exchangeable Zn was observed in loamy sand soil when Ni was applied @ 2.5 mg kg^{-1} soil over control. The results showed that the magnitude of Zn in water soluble and exchangeable form was more in light textured soil as compared to medium textured soil. Exchangeable Zn was significantly positively correlated with SAD-Zn, MnOX-Zn, ANMPOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn in both soils (Table 4.10). Interactive effect of Zn and Ni on exchangeable Zn was also significant, when Zn was applied @ 40 and 80 mg kg^{-1} soil. In both the soils exchangeable Zn decreased significantly with progressive levels of applied nickel.

4.1.3 Specifically adsorbed zinc (SAD-Zn)

Table 4.3: Effect of Ni and Zn on specifically adsorbed zinc

Levels of Zn (mg kg^{-1} soil)	SAD-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.16	0.18	0.21	0.22	0.19	0.20	0.19
2.5	0.46	0.44	0.40	0.40	0.35	0.30	0.39
5	0.56	0.54	0.48	0.45	0.41	0.36	0.47
10	0.62	0.59	0.58	0.59	0.55	0.42	0.56
20	0.96	0.90	0.81	0.75	0.76	0.68	0.81
40	1.08	1.08	0.89	0.83	0.72	0.53	0.86
80	2.35	2.17	1.78	1.55	1.16	0.87	1.65
Mean	0.88	0.84	0.74	0.68	0.59	0.48	
CD (5%)	Zn- 0.05			Ni-0.04		Zn x Ni- 0.13	
Sandy loam							
0	0.23	0.26	0.21	0.20	0.21	0.20	0.22
2.5	0.48	0.50	0.40	0.38	0.39	0.33	0.41
5	0.56	0.55	0.48	0.42	0.38	0.38	0.46
10	0.71	0.64	0.61	0.59	0.57	0.54	0.61
20	1.25	1.15	1.22	1.01	0.93	0.76	1.06
40	1.51	1.34	1.33	1.04	1.01	0.92	1.19
80	2.22	1.72	1.59	1.61	1.32	1.12	1.60
Mean	0.99	0.88	0.83	0.75	0.69	0.61	
CD (5%)	Zn- 0.06			Ni- 0.05		Zn x Ni- 0.15	

Metals held on soil surfaces by covalent type bonding (Sposito 1984) to oxidic or organic functional groups is defined as specifically adsorbed or inner sphere complexed metals. Specifically adsorbed Zn in both soils increased significantly over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil. In loamy sand soil it increased from 0.19 mg kg^{-1} soil in control to 0.39, 0.47, 0.56, 0.81, 0.86 and 1.65 mg kg^{-1} soil and in sandy loam soil it increased from 0.22 mg kg^{-1} soil to 0.41, 0.46, 0.61, 1.06, 1.19 and 1.60 mg kg^{-1} soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.3). Specifically adsorbed Zn increased by 1.05, 1.47, 1.94, 3.26, 3.52 and 7.68 times in loamy sand and by 0.86, 1.09, 1.77, 3.82, 4.41 and 6.27 times in sandy loam soil over control with application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively.

Specifically adsorbed zinc decreased significantly over control when Ni was applied @ 5, 10, 20 and 40 mg kg^{-1} soil. In loamy sand soil, it decreased from 0.88 mg kg^{-1} soil in control to 0.74, 0.68, 0.59 and 0.48 mg kg^{-1} soil with the application of 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. In sandy loam soil SAD-Zn significantly decreased from 0.99 mg kg^{-1} soil in control to 0.88, 0.83, 0.75, 0.69 and 0.61 mg kg^{-1} soil with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. A non significant decrease in SAD-Zn was observed in loamy sand soil when Ni was applied @ 2.5 mg kg^{-1} soil over control. In loamy sand soil, SAD-Zn decreased by 15.9, 22.7, 32.9 and 45.4 per cent over control with the application of 5, 10, 20 and 40 mg Ni kg^{-1} soil and in sandy loam soil application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil decreased the SAD-Zn by 11.1, 16.2, 24.2, 30.3 and 38.3 per cent over control respectively. The content of SAD-Zn was higher in sandy loam soil as compared to loamy sand soil, which may be attributed to more amount of finer fraction of soil particles in sandy loam soil. Specifically adsorbed Zn was significantly positively correlated with EXCH-Zn, MnOX-Zn, AMPOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn in both the soils and significantly negatively correlated with DTPA-Ni in both the soils (Table 4.10). A significant interaction effect of Zn and Ni levels on SAD-Zn was observed in both soils. At any level of applied Zn SAD-Zn decreased with increasing level of applied Ni in both the soils.

4.1.4 Manganese oxides bound zinc (MnOX-Zn)

Table 4.4: Effect of Zn and Ni on Mn-oxides bound zinc

Levels of Zn (mg kg^{-1} soil)	MnOx-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.77	0.61	0.66	0.66	0.56	0.57	0.64
2.5	0.98	0.89	0.76	0.78	0.69	0.70	0.80
5	1.10	1.04	0.94	0.88	0.82	0.80	0.93
10	1.25	1.21	1.17	0.97	1.07	1.02	1.11
20	2.07	1.98	1.85	1.86	1.76	1.80	1.89
40	3.38	2.98	2.33	2.54	2.36	2.29	2.65
80	3.93	3.42	3.44	3.16	3.37	2.98	3.38
Mean	1.93	1.73	1.59	1.55	1.52	1.45	
CD (5%)	Zn- 0.18		Ni-0.17		Zn x Ni- NS		
Sandy loam							
0	0.82	0.84	0.76	0.62	0.60	0.56	0.70
2.5	1.06	0.95	0.94	0.85	0.79	0.72	0.89
5	1.46	1.48	1.44	1.39	1.30	1.24	1.39
10	1.79	1.71	1.74	1.68	1.67	1.60	1.70
20	2.63	2.58	2.68	2.48	2.29	2.20	2.48
40	3.28	3.11	2.98	2.85	2.76	2.80	2.96
80	4.76	4.36	4.11	3.95	3.81	3.79	4.13
Mean	2.26	2.15	2.09	1.97	1.89	1.84	
CD (5%)	Zn- 0.21		Ni- 0.19		Zn x Ni- NS		

Zinc application significantly increased MnOX-Zn in both the soils. It increased from 0.64 mg kg^{-1} soil in control to 0.93, 1.11, 1.89, 2.65 and 3.38 mg kg^{-1} in loamy sand soil and from 0.70 mg kg^{-1} soil in control to 1.39, 1.70, 2.48, 2.96 and 4.13 mg kg^{-1} in sandy loam soil when Zn was applied @ 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil respectively (Table 4.4). A non significant increase in MnOX-Zn was observed in both soils when Zn was applied @ 2.5 mg Zn kg^{-1} soil over control. Comparatively higher amounts of MnOX-Zn were observed in sandy loam than loamy sand soil.

A significant decrease in MnOX-Zn was observed with increasing levels of applied Ni (Table 4.4). In loamy sand, application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil significantly decreased the MnOX-Zn from 1.93 mg kg^{-1} soil in control to 1.73, 1.59, 1.55, 1.52 and 1.45 mg kg^{-1} soil, which represented a decrease of 10.3, 17.6, 19.7, 21.2 and 24.9 per cent over control. In sandy loam soil, it decreased from 2.26 mg kg^{-1} soil in control to 1.97, 1.89, 1.84 mg kg^{-1} soil with the application of 10, 20 and 40 mg Ni kg^{-1} soil, which represented a decrease of 12.8, 16.4

and 18.6 per cent over control, respectively. A non significant decrease was observed when Ni was applied @ 2.5 and 5 mg Ni kg^{-1} soil. The decrease in the content of Zn in MnOx fraction may be either due to antagonistic effect of applied Ni or reduction of MnOx during soil submergence leading to decrease in MnOx-Zn. Manganese oxide bound zinc was significantly positively correlated with EXCH-Zn, SAD-Zn, AMPOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn in both soils and significantly negatively correlated with DTPA-Ni in both soils (Table 4.10). Interaction effect of Zn and Ni on MnOX-Zn was not significant.

4.1.5 Amorphous Fe and Al oxides bound zinc (AMPOX-Zn)

Table 4.5: Effect of Zn and Ni on Amorphous Fe and Al oxides bound zinc

Levels of Zn (mg kg^{-1} soil)	AMPOX-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	3.41	3.49	3.54	3.51	3.42	3.62	3.50
2.5	4.34	4.27	4.20	4.17	4.20	4.20	4.23
5	4.94	4.84	4.80	4.73	4.93	4.81	4.84
10	4.91	5.19	5.09	5.18	5.29	5.41	5.18
20	5.55	5.55	5.51	5.72	5.86	5.72	5.65
40	8.21	8.20	8.30	8.71	8.91	8.78	8.52
80	10.98	10.90	10.95	10.29	10.30	10.01	10.57
Mean	6.05	6.06	6.06	6.04	6.13	6.08	
CD (5%)	Zn- 0.32			Ni- NS		Zn x Ni- NS	
Sandy loam							
0	3.75	3.87	3.75	3.82	3.97	3.94	3.85
2.5	4.38	4.30	3.91	4.09	4.13	4.81	4.27
5	5.19	5.11	4.83	4.79	4.88	4.86	4.94
10	6.57	6.78	5.93	5.98	5.85	5.78	6.15
20	8.30	8.38	8.98	9.03	9.10	9.24	8.84
40	9.44	9.91	10.17	10.33	10.81	10.69	10.22
80	11.90	11.99	11.85	11.82	11.60	11.77	11.82
Mean	7.07	7.19	7.06	7.12	7.19	7.30	
CD (5%)	Zn- 0.74			Ni- NS		Zn x Ni- NS	

Amorphous oxides have more surface area for adsorption of metals. Zinc application significantly increased AMPOX-Zn from 3.50 mg kg^{-1} soil in control to 4.23, 4.84, 5.18, 5.65, 8.52 and 10.57 mg kg^{-1} soil in loamy sand soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively and from 3.85 mg kg^{-1} soil in control to 4.94, 6.15, 8.84, 10.22 and 11.82 mg kg^{-1} soil in sandy loam soil with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.5). Thus, the content of Zn in amorphous oxides increased by

0.21, 0.38, 0.48, 0.61, 1.43 and 2.02 times in loamy sand soil with the application of Zn @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil and by 0.28, 0.60, 1.30, 1.65 and 2.07 times in sandy loam over control with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. The absolute amounts of Zn in this fraction were observed to be more in sandy loam soil as compared to the loamy sand soil which may be due to more amount of finer fraction of soil particles in sandy loam as compared to loamy sand.

It was further observed that application of Ni had no significant effect on AMPOX-Zn. In loamy sand soil there was an increase in AMPOX-Zn when Ni was applied @ 20 mg Ni kg^{-1} soil and in sandy loam soil increase in AMPOX-Zn was observed when Ni was applied @ 10, 20 and 40 mg Ni kg^{-1} soil but this increase in AMPOX-Zn was not significant. Amorphous Fe and Al oxides bound zinc was significantly positively correlated with EXCH-Zn, SAD-Zn, MnOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn in both the soils and significantly negatively correlated with DTPA-Ni in both the soils (Table 4.10). A non-significant interaction effect of applied Zn and Ni levels on AMPOX-Zn.

4.1.6 Crystalline Fe and Al oxides bound zinc (CRYOX-Zn)

Table 4.6: Effect of applied Ni and Zn on Crystalline Fe and Al oxides bound zinc

Levels of Zn (mg kg^{-1} soil)	CRYOX-Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	16.6	16.3	16.8	16.7	16.3	17.7	16.8
2.5	17.5	16.4	16.6	16.2	16.6	16.6	16.7
5	18.8	18.1	18.2	18.7	18.2	18.9	18.5
10	19.6	19.9	19.0	18.9	18.4	18.3	19.0
20	20.1	19.2	19.0	19.7	19.2	19.3	19.4
40	21.3	21.8	20.7	20.7	19.5	19.6	20.6
80	21.9	21.2	21.8	21.3	20.4	20.6	21.2
Mean	19.4	19.0	18.9	18.9	18.4	18.7	
CD (5%)	Zn- NS			Ni- NS		Zn x Ni- NS	
Sandy loam							
0	17.1	16.1	17.8	17.2	17.8	18.3	17.4
2.5	17.7	16.4	17.9	17.2	18.1	18.3	17.6
5	18.0	18.0	18.7	18.4	18.4	19.4	18.5
10	19.0	19.8	19.0	18.7	18.9	19.8	19.2
20	19.6	19.3	19.2	19.5	19.5	19.0	19.4
40	20.3	20.8	20.1	21.4	20.3	20.8	20.6
80	21.9	21.0	21.7	21.2	21.9	20.4	21.4
Mean	19.1	18.8	19.2	19.1	19.3	19.4	
CD (5%)	Zn- NS			Ni- NS		Zn x Ni- NS	

The data on the effect of Zn and Ni application on CRYOX-Zn is presented in Table 4.6. Though application of Zn increased the content of CRYOX-Zn at each level of applied Zn in both the soils but this increase was not significant. Its content increased from 16.8 mg kg^{-1} soil in control to 18.5, 19.0, 19.4, 20.6 and 21.2 mg kg^{-1} soil in loamy sand and from 17.4 mg kg^{-1} soil in control to 18.5, 19.2, 19.4, 20.6 and 21.4 mg kg^{-1} soil in sandy loam soil, with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. It was observed that there was no significant effect of applied Ni on CRYOX-Zn. Crystalline oxides have a very typical and closed structures and entry of any metal in these minerals is very difficult. Although there was an increase in CRYOX-Zn when Ni was applied @ 5, 20 and 40 mg Ni kg^{-1} soil in sandy loam soil, but this was not significant. CRYOX-Zn was significantly positively correlated with EXCH-Zn, SAD-Zn, MnOX-Zn, AMPOX-Zn, OM-Zn, RES-Zn and DTPA-Zn and significantly negatively correlated with DTPA-Ni in both the soils (Table 4.10). Interactive effect of Zn and Ni on CRYOX-Zn was not significant.

4.1.7 Organically bound zinc (OM-Zn)

Table 4.7: Effect of Zn and Ni on organically bound zinc

Levels of Zn (mg kg^{-1} soil)	OM -Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	3.67	3.83	3.13	3.69	3.23	3.91	3.58
2.5	3.90	3.88	3.78	3.69	3.52	3.83	3.77
5	4.54	4.33	4.64	4.10	4.43	4.96	4.50
10	4.67	4.41	4.80	4.86	4.76	4.92	4.74
20	4.97	4.48	4.95	4.97	4.95	5.01	4.89
40	5.33	5.73	5.32	5.16	5.21	5.53	5.38
80	5.72	5.98	5.25	5.87	5.28	5.53	5.60
Mean	4.69	4.66	4.55	4.62	4.48	4.81	
CD (5%)	Zn- 0.53			Ni- NS		Zn x Ni- NS	
Sandy loam							
0	4.12	4.06	4.10	4.24	4.32	4.45	4.22
2.5	4.72	4.63	4.99	4.57	4.80	4.96	4.78
5	5.21	5.05	5.05	4.95	4.96	4.97	5.03
10	5.65	5.72	5.70	5.56	5.01	5.66	5.55
20	5.91	5.95	5.87	5.95	5.59	5.80	5.84
40	6.30	6.57	6.88	6.64	6.90	6.55	6.64
80	6.58	6.93	6.92	6.93	6.97	7.05	6.90
Mean	5.50	5.56	5.64	5.55	5.51	5.64	
CD (5%)	Zn- 0.59			Ni- NS		Zn x Ni- NS	

Organically bound Zn increased significantly from 3.58 mg kg^{-1} soil in control to a maximum of 5.60 mg kg^{-1} soil in loamy sand and from 4.22 mg kg^{-1} soil in control to maximum of 6.90 mg kg^{-1} soil in sandy loam soil resulting in an increase of 56.4 and 63.5 per cent over control with the application of 80 mg Zn kg^{-1} soil, respectively (Table 4.7). In loamy sand soil, organically bound Zn increased (2.56%) from 4.69 mg kg^{-1} soil in control to 4.81 mg kg^{-1} soil when Ni was applied @ 40 mg Ni kg^{-1} soil. Similarly, in sandy loam soil, its content increased (2.54%) from 5.50 mg kg^{-1} soil in control to 5.64 mg kg^{-1} soil when Ni was applied @ 40 mg Ni kg^{-1} soil. But in both soils this increase was not significant. Organic matter bound zinc was significantly positively correlated with EXCH-Zn, SAD-Zn, MnOX-Zn, AMPOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn and significantly negatively correlated with DTPA-Ni in both the soils (Table 4.10). A non significant interaction effect of Zn and Ni levels in both the soils was observed. As the content of organic matter was higher in sandy loam soil as compared to loamy sand soil so the content of Zn in organic matter was also higher in sandy loam soil as compared to loamy sand soil.

4.1.8 Residual zinc (RES-Zn)

Table 4.8: Effect of Zn and Ni on residual mineral fraction of zinc

Levels of Zn (mg kg^{-1} soil)	Residual Zn (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	30.3	30.4	30.4	30.0	31.1	28.8	30.2
2.5	30.1	31.4	31.5	32.1	32.0	31.8	31.5
5	29.8	30.9	30.7	30.9	31.0	30.0	30.5
10	33.6	33.3	34.1	34.3	34.7	34.8	34.1
20	40.8	42.4	42.4	41.6	42.1	42.2	41.9
40	54.8	54.4	56.6	56.4	57.6	57.8	56.3
80	83.8	85.1	85.8	86.8	88.4	89.5	86.6
Mean	43.3	44.0	44.6	44.6	45.3	45.0	
CD (5%)	Zn- 1.5			Ni- NS		Zn x Ni- NS	
Sandy loam							
0	28.8	29.7	28.2	28.8	28.0	27.4	28.5
2.5	28.9	30.5	29.2	30.3	29.1	28.3	29.4
5	29.3	29.6	29.3	29.9	29.9	28.9	29.5
10	31.0	30.0	31.7	32.2	32.7	31.4	31.5
20	36.9	37.3	36.6	36.8	37.3	37.8	37.1
40	53.5	52.6	53.1	52.4	53.0	52.9	52.9
80	81.4	82.9	82.9	83.7	84.0	85.5	83.4
Mean	41.4	41.8	41.6	42.0	42.0	41.8	
CD (5%)	Zn-1.6			Ni-NS		Zn x Ni- NS	

Application of Zn significantly increased the content of Zn in residual mineral fraction, when it was applied @ 10, 20, 40 and 80 mg Zn kg^{-1} soil in both the soils. It increased by 1.86 times in loamy sand and by 1.92 times in sandy loam over control with the highest level of applied Zn (Table 4.8). Effect of Ni application on content of Zn in residual mineral fraction was not significant in both the soils. Residual zinc was positively correlated with EXCH-Zn, SAD-Zn, MnOX-Zn, AMPOX-Zn, CRYOX-Zn, OM-Zn and DTPA-Zn and significantly negatively correlated with DTPA-Ni in both the soils (Table 4.10).The interaction effect of Zn and Ni was non-significant.

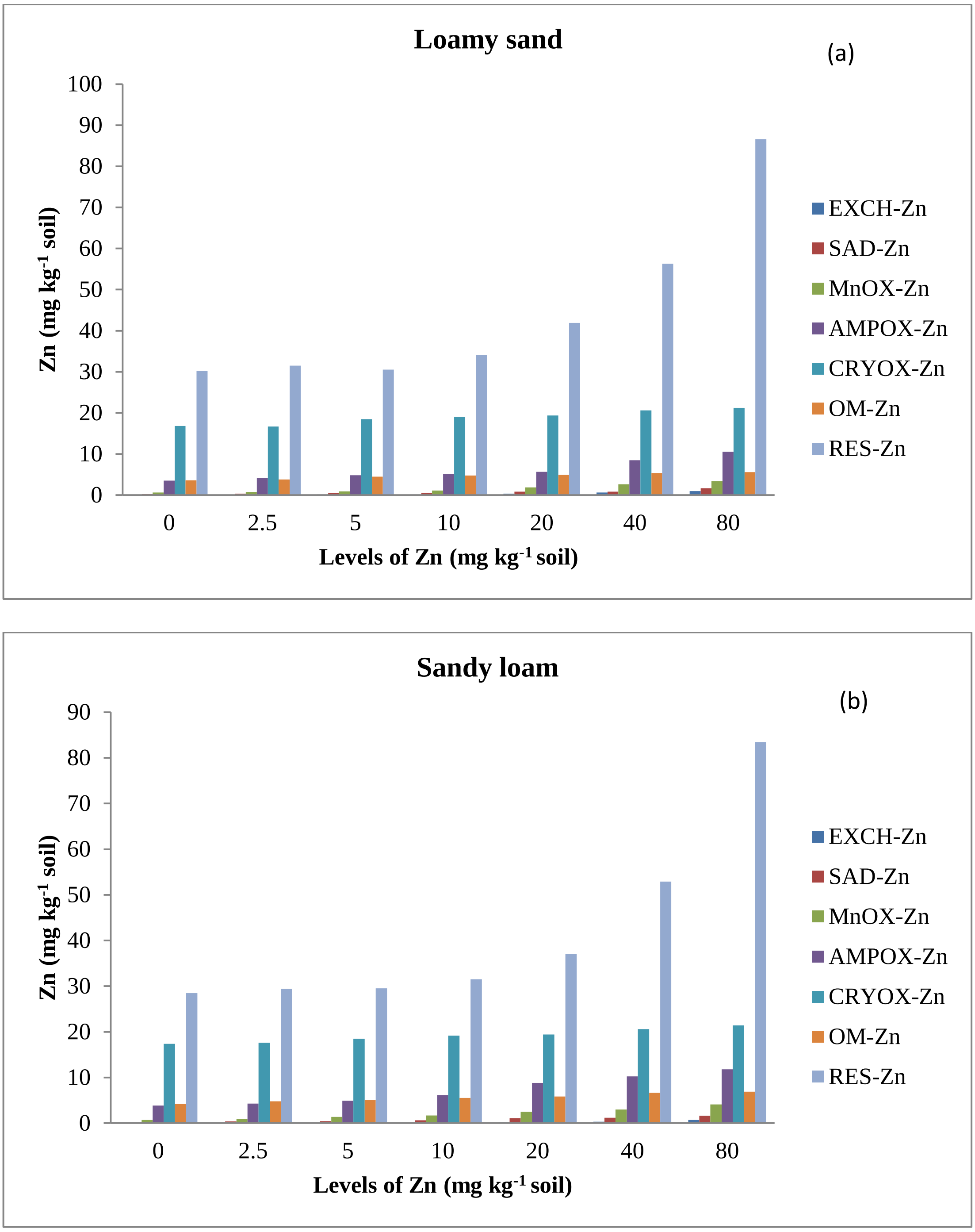


Fig.4.2: Zinc content in various chemical pools as influenced by Zn application

4.1.9 Per cent recovery of applied Zn @ 80 mg kg^{-1} soil in different chemical pools

When zinc is applied to soil through external sources many chemical reactions like adsorption, precipitation and complexation takes place. Per cent recovery of added Zn @ 80 mg kg^{-1} soil at different levels of applied Ni in a particular fraction was calculated by taking the difference of content of that fraction in Zn treated pot and the corresponding no Zn pot (Table 4.9). Soil Zn was largely found in unavailable forms and it was observed that in loamy sand soil only 1.11 and 1.82 per cent, and in sandy loam soil 0.81 and 1.72 per cent of applied Zn @ 80 mg kg^{-1} soil entered in exchangeable and specifically adsorbed fraction, respectively which are considered to be the most plant available forms. A major portion of added Zn entered in to residual mineral fraction followed by amorphous oxides and crystalline oxides in both the soils. Dhane and Shukla (1995) studied the distribution of different forms of zinc. They observed that water soluble, exchangeable, specifically adsorbed, acid soluble, Mn-occluded, organic matter-occluded, amorphous Fe-occluded, crystalline Fe-occluded fractions of zinc constituted very little whereas the residual fraction of zinc was a dominant constituent (95.9%) in these soils. Only 2.52 and 3.35 per cent of added Zn entered in to OM-Zn in loamy sand and sandy loam soils, respectively. Mandal and Mandal (1986) revealed that in rice soils more than 90 per cent of the total zinc was in clay lattice bound form which was relatively inactive and only small fraction of total zinc was in water-soluble + exchangeable (0.26%), amorphous sesquioxide bound (1.58%), crystalline sesquioxide bound (0.71%) forms.

Table 4.9 Per cent recovery of applied zinc @80 mg kg^{-1} soil in different chemical pools

Per cent of applied Zn @ 80 mg kg^{-1} soil							
Loamy sand soil							
Levels of Ni	EXCH-Zn	SAD-Zn	MnOX-Zn	AMPOX-Zn	CRYOX-Zn	OM-Zn	RES-Zn
0	1.50	2.70	3.95	9.46	6.69	2.56	66.85
2.5	1.30	2.50	3.51	9.26	6.05	2.69	68.40
5	1.10	1.96	3.47	9.26	6.15	2.65	69.20
10	1.15	1.66	3.12	8.47	5.66	2.72	70.95
20	1.11	1.21	3.51	8.60	5.10	2.56	71.62
40	0.47	0.84	3.01	7.98	3.60	2.02	75.81
Mean	1.11	1.82	3.42	8.84	5.54	2.52	70.47
Sandy loam soil							
0	1.30	2.48	4.92	10.18	6.08	3.07	65.72
2.5	1.10	1.82	4.40	10.15	6.15	3.59	66.52
5	1.10	1.72	4.18	10.12	4.79	3.52	68.31
10	0.75	1.75	4.16	10.00	5.05	3.36	68.65
20	0.40	1.39	4.01	9.54	5.12	3.31	69.97
40	0.27	1.15	4.03	9.79	2.61	3.25	72.64
Mean	0.81	1.72	4.29	9.96	4.97	3.35	68.64

Linear coefficient of correlation among various chemical pools of Zn indicated that most of these pools were significantly and positively correlated amongst themselves thereby suggesting the existence of a dynamic equilibrium among different forms (Table 4.10). Thus, depletion in the content of one pool either due to plant uptake or its transformation into other pools may be replenished by other pools.

Table 4.10: Coefficients of correlation among various pools of zinc

Loamy sand						
	EXCH-Zn	SAD-Zn	MnOX-Zn	AMPOX-Zn	CRYOX-Zn	OM-Zn
SAD-Zn	0.950**					
MnOX-Zn	0.989**	0.948**				
AMPOX-Zn	0.991**	0.949**	0.980**			
CRYOX-Zn	0.894**	0.879**	0.923**	0.919**		
OM-Zn	0.870*	0.869*	0.906**	0.904**	0.995**	
RES-Zn	0.982**	0.966**	0.956**	0.967**	0.831*	0.803*
DTPA-Zn	0.975**	0.979**	0.974**	0.981**	0.938**	0.924**
DTPA-Ni	-0.954**	-0.828*	-0.917**	-0.947**	-0.796*	-0.762*
Sandy loam						
	EXCH-Zn	SAD-Zn	MnOX-Zn	AMPOX-Zn	CRYOX-Zn	OM-Zn
SAD-Zn	0.934**					
MnOX-Zn	0.957**	0.992**				
AMPOX-Zn	0.912**	0.993**	0.986**			
CRYOX-Zn	0.918**	0.957**	0.976**	0.967**		
OM-Zn	0.888**	0.966**	0.966**	0.972**	0.987**	
RES-Zn	0.986**	0.906**	0.928**	0.884**	0.878**	0.847*
DTPA-Zn	0.991**	0.940**	0.959**	0.922**	0.918**	0.892**
DTPA-Ni	-0.957**	-0.973**	-0.989**	-0.971**	-0.981**	-0.964**

** Significant at 1 % level
*Significant at 5% level

The data on effect of Zn and Ni application on transformation and availability of Ni in soils is presented in Tables 4.11 to 4.20 and figures 4.3 and 4.4.

4.1.10 DTPA-Ni

In loamy sand soil, DTPA-Ni decreased significantly from 2.65 mg kg^{-1} soil in control to 2.19 and 2.09 mg kg^{-1} soil when zinc was applied @ 40 and 80 mg Zn kg^{-1} soil which represented a decrease of 17.3 and 21.1 per cent over control, respectively (Table 4.11, Fig. 4.3a). In sandy loam soil, a significant decrease in DTPA-Ni was observed only when Zn was applied @ 20, 40 and 80 mg Zn kg^{-1} soil. It decreased from 2.99 mg kg^{-1} soil in control to 2.83, 2.71 and 2.60 mg kg^{-1} soil, thereby resulting in a decrease of 5.3, 9.3 and 13.0 per cent over control with the application of 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.11, Fig. 4.3b). Significant decrease was observed only at higher rates of application of Zn. In loamy sand soil, at lower rates of application of Zn i.e. 2.5, 5, 10 and 20 mg kg^{-1} soil, a slight increase in DTPA-Ni was observed, but this was not significant. A linear relationship of DTPA-Ni to applied Zn indicated that in loamy sand (Fig.4.3a, R^2=0.85) DTPA-Ni decreased with increasing levels of applied Zn. Similar trend was observed for sandy loam (Fig4.3b, R^2=0.93). DTPA-Ni was significantly negatively correlated with all chemical pools of zinc viz. EXCH-Zn, SAD-Zn, MnOX-Zn, AMPOX-Zn, CRYOX-Zn, OM-Zn, RES-Zn and DTPA-Zn (Table 4.10). Wood *et al* (2004) observed Ni deficiency in soil due to an excessive amount of Zn because Zn has inhibitory effect on Ni. Its deficiency could either be due to low levels of available Ni in soils or due to high contents of Ca, Mg, Cu or Zn in soils (Wells 2005).

Table 4.11: Effect of Zn and Ni on DTPA- Ni

Levels of Zn (mg kg^{-1} soil)	DTPA-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.19	0.99	1.89	3.61	4.24	4.98	2.65
2.5	0.17	1.10	1.96	3.67	4.25	4.92	2.68
5	0.19	1.17	1.92	3.83	4.16	4.63	2.65
10	0.20	1.26	1.95	3.77	4.52	4.50	2.70
20	0.19	1.22	1.82	3.93	4.58	4.24	2.66
40	0.10	0.96	1.13	3.49	3.52	3.92	2.19
80	0.10	0.99	1.35	2.92	3.25	3.92	2.09
Mean	0.16	1.10	1.72	3.60	4.08	4.44	
CD (5%)	Zn- 0.26			Ni- 0.24		Zn x Ni- NS	
Sandy loam							
0	0.46	1.36	2.26	3.95	4.61	5.29	2.99
2.5	0.49	1.39	2.20	3.99	4.59	5.18	2.97
5	0.43	1.28	2.26	3.89	4.42	5.12	2.90
10	0.49	1.22	2.17	3.87	4.41	5.18	2.89
20	0.56	1.21	1.97	3.79	4.17	5.30	2.83
40	0.42	1.13	1.58	3.63	4.23	5.29	2.71
80	0.39	1.11	1.52	3.55	4.12	4.92	2.60
Mean	0.46	1.24	1.99	3.81	4.36	5.18	
CD (5%)	Zn- 0.15			Ni- 0.13		Zn x Ni- NS	

Application of Ni significantly increased DTPA-Ni from 0.16 mg kg^{-1} soil in control to 4.44 mg kg^{-1} soil in loamy sand soil and from 0.46 mg kg^{-1} soil in control to 5.18 mg kg^{-1} soil in sandy loam soil with the highest level of applied Ni. The extractability of Ni increased by 5.8, 9.7, 21.5, 24.5 and 26.7 times that of control in loamy sand and by 1.7, 3.3, 7.3, 8.5 and 10.3 times in sandy loam soil when 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil was applied respectively. A linear relationship of DTPA-Ni to applied Ni indicated that in loamy sand (Fig.4.3c, R^2=0.71) DTPA-Ni increased with increasing level of applied Ni. Similar trend was observed for sandy loam soil (Fig.4.3d, R^2=0.78). DTPA-Ni was significantly positively correlated with EXCH-Ni, SAD-Ni, MnOX-Ni, AMPOX-Ni, CRYOX-Ni, OM-Ni and RES-Ni in both the soils indicating that DTPA is not only extracting exchangeable, adsorbed and complexed forms of Ni but also other pools are significantly contributing to it (Table 4.20). The interaction effect of Zn and Ni levels on DTPA-Ni was not significant.

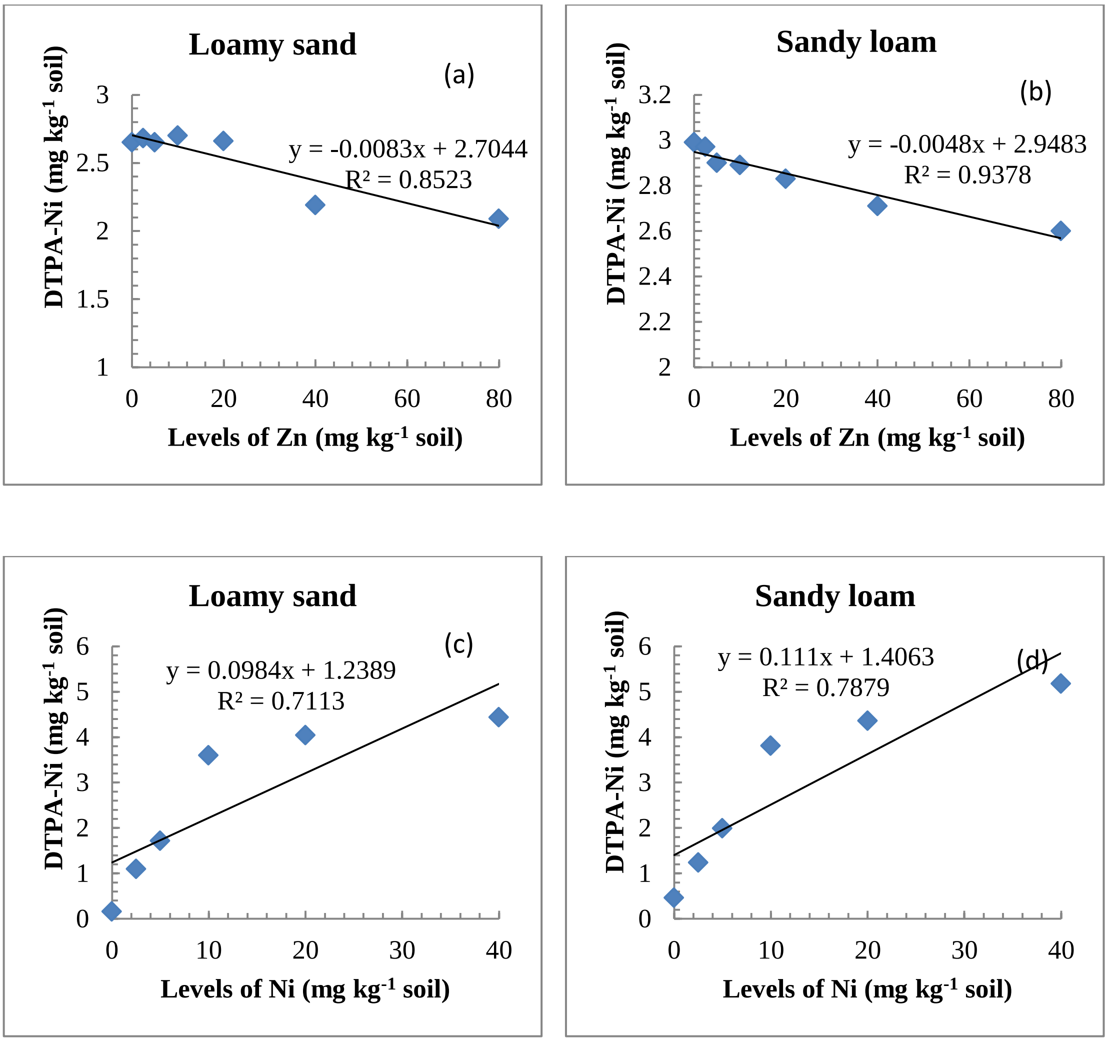


Fig.4.3: Relationship of levels of Zn and Ni on DTPA-Ni after harvest of rice

4.1.11 Exchangeable nickel (EXCH-Ni)

Table 4.12: Effect of Zn and Ni on exchangeable nickel

Levels of Zn (mg kg^{-1} soil)	EXCH-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.05	0.12	0.24	0.36	0.41	0.58	0.29
2.5	0.06	0.14	0.22	0.31	0.39	0.56	0.28
5	0.05	0.12	0.25	0.32	0.41	0.55	0.28
10	0.07	0.11	0.27	0.35	0.49	0.61	0.30
20	0.06	0.15	0.38	0.39	0.44	0.55	0.31
40	0.04	0.12	0.29	0.31	0.37	0.50	0.27
80	0.04	0.10	0.22	0.30	0.35	0.48	0.24
Mean	0.05	0.12	0.27	0.34	0.41	0.55	
CD (5%)	Zn- 0.04			Ni- 0.03		Zn x Ni- NS	
Sandy loam							
0	0.09	0.19	0.30	0.42	0.62	0.79	0.40
2.5	0.10	0.18	0.33	0.47	0.67	0.77	0.42
5	0.12	0.20	0.32	0.46	0.61	0.73	0.41
10	0.11	0.25	0.37	0.47	0.63	0.72	0.43
20	0.08	0.22	0.34	0.40	0.61	0.68	0.39
40	0.08	0.20	0.28	0.38	0.57	0.65	0.36
80	0.06	0.15	0.24	0.39	0.55	0.65	0.34
Mean	0.09	0.20	0.31	0.43	0.61	0.71	
CD (5%)	Zn- 0.05			Ni- 0.04		Zn x Ni- NS	

Exchangeable Ni in both the soils decreased significantly over control, only at the highest level of applied Zn (Table 4.12). In loamy sand soil it decreased from 0.29 mg kg^{-1} soil in control to 0.25 mg kg^{-1} soil, when Zn was applied @ 80 mg Zn kg^{-1} soil and in sandy loam soil it was decreased from 0.40 mg kg^{-1} soil in control to 0.34 mg kg^{-1} soil, when Zn was applied @ 80 mg Zn kg^{-1} soil. Exchangeable Ni decreased by 13.8 per cent in loamy sand soil, and by 15 per cent over control in sandy loam soil. A non- significant increase in exchangeable Ni was observed when Zn was applied @ 20 mg Zn kg^{-1} soil, in loamy sand soil and when Zn was applied @ 10 mg Zn kg^{-1} soil in sandy loam soil over control.

Application of Ni resulted in a significant increase in exchangeable Ni in both the soils (Fig. 4.4 a, b). It increased significantly from 0.05 mg kg^{-1} soil in control to 0.12, 0.27, 0.34, 0.41 and 0.55 mg kg^{-1} soil in loamy sand soil and from 0.09 mg kg^{-1} soil in control to 0.20, 0.31, 0.43, 0.61 and 0.71 mg kg^{-1} soil in sandy loam soil with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.12). Exchangeable Ni increased by 1.4, 4.4, 5.8, 7.2 and 10 times in loamy sand soil, and by 1.2, 2.4, 3.7, 5.7 and 6.9 times in sandy loam soil over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Exchangeable Ni was significantly positively correlated with SAD-Ni, MnOX-Ni, AMPOX-Ni, CRYOX-Ni, OM-Ni and RES-Ni in both the soils (Table 4.20). Interactive effect of Zn and Ni on exchangeable Ni was not significant.

4.1.12 Specifically adsorbed (SAD-Ni)

Table 4.13: Effect of Zn and Ni on specifically adsorbed nickel

Levels of Zn (mg kg^{-1} soil)	SAD-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.10	0.16	0.29	0.47	0.59	0.78	0.40
2.5	0.12	0.18	0.30	0.46	0.58	0.79	0.41
5	0.14	0.15	0.38	0.48	0.59	0.82	0.43
10	0.16	0.17	0.35	0.40	0.68	0.79	0.42
20	0.16	0.18	0.38	0.39	0.69	0.70	0.43
40	0.09	0.14	0.29	0.31	0.60	0.68	0.35
80	0.08	0.12	0.21	0.30	0.50	0.63	0.31
Mean	0.12	0.16	0.31	0.40	0.61	0.74	
CD (5%)	Zn-0.07			Ni-0.06		Zn x Ni- NS	
Sandy loam							
0	0.15	0.28	0.33	0.49	0.77	0.92	0.49
2.5	0.17	0.36	0.40	0.56	0.71	0.87	0.51
5	0.19	0.30	0.40	0.49	0.79	0.98	0.52
10	0.22	0.32	0.42	0.58	0.70	0.81	0.51
20	0.16	0.29	0.50	0.63	0.72	0.89	0.53
40	0.14	0.26	0.42	0.51	0.61	0.82	0.46
80	0.12	0.22	0.31	0.46	0.63	0.79	0.42
Mean	0.17	0.29	0.40	0.53	0.71	0.87	
CD (5%)	Zn- 0.05			Ni- 0.04		Zn x Ni- NS	

Like exchangeable Ni, specifically adsorbed Ni also decreased significantly over control only when Zn was applied @ 80 mg kg^{-1} soil in both the soils (Table 4.13). It decreased from 0.40 mg kg^{-1} soil in control to 0.31 mg kg^{-1} soil in loamy sand soil and from 0.49 mg kg^{-1} soil in control to 0.42 mg kg^{-1} soil in sandy loam soil with the application of 80 mg Zn kg^{-1} soil. In loamy sand soil, SAD-Ni decreased by 22.5 per cent over control with the application of 80 mg Zn kg^{-1} soil and in sandy loam soil application of 80 mg Zn kg^{-1} soil decreased the SAD-Ni by 14.3 per cent over control. The content of Ni in SAD-Ni was higher in sandy loam soil as compared to the loamy sand soil. Specifically adsorbed nickel in both the soils increased significantly over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil. In loamy sand soil it increased from 0.12 mg kg^{-1} soil in control to 0.16, 0.31, 0.40, 0.61 and 0.74 mg kg^{-1} soil and in sandy loam soil it increased from 0.17 mg kg^{-1} soil in control to 0.29, 0.40, 0.53, 0.71 and 0.87 mg kg^{-1} soil with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.13). However, SAD-Ni increased in loamy sand soil when Ni was applied @ 2.5 mg kg^{-1} soil, but this increase was not significant. Specifically adsorbed nickel increased by 0.25, 1.58, 2.33, 4.08 and 5.16 times in loamy sand soil and by 0.71, 1.36, 2.12, 3.18 and 4.12 times in sandy loam soil over control with the application of 2.5, 5, 10, 20 and 40 mg kg^{-1}

Ni soil. Specifically adsorbed Ni was significantly positively correlated with MnOX-Ni, AMPOX-Ni, CRYOX-Ni, OM-Ni and RES-Ni in both the soils (Table 4.20). Interaction effect of Zn and Ni levels on SAD-Ni was not significant in both the soils.

4.1.13 Manganese oxides bound nickel (MnOX-Ni)

Table 4.14: Effect of Zn and Ni on Mn-oxide bound nickel

Levels of Zn (mg kg^{-1} soil)	MnOx-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.28	0.57	0.65	0.76	0.84	1.13	0.70
2.5	0.26	0.54	0.66	0.78	0.89	1.23	0.73
5	0.28	0.59	0.69	0.78	0.96	1.35	0.78
10	0.29	0.64	0.72	0.81	1.05	1.29	0.80
20	0.27	0.67	0.75	0.79	0.98	1.44	0.82
40	0.28	0.61	0.67	0.70	1.02	1.61	0.82
80	0.36	0.63	0.66	0.72	1.17	1.71	0.87
Mean	0.29	0.61	0.69	0.76	0.99	1.39	
CD (5%)	Zn-0.07			Ni- 0.06		Zn x Ni- 0.18	
Sandy loam							
0	0.30	0.49	0.60	0.75	1.01	1.25	0.73
2.5	0.30	0.59	0.66	0.79	1.16	1.39	0.82
5	0.31	0.60	0.72	0.86	1.19	1.48	0.86
10	0.33	0.62	0.88	0.97	1.37	1.96	1.02
20	0.34	0.79	0.93	1.02	1.49	2.12	1.11
40	0.36	0.81	0.88	1.15	1.28	1.87	1.08
80	0.39	0.72	0.83	0.98	1.97	2.01	1.15
Mean	0.33	0.66	0.79	0.93	1.35	1.73	
CD (5%)	Zn- 0.05			Ni-0.04		Zn x Ni- 0.15	

Application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil significantly increased the MnOX-Ni by 11.4, 14.2, 17.1, 17.1 and 24.2 per cent over control in loamy sand soil. It increased from 0.70 mg kg^{-1} soil in control to 0.78, 0.80, 0.82, 0.82 and 0.87 mg kg^{-1} soil, respectively (Table 4.14). A non-significant increase was observed when Zn was applied @ 2.5 mg Zn kg^{-1} soil. In sandy loam soil, it increased from 0.73 mg kg^{-1} soil in control to 0.82, 0.86, 1.02, 1.11, 1.06 and 1.15 mg kg^{-1} soil when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil. However, it decreased by 4.5% with application of 40 mg Zn kg^{-1} soil compared with the application of 20 mg Zn kg^{-1} soil but it was not significant. Application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil significantly increased the MnOX-Ni by 12.3, 17.8, 39.7, 52.0, 0.45 and 57.5 per cent over control in sandy loam soil.

Nickel application significantly increased MnOX-Ni in both the soils. It increased from 0.29 mg kg^{-1} soil in control to 0.61, 0.69, 0.76, 0.99 and 1.39 mg kg^{-1} soil in loamy sand soil and from 0.39 mg kg^{-1} soil in control to 0.66, 0.79, 0.93, 1.35 and 1.73 mg kg^{-1} soil in sandy loam soil when nickel was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.14). In loamy sand soil this increase was about 1.10, 1.37, 1.62, 2.41 and 3.79 times over control and in sandy loam soil this increase was about 1.00, 1.39, 1.81, 3.09 and 4.24 times over control when Ni was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Comparatively higher amount of MnOX-Ni was observed in sandy loam soil than loamy sand. Manganese oxides bound Ni was significantly positively correlated with AMPOX-Ni, CRYOX-Ni, OM-Ni and RES-Ni in both the soils (Table 4.20). A significant interaction effect of Zn and Ni on MnOX-Ni revealed that when 40 mg Ni kg^{-1} soil was applied, its content increased significantly from 1.13 mg kg^{-1} soil in control to 1.61 and 1.71 mg kg^{-1} soil in loamy sand soil, and increased significantly from 1.25 mg kg^{-1} soil in control to 1.87 and 2.01 mg kg^{-1} soil in sandy loam soil when 40 and 80 mg Zn kg^{-1} soil was applied, respectively.

4.1.14 Amorphous Fe and Al oxides bound nickel (AMPOX-Ni)

Table 4.15: Effect of Zn and Ni on Amorphous Fe and Al oxide bound nickel

Levels of Zn (mg kg^{-1} soil)	AMPOX-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	1.48	1.92	2.38	3.53	4.17	5.69	3.19
2.5	1.52	2.01	2.41	3.69	4.36	5.80	3.30
5	1.51	2.12	2.52	3.66	4.49	5.87	3.36
10	1.50	2.15	2.56	3.72	4.48	6.70	3.52
20	1.58	2.19	2.79	3.69	4.82	7.40	3.75
40	1.56	2.07	2.90	3.77	4.41	7.48	3.70
80	1.69	2.19	3.31	3.97	4.86	7.73	3.96
Mean	1.55	2.09	2.70	3.72	4.51	6.67	
CD (5%)	Zn- 0.47			Ni- 0.43		Zn x Ni- NS	
Sandy loam							
0	1.75	2.20	2.52	3.94	4.70	5.34	3.41
2.5	1.80	2.50	2.61	3.97	4.77	5.40	3.51
5	1.89	2.73	2.78	4.28	4.90	5.58	3.69
10	1.90	2.90	2.98	4.39	4.93	6.16	3.88
20	1.87	3.09	3.14	4.48	4.84	6.19	3.94
40	1.83	3.12	4.27	4.96	4.76	5.99	4.15
80	2.09	3.24	4.14	5.14	5.23	6.63	4.41
Mean	1.87	2.82	3.21	4.45	4.88	5.90	
CD (5%)	Zn- 0.51			Ni- 0.47		Zn x Ni- NS	

In loamy sand soil, amorphous Fe-oxides bound nickel increased significantly over control with graded levels of applied zinc (Table 4.15). Its content increased significantly from 3.19 mg kg^{-1} soil in control to 3.75, 3.70 and 3.96 mg kg^{-1} soil with the application of 20, 40 and 80 mg Zn kg^{-1} soil which represented an increase of 17.5, 16.0 and 24.1 per cent over control. However, it decreased by 1.33% with application of 40 mg Zn kg^{-1} soil compared with the application of 20 mg Zn kg^{-1} soil but this was not significant. The differences in the content of amorphous oxides bound nickel observed with the application of 20, 40 and 80 mg Zn kg^{-1} soil were not significant. In sandy loam soil, AMPOX-Ni increased significantly by 15.5, 21.7 and 29.3 per cent over control with the graded levels of applied zinc in sandy loam soil. It increased significantly from 3.41 mg kg^{-1} soil in control to 3.94, 4.15 and 4.41 mg kg^{-1} soil with the application of 20, 40 and 80 mg Zn kg^{-1} soil, respectively. Also a non-significant increase was observed when Ni was applied @ 2.5, 5 and 10 mg Zn kg^{-1} soil.

Nickel application significantly increased AMPOX-Ni from 1.55 mg kg^{-1} soil in control to 2.09, 2.70, 3.72, 4.51 and 6.67 mg kg^{-1} soil in loamy sand soil and from 1.87 mg kg^{-1} soil in control to 2.82, 3.21, 4.45, 4.88 and 5.90 mg kg^{-1} soil in sandy loam soil with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.15). Thus, content of Ni in amorphous Fe-oxides increased by 0.34, 0.74, 1.4, 1.90 and 3.30 times in loamy sand and by 0.51, 0.72, 1.38, 1.61 and 2.15 times in sandy loam over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. The absolute amount of nickel in this pool was observed to be more in medium textured sandy loam soil as compared to light textured loamy sand soil. Amorphous oxides bound Ni was significantly positively correlated with CRYOX-Ni, OM-Ni and RES-Ni in both the soils (Table 4.20). Interaction effect of applied Zn and Ni levels on AMPOX-Ni was not significant.

4.1.15 Crystalline Fe and Al oxides bound nickel (CRYOX-Ni)

Table 4.16: Effect of Zn and Ni on crystalline Fe and Al oxides bound nickel

Levels of Zn (mg kg^{-1} soil)	CRYOX-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	1.56	2.27	3.50	3.92	4.33	5.15	3.46
2.5	1.43	2.10	3.34	3.81	4.29	4.90	3.31
5	1.37	2.05	3.41	3.69	4.16	4.82	3.25
10	1.26	1.94	3.33	3.85	4.45	4.80	3.27
20	1.39	2.10	3.25	3.43	4.13	4.70	3.17
40	1.25	1.97	3.16	3.51	4.09	4.80	3.13
80	1.30	1.84	3.20	3.14	4.17	4.69	3.06
Mean	1.37	2.04	3.31	3.62	4.23	4.84	
CD (5%)	Zn- NS			Ni- 0.35		Zn x Ni- NS	
Sandy loam							
0	1.70	2.99	3.89	4.73	5.65	6.96	4.32
2.5	1.72	2.88	3.70	4.08	5.52	6.89	4.13
5	1.62	2.73	3.83	3.91	5.45	6.80	4.06
10	1.49	2.86	3.88	4.18	5.33	6.88	4.10
20	1.52	2.72	3.87	4.08	5.10	6.76	4.01
40	1.63	2.75	3.79	3.91	5.71	6.17	3.99
80	1.60	2.80	3.88	4.23	5.18	5.98	3.94
Mean	1.61	2.82	3.83	4.16	5.42	6.63	
CD (5%)	Zn- NS			Ni- 0.29		Zn x Ni- NS	

The data on the effect of Zn and Ni application on crystalline oxides bound Ni is presented in Table 4.16. It was observed that there was no significant effect of applied Zn on crystalline oxides bound Ni. Although there was a decrease in CRYOX-Ni when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil in both soils, but this decrease was not significant. Application of nickel significantly increased the content of CRYOX-Ni at each level of applied nickel in both the soils. Its content increased from 1.37 mg kg^{-1} soil in control to 2.04, 3.31, 3.62, 4.23 and 4.84 mg kg^{-1} soil in loamy sand soil and from 1.61 mg kg^{-1} soil in control to 2.82, 3.83, 4.16, 5.42 and 6.63 mg kg^{-1} soil in sandy loam soil, with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.16). The content of Ni in this pool increased by about 0.49, 1.42, 1.64, 2.08 and 2.53 times over control in loamy sand and by 0.75, 1.38, 1.58, 2.36 and 3.11 times over control when Ni was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Crystalline oxides bound Ni was significantly positively correlated with OM-Ni and RES-Ni in both the soils (Table 4.20). Interaction effect of zinc and nickel levels on CRYOX-Ni was not significant.

4.1.16 Organically bound nickel (OM-Ni)

Table 4.17:Effect of Zn and Ni on organically bound nickel

Levels of Zn (mg kg^{-1} soil)	OM-Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	1.69	2.50	2.87	3.64	4.13	5.41	3.37
2.5	1.62	2.68	2.95	3.77	4.19	5.49	3.45
5	1.65	2.51	2.84	3.41	4.18	5.74	3.39
10	1.64	2.46	2.99	3.93	4.87	5.81	3.62
20	1.72	2.62	2.71	3.81	4.66	5.89	3.57
40	1.69	2.26	2.81	3.83	4.17	5.28	3.34
80	1.58	2.43	2.75	3.61	4.92	5.51	3.47
Mean	1.66	2.49	2.85	3.71	4.45	5.59	
CD (5%)	Zn- NS			Ni- 0.56		Zn x Ni- NS	
Sandy loam							
0	1.97	2.66	2.91	3.89	4.11	4.72	3.37
2.5	2.12	2.68	2.94	3.95	4.03	4.82	3.42
5	2.19	2.69	3.12	3.94	4.22	4.79	3.49
10	2.33	2.46	3.11	3.92	4.19	4.81	3.47
20	2.13	2.67	3.69	3.79	4.28	4.87	3.57
40	2.16	2.69	3.33	3.99	4.26	4.95	3.56
80	2.22	2.72	3.27	3.90	4.19	4.81	3.52
Mean	2.16	2.65	3.20	3.91	4.18	4.82	
CD (5%)	Zn- NS			Ni- 0.57		Zn x Ni- NS	

In loamy sand soil, organically bound Ni increased from 3.37 mg kg^{-1} soil in control to 3.45, 3.39, 3.62, 3.57 and 3.47 mg kg^{-1} soil when Zn was applied @ 2.5, 5, 10, 20 and 80 mg Zn kg^{-1} soil (Table 4.17). In sandy loam soil, its content increased from 3.37 mg kg^{-1} soil in control to 3.42, 3.49, 3.47, 3.57, 3.56 and 3.52 mg kg^{-1} soil when Zn was applied @ 2.5, 5, 10,20, 40 and 80 mg Zn kg^{-1} soil. But in both soils this increase was not significant. Organically bound nickel increased significantly from 1.66 mg kg^{-1} soil in control to 2.49, 2.85, 3.71, 4.45 and 5.59 mg kg^{-1} soil in loamy sand with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. In sandy loam soil, it increased significantly from 2.16 mg kg^{-1} soil in control to 3.20, 3.91, 4.18 and 4.82 mg kg^{-1} soil with the application of 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Thus, the content of nickel in organically bound pool increased by 0.5, 0.72, 1.23, 1.68 and 2.37 times in loamy sand and by 0.23, 0.48, 0.81, 0.93 and 1.23 times in sandy loam over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. As the content of organic matter was also higher in sandy loam soil compared to loamy sand, the content of nickel in organic matter fraction was also higher in sandy loam soil compared to loamy sand soil. Organically bound Ni was significantly positively correlated with RES-Ni in both the soils (Table 4.20). The interaction effect of zinc and nickel on OM-Ni was not significant.

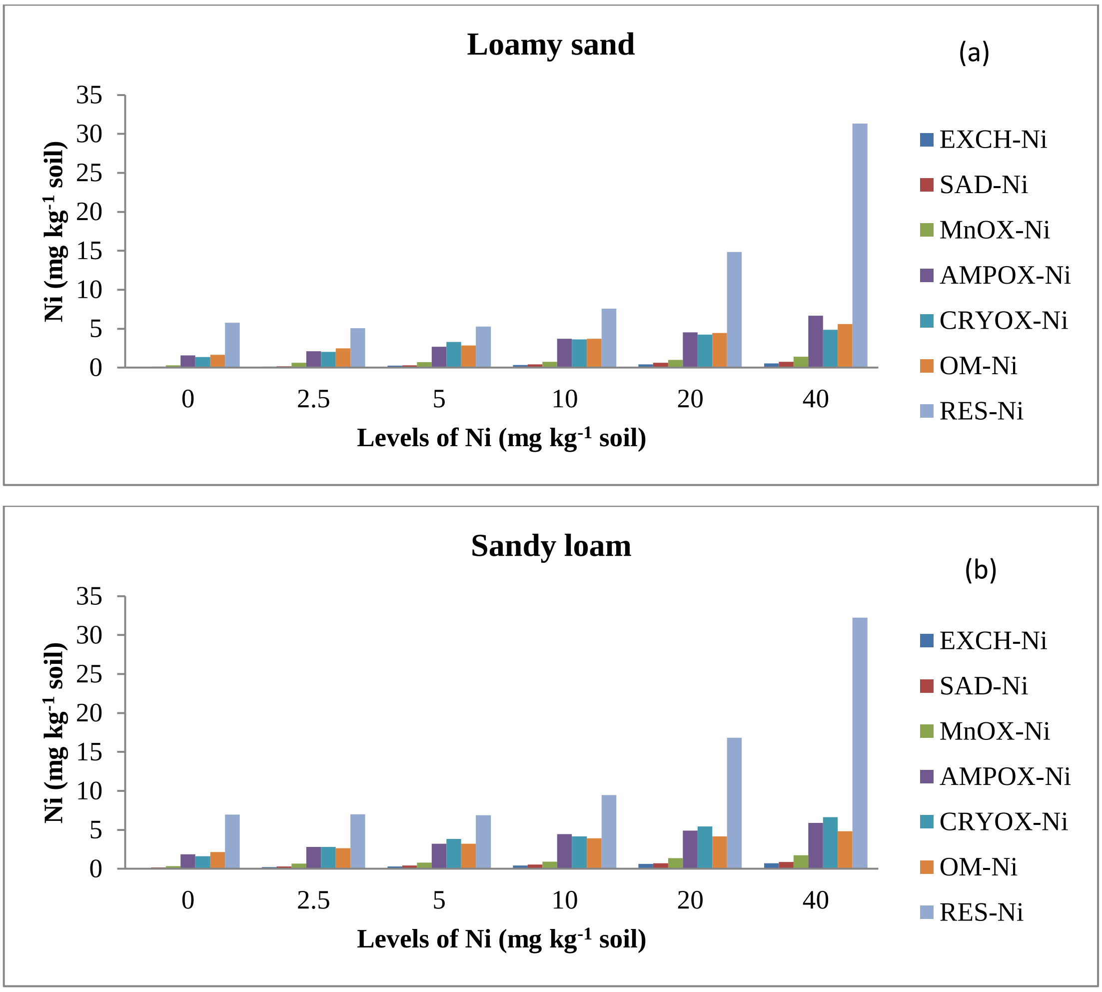


Fig.4.4: Nickel content in various chemical pools as influenced by Ni application

4.1.17 Residual nickel (RES-Ni)

Table 4.18: Effect of Zn and Ni on residual mineral fraction of nickel

Levels of Zn (mg kg^{-1} soil)	Residual Ni (mg kg^{-1} soil)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	6.04	5.69	6.45	7.78	15.13	32.04	12.19
2.5	5.78	5.31	6.36	8.18	15.13	31.86	12.11
5	5.68	5.25	5.83	8.07	14.84	31.65	11.89
10	5.61	5.10	5.36	7.50	14.86	30.66	11.51
20	5.89	4.73	4.54	7.60	14.97	30.50	11.37
40	5.80	4.67	4.03	7.11	14.81	31.56	11.33
80	5.53	4.65	4.34	6.90	14.25	31.13	11.13
Mean	5.76	5.06	5.27	7.59	14.86	31.34	
CD (5%)	Zn- NS			Ni- 0.84		Zn x Ni- NS	
Sandy loam							
0	6.84	6.96	7.07	9.33	17.54	33.26	13.50
2.5	6.99	6.84	7.12	9.18	17.29	33.22	13.44
5	7.00	6.96	6.90	9.66	17.20	32.85	13.43
10	7.07	7.03	6.78	8.95	15.98	32.00	12.97
20	6.82	6.59	6.74	9.49	16.28	31.32	12.87
40	7.10	7.33	6.88	9.57	17.34	31.65	13.31
80	6.95	7.19	6.65	9.95	16.03	31.25	13.00
Mean	6.97	6.98	6.88	9.45	16.81	32.22	
CD (5%)	Zn- NS			Ni- 0.73		Zn x Ni- NS	

Zinc application decreased non significantly the content of Ni in residual fraction over control in both the soils (Table 4.18). In loamy sand, it decreased from 12.19 mg kg^{-1} soil in control to 12.11, 11.89, 11.51, 11.37, 11.33 and 11.13 mg kg^{-1} soil and in sandy loam soil it decreased from 13.50 mg kg^{-1} soil in control to 13.44, 13.43, 12.97, 12.87, 13.31 and 13.00 mg kg^{-1} soil, when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. In sandy loam soil, it increased by 3.30 per cent with the application of 40 mg Zn kg^{-1} soil when compared to 20 mg Zn kg^{-1} soil. Application of nickel significantly increased the content of Ni in residual mineral fraction when it was applied @ 10, 20 and 40 mg Ni kg^{-1} in both the soils. Its content increased from 5.76 mg kg^{-1} soil in control to 7.59, 14.86, 31.34 mg kg^{-1} soil in loamy sand soil and from 6.97 mg kg^{-1} soil in control to 9.45, 16.81 and 32.22 mg kg^{-1} soil in sandy loam soil, with the application of 10, 20 and 40 mg Ni kg^{-1} soil, respectively. It increased by 0.32, 1.58 and 4.44 times in loamy sand and by 0.35, 1.41 and 3.62 times in sandy loam soil over control, when Ni was applied @ 10, 20 and 40 mg Ni kg^{-1} soil, respectively. However its content decreased from 5.76 mg kg^{-1} soil in control to 5.06 and 5.27 mg kg^{-1} soil in loamy sand and from 6.97 mg kg^{-1} soil in control to 6.94 and 6.88 mg kg^{-1} soil in sandy loam with the application of 2.5 and 5 mg Ni kg^{-1} soil, respectively. But this decrease was not significant. The interaction effect of Zn and Ni levels on residual nickel was also not significant.

4.1.18 Per cent recovery of applied Ni @ 40 mg kg^{-1} soil in different chemical pools

Table 4.19 Per cent recovery of applied Ni @ 40 mg kg^{-1} soil in different pools

Per cent of applied Zn @ mg kg^{-1} soil							
Loamy sand soil							
Levels of Zn	EXCH-Ni	SAD-Ni	MnOX-Ni	AMPOX-Ni	CRYOX-Ni	OM-Ni	RES-Ni
0	1.32	1.70	2.12	10.52	8.90	9.30	65.00
2.5	1.25	1.67	2.42	10.70	8.60	9.67	65.20
5	1.25	1.70	2.67	10.90	8.60	10.2	64.92
10	1.35	1.57	2.50	13.00	8.88	10.4	62.62
20	1.22	1.35	2.92	14.55	8.27	10.4	61.52
40	1.15	1.47	3.32	14.80	8.87	8.97	64.40
80	1.10	1.37	3.37	15.10	8.47	9.82	64.00
Mean	1.25	1.55	2.75	12.80	8.67	9.82	63.95
Sandy loam soil							
0	1.75	1.92	2.37	8.97	13.15	6.87	66.05
2.5	1.67	1.75	2.72	9.00	12.92	6.75	65.57
5	1.52	1.97	2.92	9.22	12.95	6.50	64.62
10	1.52	1.47	4.07	10.6	13.47	6.20	62.32
20	1.50	1.82	4.45	10.8	13.10	6.85	61.25
40	1.42	1.70	3.77	10.4	11.35	6.97	61.37
80	1.47	1.67	4.05	11.3	10.95	6.47	60.75
Mean	1.55	1.75	3.50	10.0	12.55	6.65	63.12

When an element is applied to soil through external sources many chemical reactions like adsorption, precipitation and complexation takes place. The per cent recovery of added Ni @ 40 mg kg^{-1} soil at different levels of applied Zn in a particular fraction was calculated by taking the difference of the content of Ni in that fraction in nickel treated pot and the corresponding no nickel pot. Soil Ni was largely found in unavailable forms and it was observed that in loamy sand soil only 1.25 and 1.55 per cent and in sandy loam 1.55 and 1.75 per cent of applied nickel @ 40 mg kg^{-1} soil entered in to exchangeable and specifically adsorbed fractions, respectively which are considered to be the most plant available forms. (Table 4.19) A major portion of the added Ni entered in to residual mineral fraction followed by amorphous Fe-oxides and organically bound Ni in loamy sand whereas in sandy loam, a major portion of the added Ni entered in to residual mineral fraction followed by crystalline and amorphous oxides. Only 2.75 and 3.5 per cent of added nickel entered in to MnOX bound-Ni in loamy sand and sandy loam soil, respectively. Narwal and Singh (1998) studied that Ni was present in small quantities in exchangeable form. Wang and Qu (1992) reported the distribution of chemical forms of Ni in manured loessial soil. Their results revealed that Ni was mainly in residual form, second dominant form Fe oxide bound, third organic matter or carbonates and exchangeable was very less. Ma and Rao (1997) reported that residual fraction was the most abundant pool for Cd, Cu, Ni and Zn in nine contaminated soils.

Linear coefficients of correlation among various chemical pools of Ni alsio indicated that most of these pools were significantly and positively correlated amongst themselves thereby suggesting the existence of a dynamic equilibrium among different forms. Thus, depletion in the concentration of one pool either due to plant uptake or its transformation may be replenished by other pools.

Table 4.20: Coefficients of correlation among various pools of nickel

Loamy sand						
	EXCH-Ni	SAD-Ni	MnOX-Ni	AMPOX-Ni	CRYOX-Ni	OM-Ni
SAD-Ni	0.980^{**}					
MnOX-Ni	0.961^{**}	0.956^{**}				
AMPOX-Ni	0.969^{**}	0.975^{**}	0.977^{**}			
CRYOX-Ni	0.991^{**}	0.963^{**}	0.937^{**}	0.930^{**}		
OM-Ni	0.982^{**}	0.983^{**}	0.983^{**}	0.988^{**}	0.959^{**}	
RES-Ni	0.833^{*}	0.879^{*}	0.902^{*}	0.937^{**}	0.761	0.884^{*}
DTPA-Ni	0.959^{**}	0.947^{**}	0.899^{*}	0.918^{**}	0.959^{**}	0.959^{**}
DTPA-Zn	-0.960^{**}	-0.913^{*}	-0.920^{**}	-0.885^{*}	-0.980^{**}	-0.937^{**}
Sandy loam						
	EXCH-Ni	SAD-Ni	MnOX-Ni	AMPOX-Ni	CRYOX-Ni	OM-Ni
SAD-Ni	0.998^{**}					
MnOX-Ni	0.985^{**}	0.992^{**}				
AMPOX-Ni	0.986^{**}	0.989^{**}	0.973^{**}			
CRYOX-Ni	0.989^{**}	0.991^{**}	0.991^{**}	0.978^{**}		
OM-Ni	0.987^{**}	0.987^{**}	0.965^{**}	0.996^{**}	0.980^{**}	
RES-Ni	0.857^{*}	0.884^{*}	0.911^{*}	0.847^{*}	0.863^{*}	0.828^{*}
DTPA-Ni	0.984^{**}	0.981^{**}	0.951^{**}	0.993^{**}	0.961^{**}	0.994^{**}
DTPA-Zn	-0.977^{**}	-0.988^{**}	-0.987^{**}	-0.977^{**}	-0.981^{**}	-0.974^{**}

**Significant at 1% level

* Significant at 5% level

4.2 Interactive effects of Zn and Ni application on root dry matter, grain and straw yield

4.2.1 Visual observations

In absence of applied Zn, growth of crop reduced with graded levels of applied Ni in loamy sand (Plate1). In absence of applied Ni, growth of crop reduced with graded levels of applied Zn in loamy sand (Plate2). However, when each level of Ni was applied in combination with 5 mg Zn kg^{-1} soil in loamy sand, growth of crop was improved (Plate3) as well as when each level of Ni was applied in combination with 10 mg Zn kg^{-1} and soil in loamy sand, growth of crop was improved (Plate4).

4.2.2 Root dry matter yield (RDMY)

Table 4.21: Effect of Zn and Ni on root dry matter yield of rice

Levels of Zn (mg kg^{-1} soil)	Root dry matter yield (g pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	2.51	2.85	3.75	3.64	3.57	3.42	3.29
2.5	3.64	4.53	4.89	4.70	4.46	4.17	4.40
5	4.08	4.65	4.97	5.16	5.19	5.13	4.86
10	4.73	4.81	5.12	5.60	5.47	5.29	5.17
20	4.78	4.99	5.27	5.77	5.52	5.47	5.30
40	5.04	5.33	5.51	5.69	5.62	5.52	5.45
80	4.94	5.50	5.87	5.91	5.82	5.74	5.63
Mean	4.25	4.67	5.05	5.21	5.09	4.96	
CD (5%)	Zn- 0.25			Ni-0.23		Zn x Ni- NS	
Sandy loam							
0	3.39	3.97	3.64	3.37	3.24	2.76	3.39
2.5	3.55	4.70	4.73	4.88	3.34	2.86	4.01
5	3.85	4.68	4.80	4.79	3.02	2.59	3.95
10	3.66	4.88	4.84	4.80	3.03	2.58	3.96
20	3.33	4.76	4.89	4.69	3.76	2.63	4.01
40	3.14	4.07	4.01	4.35	4.14	2.52	3.71
80	2.91	3.89	3.59	3.35	3.12	2.88	3.29
Mean	3.40	4.42	4.36	4.32	3.38	2.69	
CD (5%)	Zn- 0.48			Ni- 0.44		Zn x Ni- NS	

The data on dry matter yield of root (RDMY) as influenced by Zn and Ni application is presented in Table 4.21. In loamy sand soil, Zn application @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil significantly increased the mean RDMY by 33.7, 47.7, 57.1, 61.0, 65.6 and 71.1 per cent over control. It increased from 3.29 g pot^{-1} in control to 4.40, 4.86, 5.17, 5.30, 5.45 and

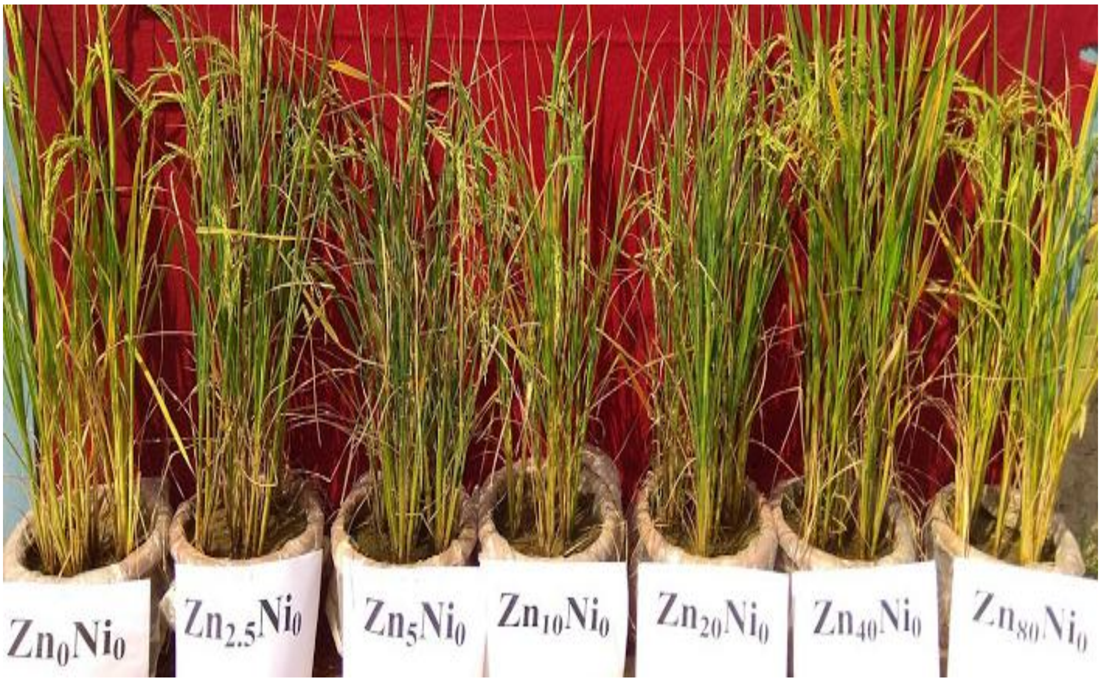


Plate 1: Growth of rice as influenced by graded levels of applied Zn in the absence of applied Ni in loamy sand

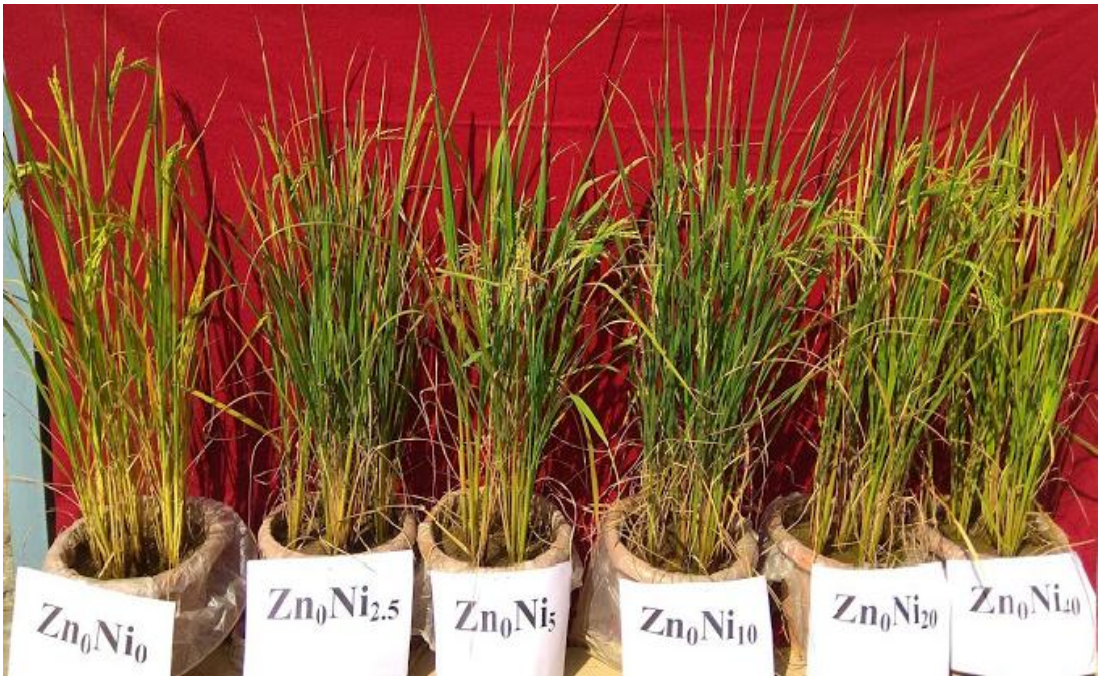


Plate 2: Growth of rice as influenced by graded levels of applied Ni in the absence of applied Zn in loamy sand

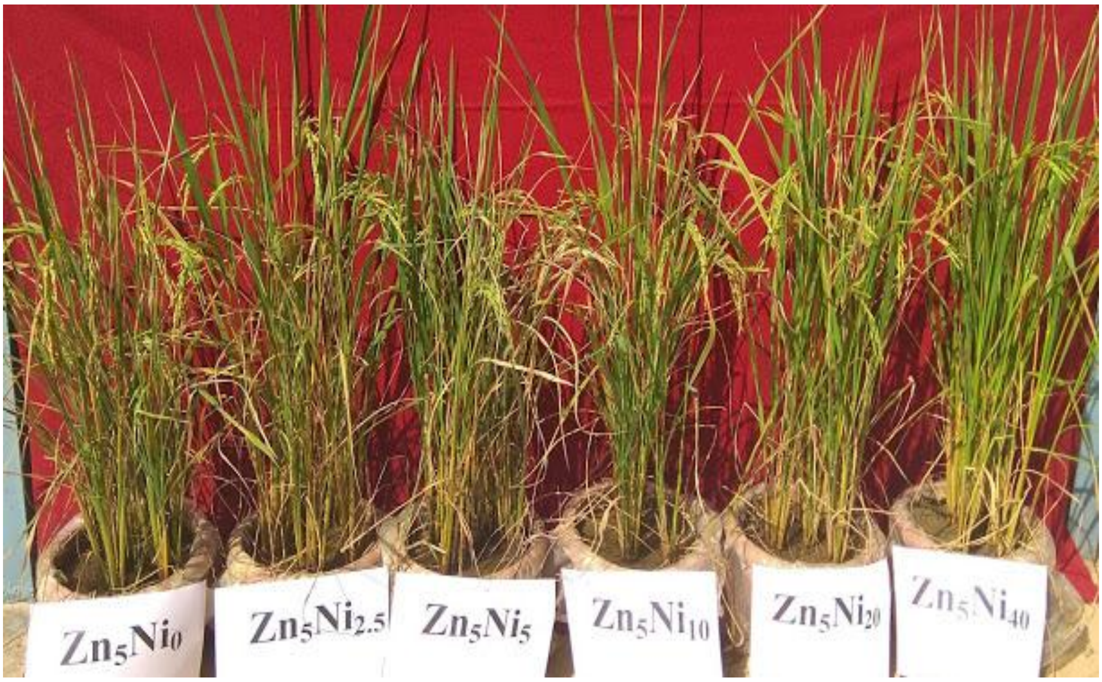


Plate 3: Growth of rice as influenced by graded levels of applied Ni when Zn was applied @ 5 mg kg^{-1} soil, in loamy sand

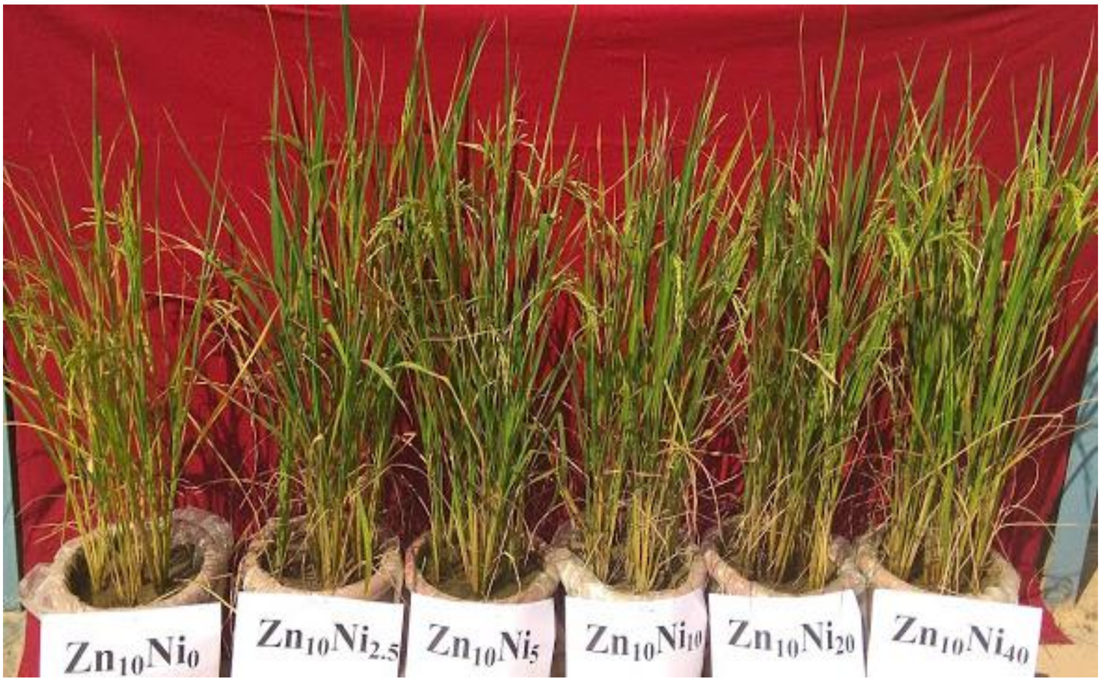


Plate 4: Growth of rice as influenced by graded levels of applied Ni when Zn was applied @ 10 mg kg^{-1} soil, in loamy sand

5.63 g pot^{-1} when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil. However, the differences in RDMY produced with application of 20, 40 and 80 mg Zn kg^{-1} soil, were not significant. In sandy loam soil, the mean RDMY increased by 18.2, 16.5, 16.8, 18.2 per cent over control with the application of 2.5, 5, 10 and 20 mg Zn kg^{-1} soil, respectively. The differences in RDMY produced with application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil were not significant, which may be attributed more amount of DTPA-Zn (1.20 mg kg^{-1} soil) in sandy loam as compared to loamy sand (1.0 mg DTPA-Zn kg^{-1} soil). The quadratic response of relative dry matter yield of root to DTPA-Zn indicated that in loamy sand (Fig.4.5a, R^2=0.85) the root yield increased up to level of 2.72 mg DTPA-Zn kg^{-1} soil and thereafter it declined, whereas in sandy loam (Fig.4.5b, R^2=0.56) the root yield increased up to level of 2.27 mg DTPA-Zn kg^{-1} soil and thereafter it declined. Irrespective of soils, the critical level to produce 90 and 50 per cent of the maximum RDMY as estimated by Mitscherlich and quadratic model was observed to be 0.52 (Table 4.22) and 12.07 (Table 4.23) mg DTPA-Zn kg^{-1} soil, respectively. Fageria (2002) reported that addition of zinc increased the root dry weight in upland rice. Sriramachandrasekharan and Mathan (1988) conducted a field experiment to study the influence of zinc on the growth characters of root. Application of zinc increased root length, root volume and root weight and root length density.

In loamy sand soil, the mean RDMY increased significantly from 4.25 g pot^{-1} in control to a maximum of 5.21 g pot^{-1} when Ni was applied @ 10 mg kg^{-1} soil. Thereafter, it deceased up to a level of 40 mg Ni kg^{-1} soil. However, in sandy loam soil mean RDMY increased significantly from 3.40 g pot^{-1} in control to a maximum of 4.42 g pot^{-1} with the lowest level of applied Ni and thereafter it decreased significantly from 3.40 g pot^{-1} in control to 2.69 g pot^{-1} when Ni was applied @ 40 mg Ni kg^{-1} soil (Table 4.21). In loamy sand soil, RDMY increased by 9.8, 18.8, 22.5, 19.7 and 16.7 per cent over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg $^{-1}$ soil, respectively whereas in sandy loam soil it increased by 30, 28.2 and 27.0 per cent over control with the application of 2.5, 5 and 10 mg Ni kg $^{-1}$ soil, respectively. The quadratic response of relative dry matter yield of root to DTPA-Ni in both the soils (Fig.4.5c, R^2=0.97 and Fig.4.5d, R^2=0.91) indicated that 90 per cent of maximum relative root dry matter yield was produced when soil contained 2 mg DTPA-Ni kg^{-1} soil. Kumar (1992) observed that mean dry matter yield of maize root increased significantly when Ni was applied @ 20 µg g^{-1} soil, but when rate of application of Ni was increased to 100 µg g^{-1} soil, dry matter yield of root decreased. The interaction effect of applied Zn and Ni on RDMY was non-significant. Irrespective of soils the critical level of DTPA-Ni to produce 50 per cent of maximum RDMY was found to be 5.3 mg kg^{-1} soil (Table 4.23).

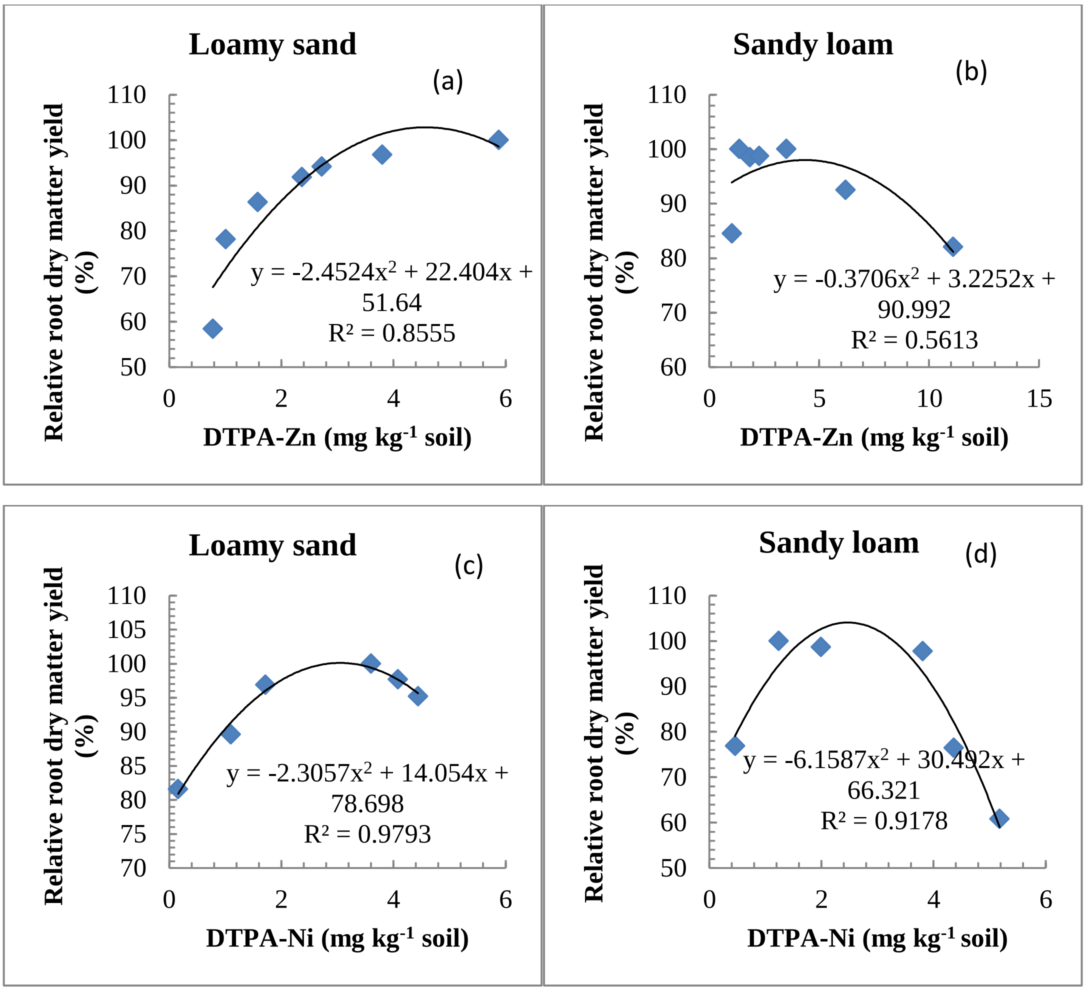


Fig.4.5: Relationship of DTPA-Zn and DTPA-Ni in soil with relative root dry matter yield

Table 4.22: Critical levels of Zn and Ni in soil and plant parts for production of 90% of maximum yield

Plant parts	Mitscherlich model	R^2	Critical level for 90% production of maximum yield
			DTPA-Zn (mg kg^{-1} soil)
Root	$Y=77.50(1-0.22e^{-1.38x})$	0.110	0.56
Straw	$Y=84.08(1-0.19e^{-1.55x})$	0.185	0.43
			Root Zn (µg g^{-1})
Root	$Y=78.24(1-0.31e^{-0.05x})$	0.177	20.6
			Grain Zn (µg g^{-1})
Grain	$Y=86.24(1-1.84e^{-0.32x})$	0.110	9.04
			Root Ni (µg g^{-1})
Root	$Y=80.02(1-0.01e^{0.04x})$	0.017	53.8
			Straw Ni (µg g^{-1})
Straw	$Y=81.32(1-0.62e^{-1.45x})$	0.069	1.26

Table 4.23: Critical levels of Zn and Ni in soil and plant parts for reduction of 50% of maximum yield

Plant parts	Quadratic model	R^2	Critical level for 50% reduction of maximum yield
			DTPA-Zn (mg kg^{-1} soil)
Root	$y = -0.7933x^2 + 8.8108x + 59.188$	0.215**	12.0
Grain	$y = -0.3873x^2 + 4.7584x + 77.179$	0.214**	16.5
Straw	$y = -0.5137x^2 + 6.0587x + 70.313$	0.198**	14.5
			DTPA-Ni (mg kg^{-1} soil)
Root	$y = -4.3625x^2 + 21.927x + 58.062$	0.301**	5.37
Grain	$y = -2.0163x^2 + 11.795x + 74.052$	0.297**	7.45
Straw	$y = -2.4558x^2 + 15.548x + 63.412$	0.351**	7.10
			Root Zn (µg g^{-1})
Root	$y = -0.004x^2 + 0.7525x + 45.098$	0.177**	181.3
			Root Ni (µg g^{-1})
Root	$y = -0.0108x^2 + 0.271x + 74.55$	0.117**	61.8
			Grain Ni (µg g^{-1})
Grain	$y = -1.1825x^2 + 5.1229x + 81.833$	0.026	7.79
			Straw Ni (µg g^{-1})
Straw	$y = -0.1145x^2 + 2.4946x + 70.111$	0.091*	28.0

4.2.3 Grain yield

Table 4.24:Effect of Zn and Ni on grain yield of rice

Levels of Zn (mg kg^{-1} soil)	Grain yield (g pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	21.1	26.8	29.8	29.1	27.8	26.3	26.8
2.5	26.2	27.4	31.1	29.6	33.4	30.4	29.7
5	27.4	28.8	36.6	28.7	27.6	26.1	29.2
10	30.3	33.2	35.4	35.0	32.2	30.4	32.7
20	31.2	32.8	35.1	33.1	36.2	33.5	33.7
40	31.2	34.7	34.8	36.6	36.1	36.8	35.0
80	30.8	33.5	32.9	35.0	37.5	35.8	34.3
Mean	28.3	31.0	33.7	32.5	33.0	30.7	
CD (5%)	Zn- 2.23			Ni- 2.07		Zn x Ni- NS	
	Sandy loam						
0	25.3	30.0	32.7	33.4	34.7	30.1	31.0
2.5	29.9	30.7	33.4	33.7	34.5	30.4	32.1
5	32.9	33.8	33.5	34.8	33.3	33.6	33.7
10	31.7	34.8	34.6	34.6	35.2	30.8	33.6
20	30.5	32.3	34.5	34.8	35.4	31.5	33.2
40	29.9	33.2	32.2	35.1	35.9	30.3	32.8
80	28.5	30.8	32.0	31.0	33.6	28.7	31.8
Mean	29.8	32.2	33.3	33.9	34.7	30.8	
CD (5%)	Zn- 1.97			Ni- 1.82		Zn x Ni-NS	

The data on the grain yield of rice as influenced by graded levels of applied Zn and Ni is presented in Table 4.24. The mean grain yield increased significantly from 26.8 g pot^{-1} in control to 29.7, 29.2, 32.7, 33.7, 35.0 and 34.3 g pot^{-1} thereby representing a increase of 10.8, 8.9, 22.0, 25.7, 30.6 and 27.9 per cent over control as Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil, respectively in loamy sand soil. In sandy loam soil, the mean grain yield increased significantly from 31.0 g pot^{-1} over control to 33.7, 33.6 and 33.2 g pot^{-1} resulting in an increase of 8.7, 8.3 and 7.1 per cent over control when Zn was applied @ 5, 10 and 20 mg Zn kg^{-1} soil but thereafter with the application of 40 and 80 mg Zn kg^{-1} soil the increase in grain yield was not significant. The quadratic response of relative grain yield to DTPA-Zn indicated in loamy sand (Fig.4.6a, R^2=0.93) soil, maximum grain yield was produced when DTPA-Zn was 3.80 mg DTPA-Zn kg^{-1} soil and thereafter yield declined whereas in sandy loam (Fig.4.6b, R^2=0.37) soil, maximum grain yield was produced when DTPA-Zn was 2.27 md DTPA-Zn kg^{-1} soil and thereafter it declined. An increase of about 4.9 and 6.1% in paddy yield with application of 5 and 10 mg Zn kg^{-1} soil, respectively over control was observed by Kausar *et al* (2001).

Growth of crop was improved with graded levels of applied Ni in both the soils. In loamy sand soil, the mean grain yield of rice increased significantly from 28.3 g pot^{-1} in control to 31.0, 33.7, 32.5 and 33.0 g pot^{-1} resulting in an increase of 9.54, 19.0, 14.8 and 16.6 per cent over control with the application of 2.5, 5, 10 and 20 mg Ni kg^{-1} soil, respectively. The differences in grain yield observed with the application of 5, 10 and 20 mg Ni kg^{-1} soil were not significant. In sandy loam soil, grain yield increased significantly from 29.8 g pot^{-1} in control to 32.2, 33.3, 33.9 and 34.7 g pot^{-1} producing an increase of 8.0, 11.7, 13.7 and 16.4 per cent over control with graded levels of applied Ni, respectively (Table 4.24). The increase in grain yield was observed only up to a level of 20 mg Ni kg^{-1} soil and thereafter it decreased. A significant decrease of 7-11% in grain yield was observed in both soils when Ni was applied @ 40 mg kg^{-1} soil over the application of 20 mg kg^{-1} soil. The quadratic response of relative grain yield to DTPA-Ni indicated that in loamy sand (Fig.4.6c, R^2=0.88) soil, maximum grain yield was produced when DTPA-Ni content was 1.72 mg DTPA-Ni kg^{-1} soil and there after yield declined whereas in sandy loam (Fig.4.6d, R^2=0.86) soil, maximum grain yield was produced when DTPA-Ni content was 4.36 mg DTPA-Ni kg^{-1} soil and thereafter yield declined. Singh (1994) reported that initial rate of Ni up to 5 and 10 µg g^{-1} soil in sandy and clay loam soil respectively, had slight beneficial effect on wheat grain yield, but the yield decreased significantly when Ni was applied @ 40 and 80 µg Ni g^{-1} of sandy and clay loam soil respectively. Paulik (1997) studied that when oats were grown at 0, 14, 28, 56, 84 and 168 µg Ni g^{-1} soil in green house experiment, grain yield increased significantly with 14-56 µg Ni g^{-1}, while 168 µg Ni g^{-1} soil resulted in plant mortality. The interaction effect of applied Zn and Ni on grain yield was non-significant. Irrespective of the soils the critical level to produce 50 per cent of the maximum grain yield of rice as estimated by quadratic model was found to be 16.5 mg DTPA-Zn and 7.45 mg DTPA-Ni kg^{-1} soil (Table 4.23). Das *et al* (2004) reported a significant positive correlation (r=0.82**) between grain yield and Zn content in grain, suggesting an important role of Zn contributing towards yield of rice.

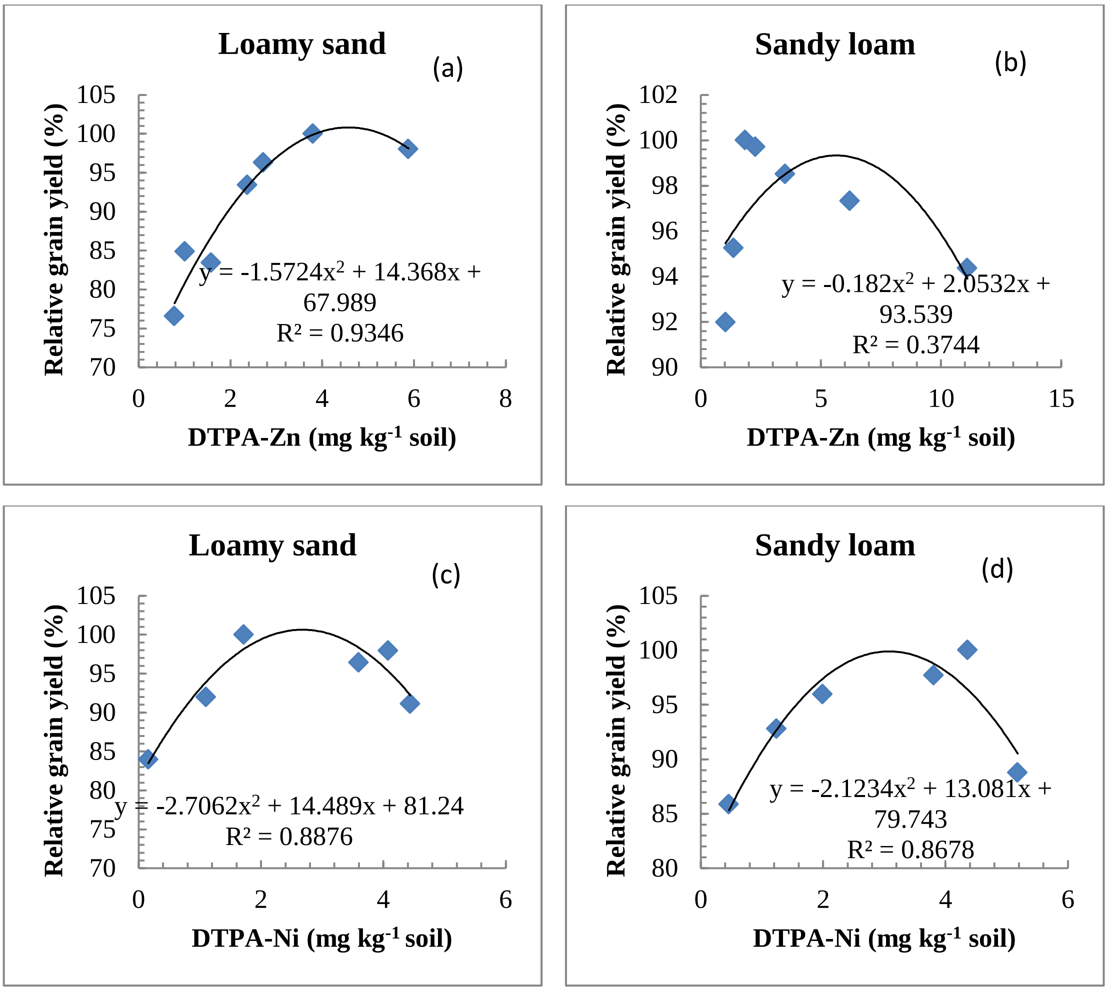


Fig.4.6 Relationship of DTPA-Zn and DTPA-Ni in soil with relative grain yield

4.2.4 Straw yield

The data on the effect of Zn and Ni application on straw yield is presented in Table 4.25. Zinc application significantly increased the straw yield from 33.4 g pot^{-1} in control to 39.2, 41.9, 47.0, 47.9, 48.7 and 45.5 g pot^{-1} thus representing a increase of 17.4, 25.4, 40.7, 43.4, 45.8 and 36.2 per cent over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively in loamy sand soil. In sandy loam soil, straw yield increased significantly from 41.5 g pot^{-1} in control to 46.3, 46.4, 46.2 and 46.0 g pot^{-1} thus representing a increase of 11.6, 11.8, 11.3 and 10.8 per cent over control with the application of 5, 10, 20 and 40 mg Zn kg^{-1} soil, respectively. A significant decrease in straw yield was observed in both soils when Zn was applied @ 80 mg kg^{-1} soil over the application of 40 mg kg^{-1} soil. The quadratic response of relative straw yield to DTPA-Zn indicated that in loamy sand (Fig.4.7a, R^2=0.94) soil, maximum straw yield was produced when DTPA-Zn was 2.72 mg DTPA-Zn kg^{-1} soil and thereafter yield declined whereas in sandy loam (Fig.4.7b, R^2=0.73), soil maximum straw yield was produced when DTPA-Zn content was 2.27 mg DTPA-Zn kg^{-1} soil. Irrespective of soils, the critical level to produce 90 and 50 per cent of maximum straw yield as estimated by Mitscherlich and quadratic model was observed to be 0.43 (Table 4.22) and 14.5 (Table 4.23) mg DTPA-Zn kg^{-1} soil, respectively. Fageria (2001) and Ghatak *et al* (2005) concluded that application of zinc fertilizers (zinc sulphate heptahydrate or zinc oxide) significantly increased the no. of effective tillers, panicle length, plant height, grain/panicle, grain and straw yield. Application of 30 kg zinc sulphate ha^{-1} recorded highest values of yield attributes. Nathan *et al* (2005) observed that dry matter accumulation in rice significantly increased with the application of 13.5 kg Zn ha^{-1}. Dry matter yield of rice was higher (13.6%) with the application of Zn as compared to the control (9.4%). A significant impact on growth and yield of rice due to zinc application was also observed by Malik *et al* (2011), however the fresh and dry matter production of rice was adversely affected when Zn was supplied @ 200 ppm.

Table 4.25: Effect of Zn and Ni on straw yield of rice

Levels of Zn (mg kg^{-1} soil)	Straw yield (g pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	25.3	34.9	38.7	36.7	33.3	31.5	33.4
2.5	32.7	35.3	40.4	37.8	46.7	42.5	39.2
5	33.7	36.8	54.8	38.4	46.9	40.7	41.9
10	39.7	46.4	49.5	52.4	48.3	45.6	47.0
20	39.2	48.2	49.1	46.3	54.3	50.2	47.9
40	39.5	50.6	48.7	50.1	49.8	53.7	48.7
80	38.1	49.5	46.0	49.0	52.4	50.1	45.5
Mean	35.5	43.1	46.8	44.4	47.4	44.9	
CD (5%)	Zn-2.4		Ni- 2.2		Zn x Ni- NS		
Sandy loam							
0	30.3	38.8	42.5	46.7	48.6	42.1	41.5
2.5	38.8	41.1	45.0	47.2	47.9	43.1	43.9
5	42.8	43.9	46.9	50.1	45.9	48.0	46.3
10	40.5	48.7	48.4	48.0	50.7	42.2	46.4
20	39.6	45.2	47.9	48.3	51.3	45.0	46.2
40	37.3	46.5	44.1	51.5	53.8	43.0	46.0
80	35.3	40.0	43.8	40.3	47.4	40.1	41.1
Mean	37.8	43.4	45.5	47.4	49.4	43.4	
CD (5%)	Zn- 3.2		Ni-3.0		Zn x Ni- NS		

In both the soils straw yield increased significantly over control with the graded levels of applied Ni. In loamy sand soil, straw yield increased from 35.5 g pot^{-1} in control to 43.1, 46.8, 44.4 and 47.4 g pot^{-1} and in sandy loam soil it increased from 37.8 g pot^{-1} in control to 43.4, 45.5, 47.4 and 49.4 g pot^{-1} with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. A significant increase of 21.4, 31.8, 25.0 and 33.5 per cent in loamy sand soil and 14.8, 20.4, 25.4 and 30.7 per cent in sandy loam soil was observed with application of 2.5, 5, 10 and 20 mg Ni kg^{-1} soil, respectively (Table 4.25). A significant decreased in straw yield was observed in both soils when Ni was applied @ 40 mg kg^{-1} soil over the application of 20 mg kg^{-1} soil. The quadratic response of relative straw yield to DTPA-Ni indicated that in loamy sand (Fig.4.7c, R^2=0.86) and sandy loam (Fig.4.7d, R^2=0.91) soils, maximum straw yield was produced when soil contained about 4.08 and 4.36 mg DTPA-Ni kg^{-1} soil, respectively and thereafter the yield declined. Irrespective of soils the critical level of DTPA-Ni to produce 50 per cent of maximum straw yield was found to be 7.10 mg kg^{-1} soil (Table 4.23).

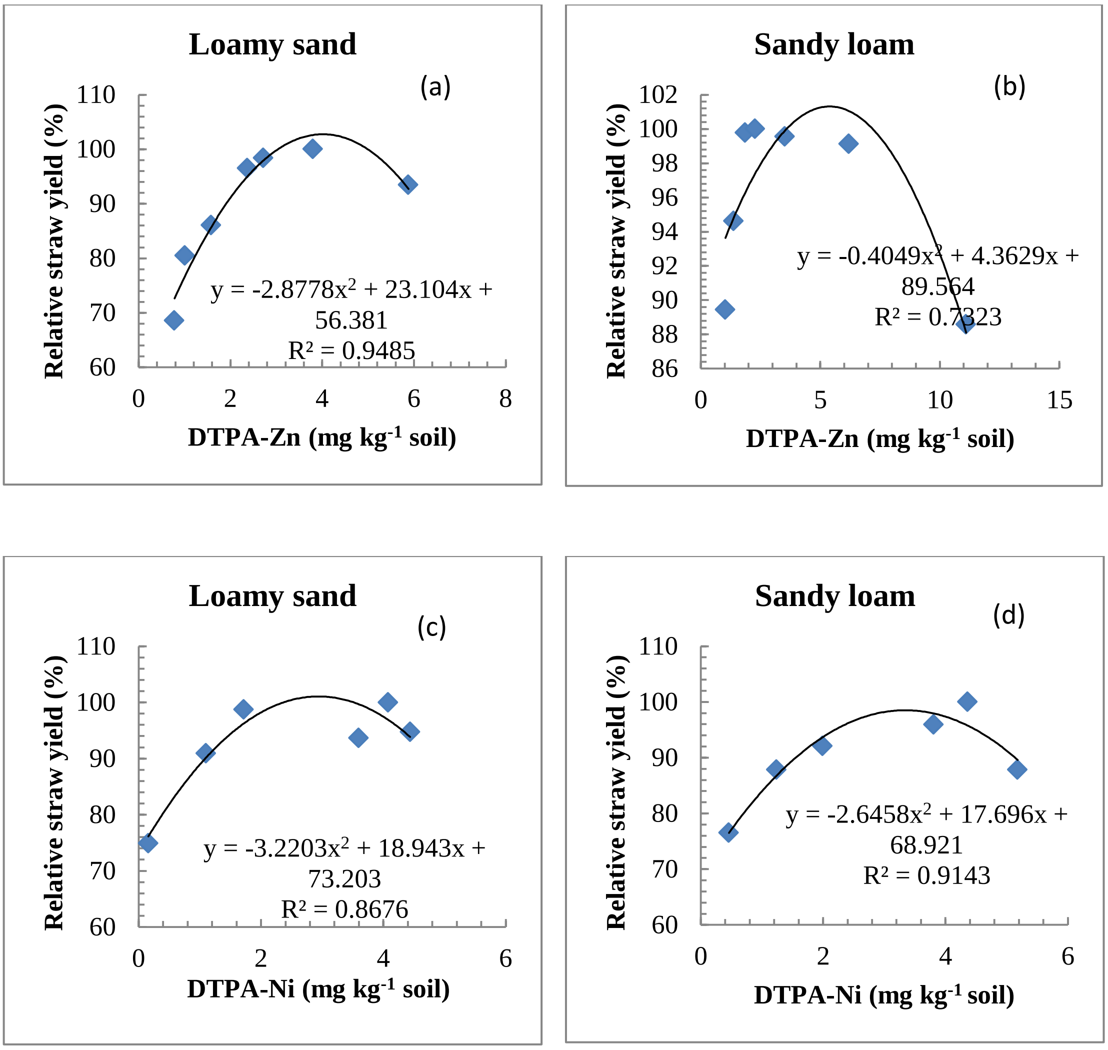


Fig.4.7: Relationship of DTPA-Zn and DTPA-Ni in soil with relative straw yield

Singh (1994) reported that application of 5 and 10 µg Ni g^{-1} soil in sandy and clay loam soil respectively, increase the straw yield of wheat. The yield decreased significantly when Ni was applied @ 40 and 80 µg Ni g^{-1} of sandy and clay loam soil respectively. Kumar (1992) observed that mean dry matter yield of maize shoot increased significantly from 18.33 g pot^{-1} in control to 19.86 g pot^{-1}, when Ni was added at a rate of 20 µg Ni g^{-1} to soils. But when rate of application of Ni was increased to 100 µg Ni g^{-1} soil, it decreased significantly. A non-significant interaction effect of applied Zn and Ni on straw yield was observed in both the soils.

Table 4.26: Coefficients of correlation of root, grain and straw yield of rice with various chemical pools of zinc

Loamy sand soil			
	Root dry matter yield	Grain yield	Straw yield
EXCH-Zn	0.696	0.768*	0.564
SAD-Zn	0.767*	0.768*	0.601
MnOX-Zn	0.756*	0.835*	0.652
AMPOX-Zn	0.759*	0.797*	0.621
CRYOX-Zn	0.881**	0.892**	0.827*
OM-Zn	0.922**	0.916**	0.866*
RES-Zn	0.631	0.687	0.462
DTPA-Zn	0.787*	0.823*	0.660
DTPA-Ni	-0.545	-0.631	-0.408
Sandy loam soil			
	Root dry matter yield	Grain yield	Straw yield
EXCH-Zn	-0.566	-0.135	-0.356
SAD-Zn	-0.344	0.051	-0.099
MnOX-Zn	-0.400	0.059	-0.121
AMPOX-Zn	-0.355	0.062	-0.060
CRYOX-Zn	-0.333	0.182	0.012
OM-Zn	-0.232	0.213	0.077
RES-Zn	-0.641	-0.247	-0.446
DTPA-Zn	-0.584	-0.163	-0.360
DTPA-Ni	0.444	-0.034	0.140

**Significant at 1% level
* Significant at 5% level

Table 4.27: Coefficients of correlation of root, grain and straw yield of rice with various pools of nickel

Loamy sand soil			
	Root dry matter yield	Grain yield	Straw yield
EXCH-Ni	0.749	0.458	0.702
SAD-Ni	0.646	0.358	0.631
MnOX-Ni	0.630	0.345	0.665
AMPOX-Ni	0.581	0.238	0.547
CRYOX-Ni	0.817*	0.569	0.782
OM-Ni	0.671	0.354	0.647
RES-Ni	0.269	-0.068	0.293
DTPA-Ni	0.796	0.486	0.700
DTPA-Zn	-0.881*	-0.651	-0.855*
Sandy loam soil			
	Root dry matter yield	Grain yield	Straw yield
EXCH-Ni	-0.553	0.356	0.622
SAD-Ni	-0.577	0.303	0.578
MnOX-Ni	-0.595	0.246	0.531
AMPOX-Ni	-0.493	0.341	0.613
CRYOX-Ni	-0.516	0.331	0.602
OM-Ni	-0.479	0.368	0.632
RES-Ni	-.0824*	-0.169	0.139
DTPA-Ni	0.486	0.393	0.650
DTPA-Zn	0.627	-0.172	-0.465

**Significant at 1% level
* Significant at 5% level

4.3 Interactive effects of Zn and Ni application on their concentration in root, grain and straw.

4.3.1 Zinc concentration in root

Table 4.28: Effect of Zn and Ni on Zn concentration (µg g^{-1}) in root

Levels of Zn (mg kg^{-1} soil)	Root Zn concentration (µg g^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	47.9	44.7	40.1	34.1	26.5	14.6	34.7
2.5	62.4	58.9	47.2	38.8	33.0	19.3	43.8
5	74.9	71.9	59.9	49.6	40.0	28.4	54.1
10	82.7	76.9	61.8	54.4	43.1	37.0	59.3
20	100.9	94.0	86.1	68.6	60.2	48.6	76.4
40	130.2	113.3	98.2	83.3	77.5	61.1	93.9
80	156.3	135.6	119.1	101.6	88.5	79.9	113.5
Mean	93.6	85.0	73.2	61.5	52.7	41.3	
CD (5%)	Zn-8.9			Ni- 8.2		Zn x Ni- NS	
Sandy loam							
0	42.3	40.9	35.4	27.6	22.3	12.6	30.2
2.5	61.0	51.9	45.6	38.1	28.3	17.1	40.4
5	70.7	64.1	52.1	43.2	30.6	23.0	47.3
10	78.2	69.7	66.7	46.3	38.6	25.0	54.1
20	97.6	90.7	83.7	67.0	61.0	43.3	73.9
40	132.8	105.0	90.3	85.6	74.6	65.9	92.4
80	153.7	130.4	113.6	99.4	80.9	82.0	110.0
Mean	90.9	78.9	69.6	58.2	48.0	38.4	
CD (5%)	Zn- 7.7			Ni- 7.2		Zn x Ni- NS	

Root Zn concentration increased significantly from 34.7 µg g^{-1} dry matter in control to 43.8, 54.1, 59.3, 76.4, 93.9 and 113.5 µg g^{-1} dry matter in loamy sand soil and from 30.2 µg g^{-1} dry matter in control to 40.4, 47.3, 54.1, 73.9, 92.4 and 110.0 µg g^{-1} dry matter in sandy loam soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.28). In loamy sand, Zn concentration in root increased by about 0.26, 0.56, 0.72, 1.20, 1.71 and 2.27 times and in sandy loam increased by 0.34, 0.57, 0.79, 1.44, 2.06 and 2.64 times over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. A positive linear relationship of root Zn concentration with DTPA-Zn in loamy sand (Fig.4.8a, R^2=0.96) and in sandy loam (Fig.4.8b, R^2=0.89) was observed. A significant positive coefficient of correlation of dry matter yield of root with root Zn concentration in loamy sand (r=0.840*) soil was observed (Table 4.34). Malik *et al* (2011) studied the effects of zinc treatments on its concentration in roots, they observed that when the zinc levels in soil solution increased, it's concentrations in roots were also increased. The average Zn concentration ranged from 116.00 to 11549.3 ppm in roots. The maximum concentration (11549.3 ppm) was noticed at 400 ppm Zn and the minimum value (116.0 ppm) was found at the control. A gradual increase of zinc concentration was observed with the increasing Zn levels.

In loamy sand soil, Zn concentration of root decreased significantly from 93.6 µg g^{-1} dry matter to 85.0, 73.2, 61.5, 52.7 and 41.3 µg g^{-1} dry matter when Ni was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil resulting in decrease of 9.2, 21.8, 34.3, 43.7 and 55.9 per cent, respectively over control. In sandy loam soil Zn concentration in root decreased significantly by 13.2, 23.4, 35.9, 47.2 and 57.7 per cent over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. It decreased from 90.9 µg g^{-1} dry matter in control to 38.4 µg g^{-1} dry matter with the application of 40 mg Ni kg^{-1} soil (Table 4.28). A linear negative relationship of root Zn concentration with DTPA-Ni in loamy sand (Fig.4.8c, R^2=0.96) and in sandy loam (Fig.4.8d, R^2=0.98) was observed. Rahman *et al* (2005) reported that concentration of Zn in roots of barley decreased with increasing supply of Ni in the nutrient solution. A non-significant interaction effect of Zn and Ni levels on root Zn concentration was observed in both soils. Irrespective of the soils, critical level of root Zn concentration to produce 90 and 50 per cent of the maximum RDMY as estimated by Mitscherlich and quadratic model was observed to be 20.6 (Table 4.22) and 181.3 (Table 4.23) µg g^{-1}, respectively.

Root Zn concentration to produce 90 per cent of the maximum RDMY was observed to be 59.3 µg g^{-1} in loamy sand and 65.2 µg g^{-1} in sandy loam soil (Fig.4.11a, b).

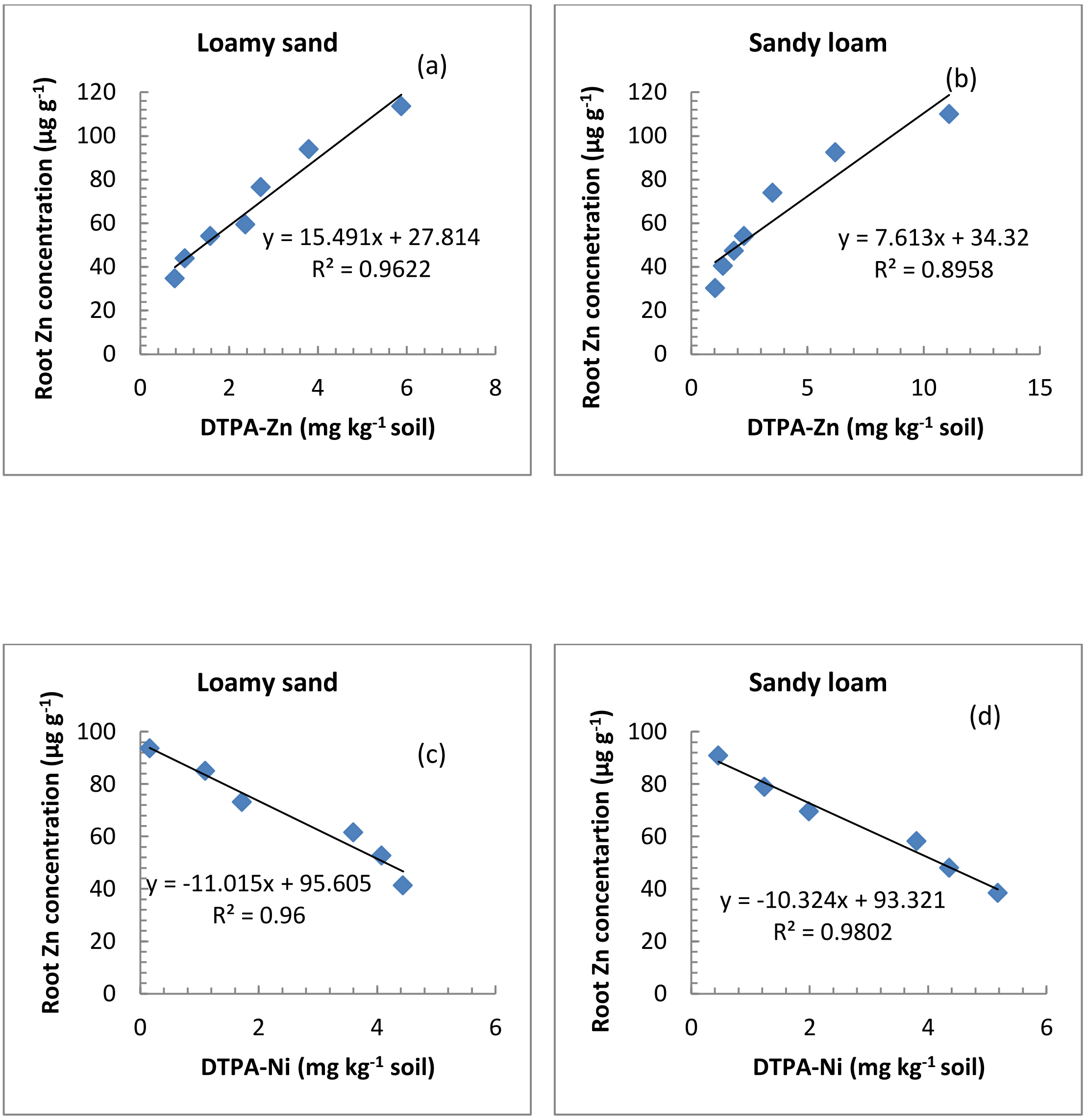


Fig.4.8: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn concentration in root

4.3.2 Zinc concentration in grain

Table 4.29:Effect of Zn and Ni on Zn concentration ($\mu g\ g^{-1}$) in grain

Levels of Zn (mg kg^{-1} soil)	Grain Zn concentration ($\mu g\ g^{-1}$)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	19.0	19.1	19.8	20.5	17.3	15.9	18.6
2.5	20.8	21.3	21.4	20.8	19.2	16.3	20.5
5	24.8	21.8	21.9	20.7	20.1	17.4	21.1
10	25.5	22.6	21.8	20.9	19.9	17.6	21.4
20	26.4	23.6	22.1	20.5	20.6	18.6	22.0
40	28.7	24.5	22.8	22.3	19.6	18.4	22.7
80	28.9	25.9	21.6	21.4	19.5	18.9	22.7
Mean	24.9	22.7	21.6	21.0	19.4	17.6	
CD (5%)	Zn- 1.8		Ni- 1.7		Zn x Ni- NS		
Sandy loam							
0	18.1	18.4	18.5	18.2	14.7	13.2	16.8
2.5	20.5	20.3	19.5	18.9	16.2	16.2	18.6
5	21.1	21.2	19.8	19.1	16.4	16.5	19.0
10	21.9	21.2	19.5	20.5	19.5	17.0	19.9
20	23.8	23.7	22.9	23.1	19.5	17.2	21.7
40	27.9	23.7	22.2	22.8	20.5	19.0	22.7
80	28.6	25.8	24.5	23.6	21.2	21.1	24.1
Mean	23.1	22.0	21.0	20.9	18.3	17.2	
CD (5%)	Zn- 1.4		Ni- 1.3		Zn x Ni- NS		

The data on the effect of Zn and Ni levels on grain Zn concentration is presented in Table 4.29. Grain Zn concentration increased significantly with the application of graded levels of Zn in both the soils. Mean grain Zn concentration increased from 18.6 $\mu g\ g^{-1}$ in control to 20.5, 21.1, 21.4, 22.0, 22.7 and 22.7 $\mu g\ g^{-1}$ in loamy sand soil and from 16.8 $\mu g\ g^{-1}$ in control to 18.6, 19.0, 19.9, 21.7, 22.7 and 24.1 $\mu g\ g^{-1}$ in sandy loam soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. The increase in grain Zn content over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil was of the order of 10.0, 13.0, 15.0, 18.2, 22.0 and 22.0 per cent in loamy sand and 10.7, 13.1, 18.4, 29.1, 35.1 and 43.4 per cent in sandy loam soil, respectively. The quadratic response of grain Zn concentration to DTPA-Zn indicated that in loamy sand (Fig.4.9a, R^2=0.88) grain Zn concentration increased with increasing level of Zn. A linear positive relationship of grain Zn concentration with DTPA-Zn in sandy loam (Fig.4.9b, R^2=0.81) was observed. A significant positive coefficients of correlation of grain yield with grain Zn concentration in loamy sand (r=0.945**) soil was observed (Table 4.34). Shivay *et al* (2008) reported that 1.0% coating of urea either with zinc sulphate or zinc oxide increased Zn concentration in rice grain.

In loamy sand soil, the mean grain Zn concentration decreased significantly from 24.9 µg g^{-1} in control to 22.7, 21.6, 21.0, 19.4 and 17.6 µg g^{-1} thereby resulting in a decrease of 8.8, 13.2, 15.7, 22.0 and 29.3 per cent over control when Ni was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. Whereas in sandy loam soil, grain Zn concentration significantly decreased from 23.1 µg g^{-1} dry matter in control to 21.0, 20.9, 18.3 and 17.2 µg g^{-1} thereby producing a decrease of 9.1, 9.5, 20.7 and 25.5 per cent over control when Ni was applied @ 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.29). However, the differences in grain Zn concentration observed with the application of 2.5, 5 and 10 mg Ni kg^{-1} soil were not significant. A linear negative relationship of grain Zn concentration with DTPA-Ni, in loamy sand (Fig.4.9c, R^2=0.88) and in sandy loam (Fig4.9d, R^2=0.87) was observed. Irrespective of the soils, critical level of Grain Zn concentration to produce 90 per cent of maximum Grain yield was found to be 9.04 µg g^{-1}(Table 4.22). Grain Zn concentration to produce 90 per cent of maximum grain yield was found to be 21.4 µg g^{-1} in loamy sand and 15.5 µg g^{-1} in sandy loam soil (Fig. 4.11c, d). Singh *et al* (1990) observed that Ni had an antagonistic effect on N, Cu, Mn, Zn concentration of wheat grain. The interaction effect of Zn and Ni levels on grain Zn concentration was not significant.

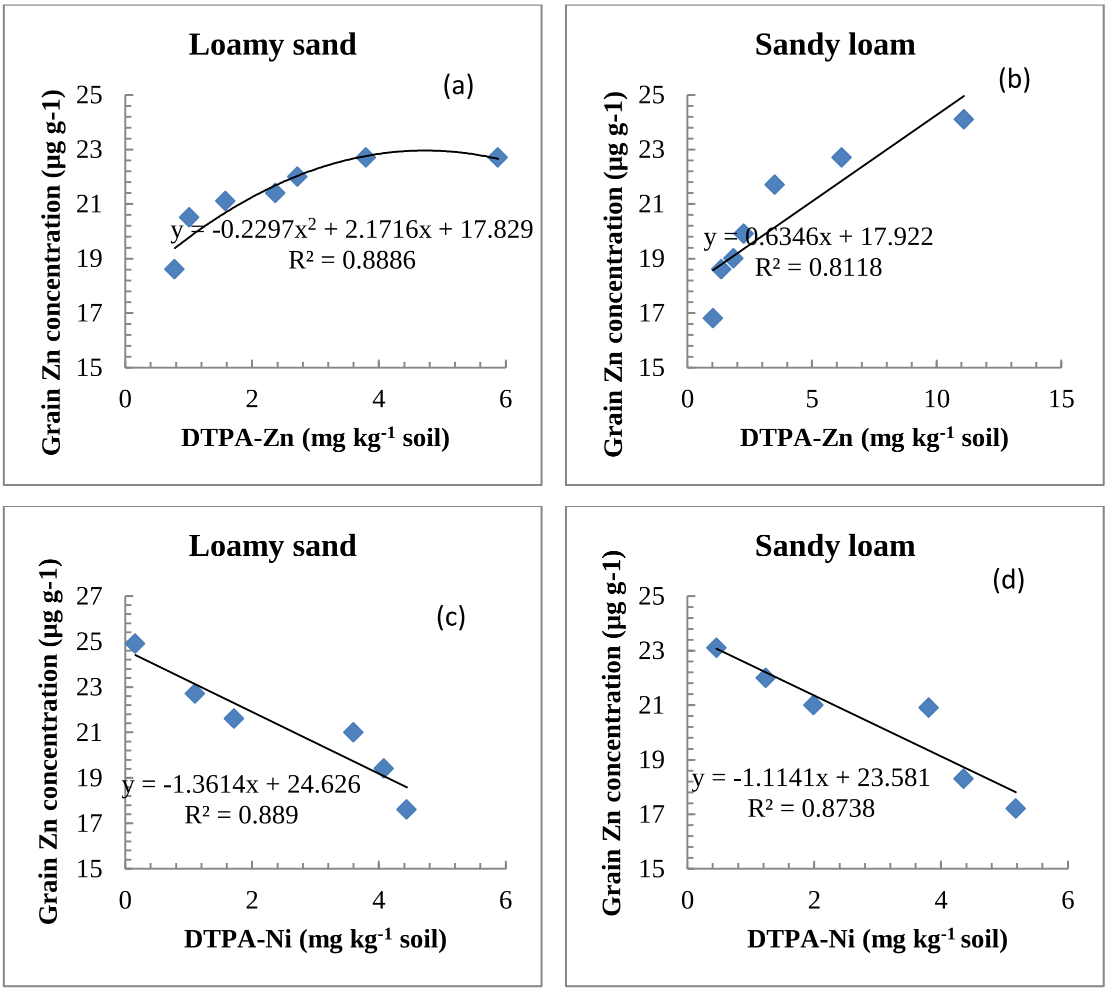


Fig.4.9: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn concentration in grain

4.3.3 Zinc concentration in straw

Table 4.30: Effect of Zn and Ni on Zn concentration ($\mu g\ g^{-1}$) in straw

Levels of Zn (mg kg^{-1} soil)	Straw Zn concentration ($\mu g\ g^{-1}$)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	35.0	35.4	36.8	37.4	30.5	29.4	34.1
2.5	36.4	36.7	37.9	38.0	32.4	30.9	35.4
5	37.2	38.5	38.7	38.7	32.8	30.1	36.0
10	37.8	38.3	38.0	38.7	33.2	31.8	36.3
20	38.1	38.6	39.2	39.5	34.8	33.2	37.3
40	39.2	39.8	39.1	45.1	40.3	36.6	40.0
80	38.8	39.7	40.6	40.6	41.8	38.8	40.1
Mean	37.5	38.1	38.6	39.1	35.1	33.0	
CD (5%)	Zn- 2.2			Ni-2.0		Zn x Ni-NS	
Sandy loam							
0	27.8	26.4	25.5	22.5	22.8	16.4	23.6
2.5	30.1	27.6	26.2	23.1	22.2	20.4	25.0
5	31.6	28.0	26.4	24.5	24.7	22.2	26.3
10	35.8	35.1	31.1	31.3	27.9	28.1	31.6
20	38.5	38.7	33.0	33.4	28.6	28.4	33.4
40	38.8	38.6	36.0	36.0	32.6	30.9	35.5
80	39.7	38.2	39.0	37.9	33.7	31.2	36.6
Mean	34.6	33.2	31.0	29.8	27.5	25.4	
CD (5%)	Zn- 1.8			Ni-1.6		Zn x Ni- NS	

The data on effect of Zn and Ni levels on Zn concentration in straw is presented in Table 4.30. The magnitude of Zn concentration in straw was high in loamy sand soil as compared to sandy loam soil. Zinc application significantly increased the Zn concentration in rice straw in both the soils. In loamy sand soil its concentration increased from 34.1 µg g^{-1} in control to 37.3, 40.0 and 40.1 µg g^{-1} resulting in increase by 9.3, 17.3 and 17.6 per cent over control with the application of 20, 40 and 80 mg Zn kg^{-1} soil, respectively. In sandy loam soil it increased from 23.6 µg g^{-1} in control to 26.3, 31.6, 33.4, 35.5 and 36.6 µg g^{-1} when Zn was applied @ 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. The corresponding values of per cent increase in straw Zn concentration over control with these levels of applied Zn were 11.4, 33.9, 41.5, 50.4 and 55.0 for sandy loam soil, respectively. A linear positive relationship of straw Zn concentration with DTPA-Zn in loamy sand (Fig.4.10a, R^2=0.87) and in sandy loam (Fig.4.10b, R^2=0.0.68) soil was observed. A significant positive coefficients of correlation of straw yield with straw Zn concentration in loamy sand (r=0.769**) was observed (Table 4.34). Denre *et al* (2017) observed that, all three levels of Zn applications i.e., 2.5, 5.0 and 7.5 kg ha^{-1}were found to be significantly superior to the control. The Zn concentration in straw gradually increases with the application of increasing doses of zinc. Similar result was also reported by Naik and Das (2008).

In both the soils Zn concentration in straw decreased significantly over control with increasing levels of applied Ni. Straw Zn concentration decreased significantly from 37.5 µg g^{-1} in control to 35.1 and 33.0 µg g^{-1} in loamy sand soil resulting in a decrease of 6.4 and 12.0 per cent over control with the application of 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.30). When Ni was applied @ 2.5, 5 and 10 mg Ni kg^{-1} soil, Zn concentration in straw increased over control, but this increase was not significant. In sandy loam soil straw Zn concentration was increased from 34.6 µg g^{-1} in control to 31.0, 29.8, 27.5 and 25.4 µg g^{-1} in sandy loam soil, respectively. The corresponding values of per cent decrease in straw Zn concentration over control with these levels of applied Ni were 10.4, 13.9, 20.5 and 26.6 for sandy loam soil, respectively. The quadratic response of straw Zn concentration to DTPA-Ni indicated that in loamy sand (Fig.4.10c, R^2=0.74) straw Zn concentration increased up to 2.35 mg DTPA-Ni kg^{-1} soil and thereafter it declined. A linear negative relationship of straw Zn concentration with DTPA-Ni in sandy loam soil (Fig.4.10d, R^2=0.95) was observed. Naseem *et al* (1986) reported that concentration of zinc in cotton plants decreased in response to rising Ni rates in soil.

A non-significant interaction effect of Zn and Ni levels on Zn concentration in straw was observed. Straw Zn concentration to produce 90 per cent of the maximum straw yield was found to be 36.1 µg g^{-1} in loamy sand and 24.2 µg g^{-1} in sandy loam soil (Fig.4.11e, f). Khalid and Tinsely (1980), in glass house experiment found that Ni concentration of ryegrass increased but Zn concentration decreased with increasing level of Ni from 0 to 270 µg g^{-1} soil. The concentration of Zn in straw was much lower as compared to roots.

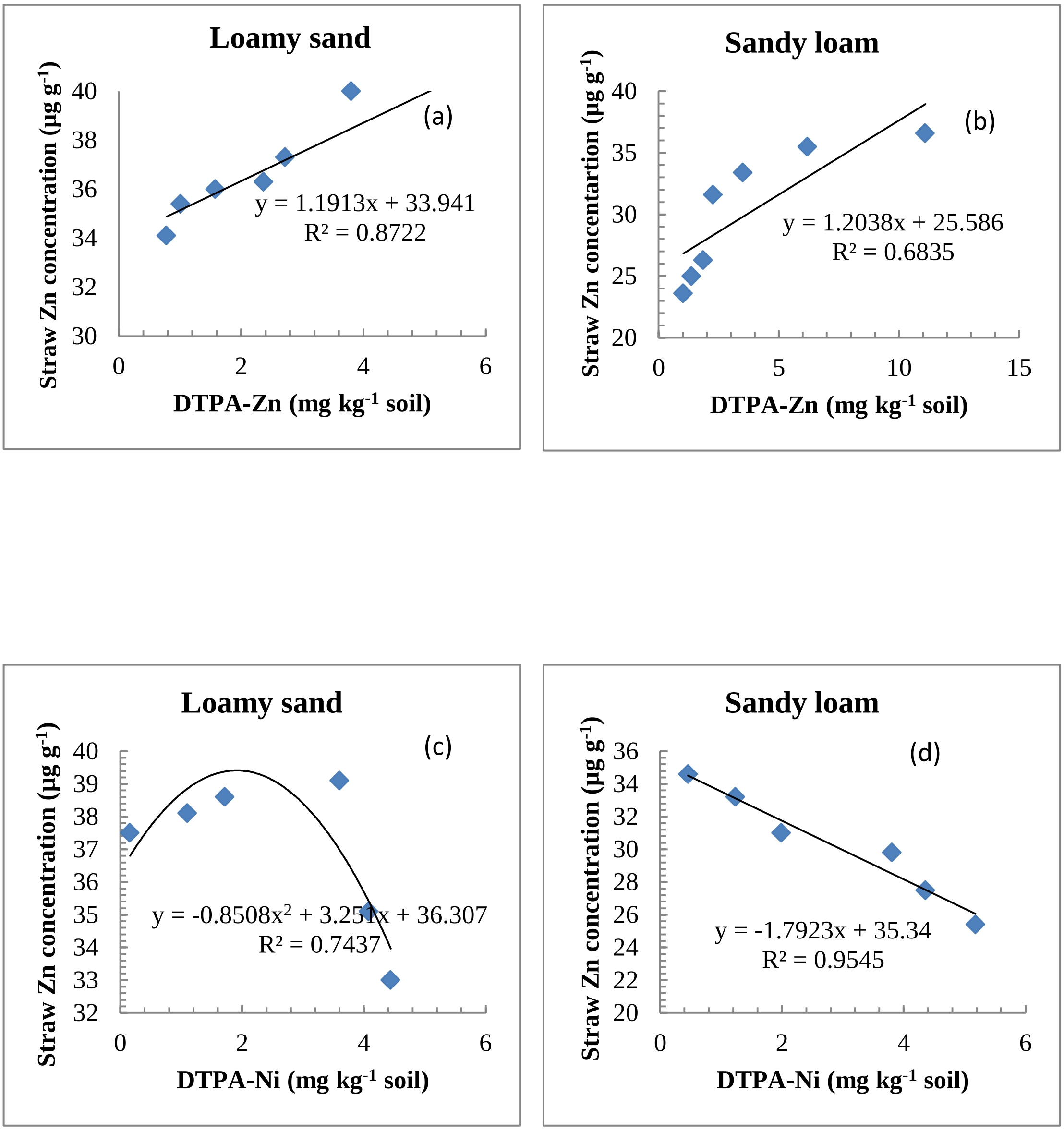


Fig.4.10: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn concentration in straw

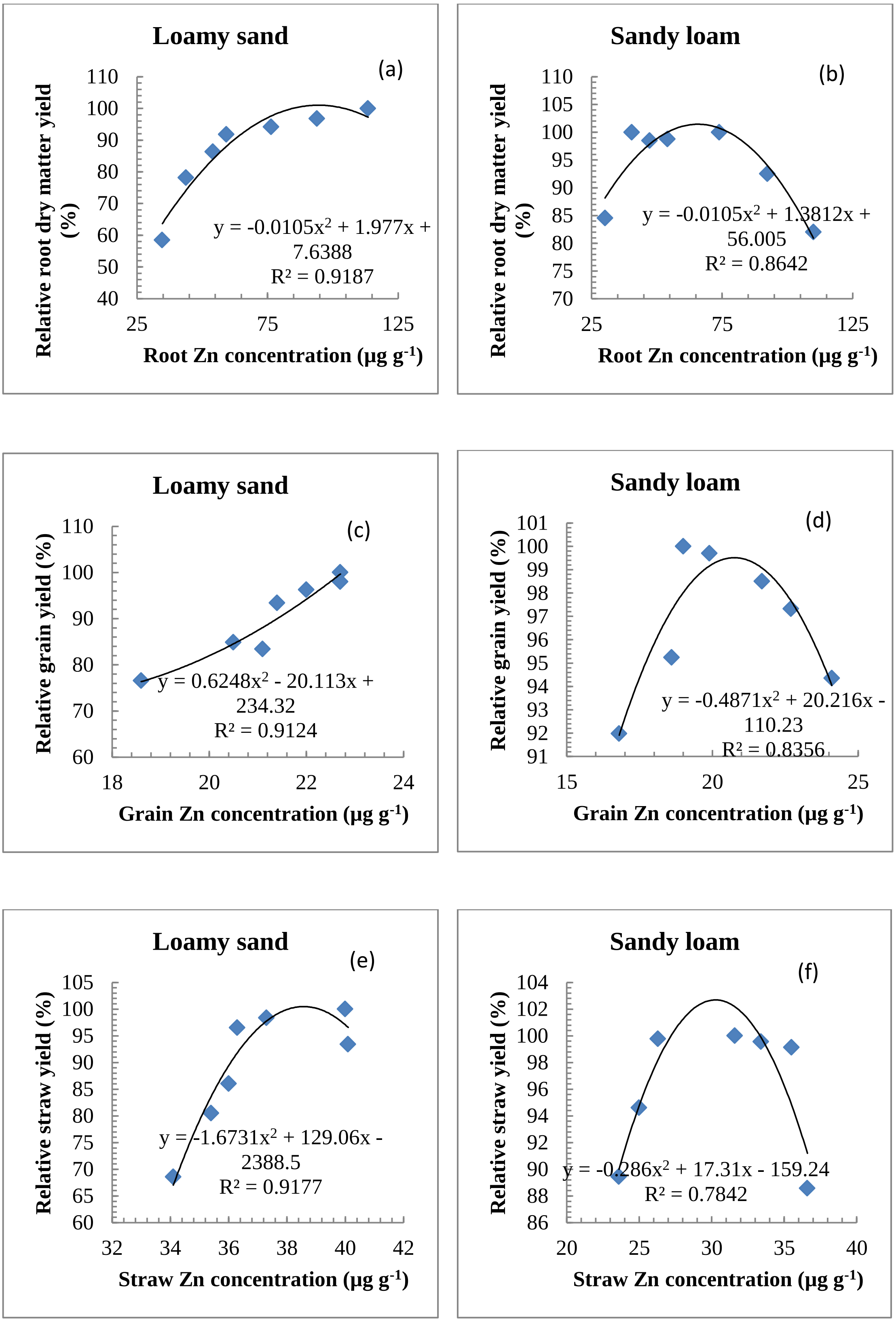


Fig4.11 Relationship of Zn concentration in root, grain and straw with relative root (a, b), grain (c, d) and straw yield (e, f)

4.3.4 Nickel concentration in root

Table 4.31: Effect of Zn and Ni on Ni concentration (μg g^{-1}) in root

Levels of Zn (mg kg^{-1} soil)	Root Ni concentration (μg g^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	20.1	30.0	33.2	40.8	48.5	62.1	39.1
2.5	13.5	17.9	24.8	35.0	43.0	55.5	31.6
5	10.2	14.8	20.3	28.9	38.6	48.5	26.9
10	8.7	10.8	14.0	17.9	26.8	36.8	19.2
20	7.3	8.9	10.4	15.5	21.5	28.4	15.3
40	5.7	8.3	10.6	14.8	18.1	22.8	13.4
80	3.7	4.1	5.8	8.6	11.0	16.9	8.3
Mean	9.9	13.5	17.0	23.1	29.7	38.7	
CD (5%)	Zn-2.4			Ni- 2.2		Zn x Ni-5.8	
Sandy loam							
0	18.9	27.2	31.4	39.0	46.6	59.6	37.1
2.5	11.2	17.5	25.7	37.4	45.8	56.0	32.2
5	8.8	14.2	18.0	26.7	37.0	48.4	25.5
10	7.7	10.4	13.0	18.3	26.3	34.0	18.3
20	6.6	7.8	10.1	15.4	20.8	28.1	14.8
40	4.8	7.1	9.4	14.3	17.5	21.9	12.5
80	2.7	3.9	5.5	8.2	10.1	13.7	7.3
Mean	8.7	12.6	16.2	22.8	29.2	37.4	
CD (5%)	Zn- 2.2			Ni-2.0		Zn x Ni- 5.4	

Root Ni concentration decreased significantly from 39.1 µg g^{-1} dry matter in control to 31.6, 26.9, 19.2, 15.3, 13.4 and 8.3 µg g^{-1} in loamy sand soil and from 37.1 µg g^{-1} in control to 32.2, 25.5, 18.3, 14.8, 12.5 and 7.3 µg g^{-1} in sandy loam soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.31). The corresponding values of per cent decrease in root Ni concentration over control with these levels of applied Zn were 19.1, 31.2, 50.8, 60.8, 65.7 and 78.7 for loamy sand and 13.2, 31.2, 50.6, 60.1, 66.3 and 80.3 for sandy loam soil, respectively. A linear negative relationship of root Ni concentration with DTPA-Zn in loamy sand (Fig.4.12a, R^2=0.82) was observed. A quadratic response of root Ni concentration to DTPA-Zn indicated that in sandy loam (Fig.4.12b, R^2=0.87) Ni concentration decreased to the minimum, up to level of 11.10 mg DTPA-Zn kg^{-1} soil.

In loamy sand soil, Ni concentration in root increased significantly over control with the graded levels of applied Ni. It increased from 9.9 µg g^{-1} in control to 13.5, 17.0, 23.1, 29.7 and 38.7 µg g^{-1} resulting in an increase of 0.36, 0.71, 1.33, 2.0 and 2.9 times over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. In sandy loam soil, it increased from 8.7 µg g^{-1} in control to 12.6, 16.2, 22.8, 29.2 and 37.4 µg g^{-1} resulting in an increase of 0.45, 0.86, 1.62, 2.36 and 3.29 times over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.31). A linear positive relationship of root Ni concentration with DTPA-Ni in loamy sand (Fig.4.12c, R^2=0.89) and in sandy loam (Fig.4.12d, R^2=0.95) was observed.

A significant interaction effect of Zn and Ni levels on Ni concentration in root revealed that at each level of applied Zn, it decreased significantly over control when Ni was applied @ 40 mg Ni kg^{-1} soil, in both the soils. In loamy sand a concentration of 62.1, 55.5, 48.5, 36.8, 28.4, 22.8 and 16.9 µg g^{-1} was observed when 40 mg Ni kg^{-1} soil was applied along with 0, 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.29). In sandy loam soil, significant interaction effect on root Ni concentration indicated that in the absence of applied Ni, the root Ni concentration decreased significantly when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil. Thus indicating an antagonistic effect of applied Zn on N

i in rice roots. However, the differences in root Ni concentration at these levels of applied Zn were not significant. Irrespective of the soils, critical level of root Ni concentration to produce 90 and 50 per cent of the maximum RDMY as estimated by Mitscherlich and quadratic model was observed to be 53.8 (Table 4.22) and 61.8 (Table 4.23) µg g^{-1}, respectively. Root Ni concentration to produce 90 per cent of the maximum RDMY was observed to be 15.4 µg g^{-1} in loamy sand and 12.0 µg g^{-1} in sandy loam soil (Fig.4.15a, b). Kumar (1992) observed a significant increase in the content of Ni, Fe and Mn and a significant decrease in Ni content of maize root with application of Zn.

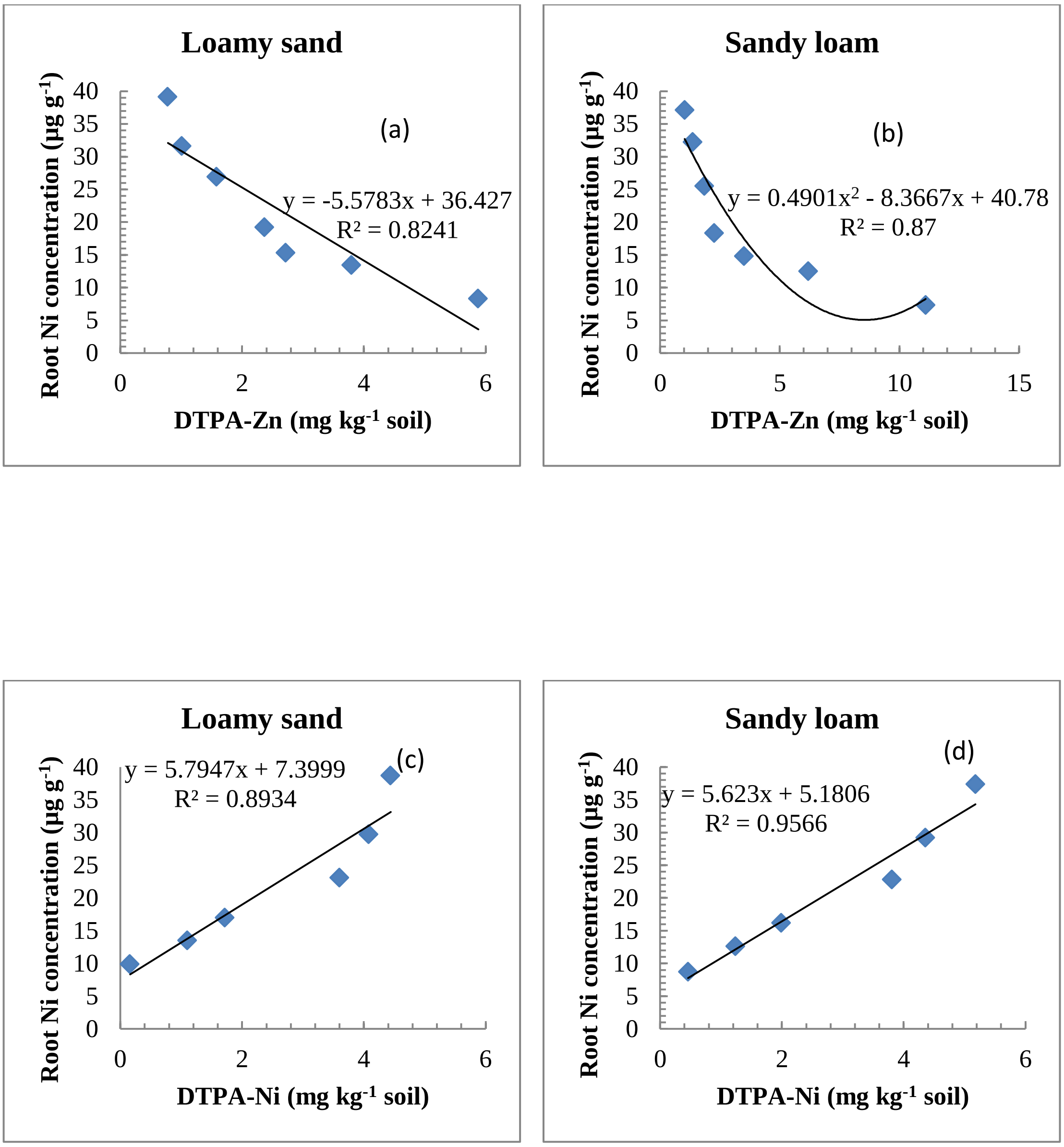


Fig.4.12: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni concentration in root

4.3.5 Nickel concentration in grain

Table 4.32: Effect of Zn and Ni on Ni concentration (µg g^{-1}) in grain

Levels of Zn (mg kg^{-1} soil)	Grain Ni concentration (µg g^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.35	0.66	0.63	0.94	1.04	1.64	0.88
2.5	0.45	0.49	0.66	0.88	0.98	1.51	0.83
5	0.45	0.49	0.52	0.77	0.96	1.45	0.77
10	0.34	0.33	0.47	0.73	0.92	1.29	0.68
20	0.39	0.38	0.41	0.66	0.92	1.07	0.64
40	0.26	0.31	0.47	0.62	0.91	0.95	0.59
80	0.23	0.32	0.49	0.53	0.61	0.76	0.49
Mean	0.35	0.42	0.52	0.73	0.91	1.24	
CD (5%)	Zn- 0.16			Ni- 0.15		Zn x Ni- NS	
Sandy loam							
0	1.22	1.92	2.48	2.80	2.56	3.94	2.49
2.5	0.88	1.02	1.47	2.16	2.84	3.92	2.05
5	0.81	1.02	1.47	2.19	2.61	3.90	2.00
10	0.75	1.03	1.40	1.95	2.45	3.66	1.87
20	0.75	1.05	1.26	1.62	2.27	3.00	1.66
40	0.47	0.71	1.26	1.52	2.01	2.83	1.47
80	0.50	0.64	1.25	1.50	1.96	2.56	1.40
Mean	0.77	1.06	1.51	1.96	2.39	3.40	
CD (5%)	Zn-0.40			Ni- 0.37		Zn x Ni- NS	

The data on the effect of Zn and Ni levels on grain Ni concentration is presented in Table 4.32. In loamy sand soil, the mean grain Ni concentration decreased significantly from 0.88 µg g^{-1} in control to 0.68, 0.64, 0.59 and 0.49 µg g^{-1} thereby resulting in a decrease of 22.7, 27.2, 32.9 and 44.3 per cent over control when Zn was applied @ 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. Whereas in sandy loam soil, grain Ni concentration significantly decreased from 2.49 µg g^{-1} in control to 2.05, 2.00, 1.87, 1.66, 1.47 and 1.40 µg g^{-1} thereby producing a decrease of 17.6, 19.6, 24.8, 33.3, 40.9 and 43.7 per cent over control when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. However, the differences in grain Ni concentration observed with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil were not significant. A linear negative relationship of grain Ni concentration with DTPA-Zn in loamy sand (Fig.4.13a, R^2=0.93) was observed. A quadratic response of grain Ni concentration to DTPA-Zn in sandy loam (Fig.4.13b, R^2=0.89), Ni concentration of grain decreased with increase in content of DTPA-Zn was observed.

Grain Ni concentration increased significantly with the application of graded levels of Ni in both the soils. Mean grain Ni concentration increased from 0.35 µg g^{-1} in control to 0.52, 0.73, 0.91 and 1.24 µg g^{-1} in loamy sand soil and from 0.77 µg g^{-1} in control to 1.51, 1.96, 2.39 and 3.40 µg g^{-1} in sandy loam soil with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.32). The increase in grain Ni concentration over control with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil was of order of 0.48, 1.08, 1.6 and 2.54 times in loamy sand soil and 0.96, 1.54, 2.10 and 3.41 times in sandy loam soil, respectively. A linear positive relationship of grain Ni concentration with DTPA-Ni for loamy sand (Fig 4.13c, R^2=0.86) as well as for sandy loam (Fig.4.13d, R^2=0.92) soil was observed. A non-significant interaction of applied Zn and Ni on grain Ni concentration was observed. Irrespective of the soils the critical level of grain Ni concentration to produce 50 per cent of maximum grain yield was found to be 7.79 µg g^{-1} (Table 4.23). Grain Ni concentration to produce 90 per cent of the maximum grain yield was found to be 0.4 µg g^{-1} in loamy sand and 1.0 µg g^{-1} in sandy loam soil (Fig.4.15c, d). Kumar *et al* (2018) studied that the concentration of Ni in grain increased with increasing levels concentration of foliar application of $NiSO_4 \cdot 7H_2O$ and the maximum concentration was observed with foliar application of 1.0% $NiSO_4 \cdot 7H_2O$ which showed an increase of 86 fold (2012–2013) and 91 fold (2013–2014) as compared to that treatments which did not receive Ni application.

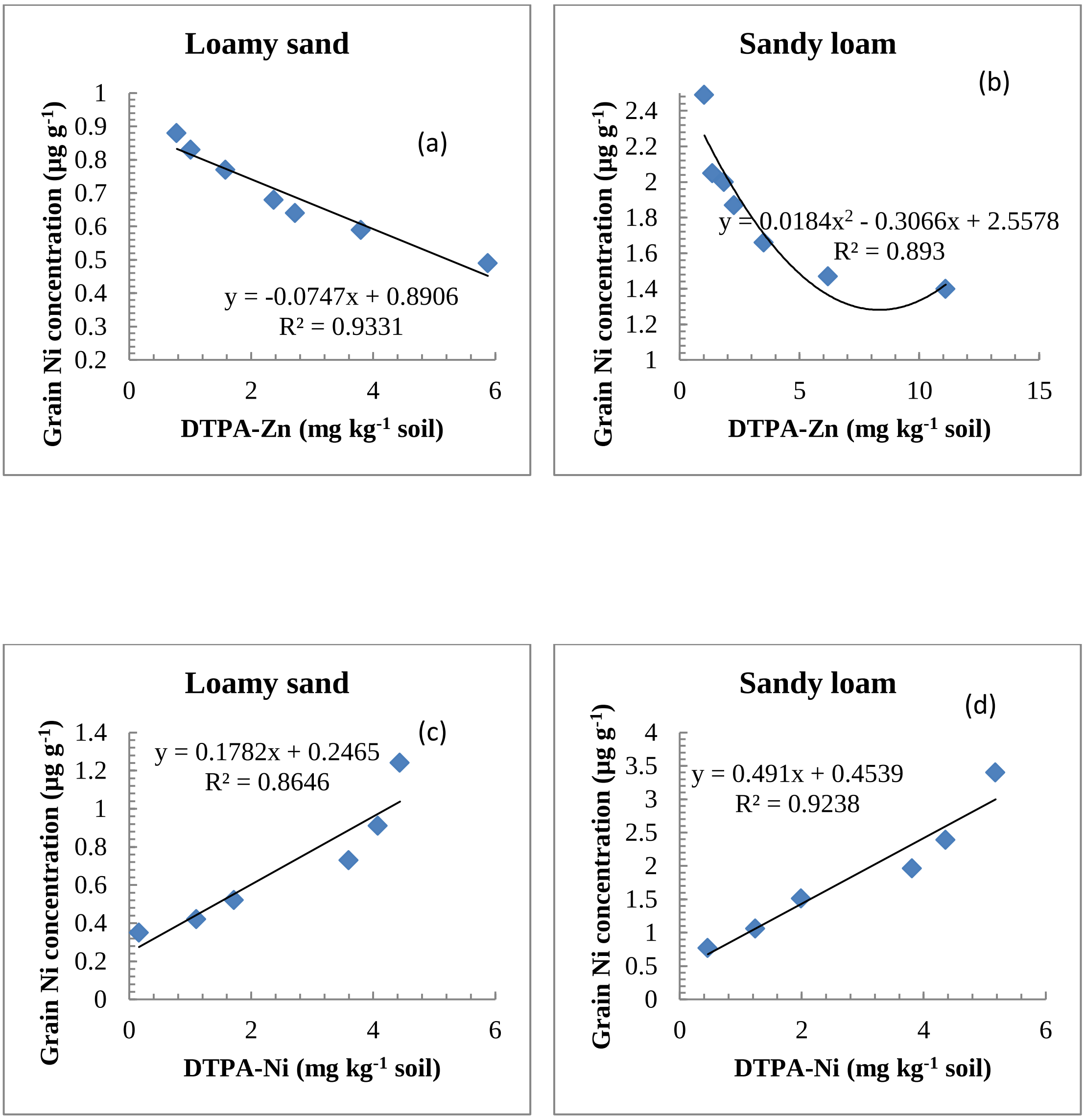


Fig.4.13: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni concentration in grain

4.3.6 Nickel concentration in straw

Table 4.33: Effect of Zn and Ni on Ni concentration ($\mu g\ g^{-1}$) in straw

Levels of Zn (mg kg^{-1} soil)	Straw Ni concentration ($\mu g\ g^{-1}$)						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	7.73	10.20	12.42	14.29	19.32	22.16	14.35
2.5	6.84	9.53	12.52	13.85	15.93	21.48	13.36
5	5.34	7.88	8.94	7.56	16.77	20.46	11.16
10	3.69	4.60	7.11	7.01	14.05	16.55	8.84
20	2.55	4.30	6.27	7.28	11.10	16.76	8.04
40	1.88	3.18	4.67	6.21	11.02	15.42	7.06
80	1.97	3.36	2.58	4.02	11.76	13.29	6.16
Mean	4.29	6.15	7.79	8.60	14.28	18.02	
CD (5%)	Zn- 0.55			Ni- 0.51		Zn x Ni-1.36	
Sandy loam							
0	8.99	11.83	12.93	14.94	15.72	18.81	13.87
2.5	6.42	8.38	8.73	10.80	14.36	18.22	11.15
5	4.47	6.94	6.93	9.17	10.97	16.89	9.23
10	2.80	5.63	7.67	8.92	10.22	16.69	8.66
20	1.90	4.52	7.25	9.17	9.64	14.05	7.76
40	1.52	4.21	7.73	9.69	9.65	14.72	7.92
80	1.42	2.81	4.39	5.73	9.54	12.44	6.05
Mean	3.93	6.33	7.95	9.77	11.44	15.98	
CD (5%)	Zn- 0.68			Ni- 0.63		Zn x Ni- 1.68	

The data on effect of Zn and Ni levels on nickel concentration in straw is presented in Table 4.33. In both the soils nickel concentration in straw decreased significantly over control with increasing levels of applied Zn. Straw Ni concentration decreased significantly from 14.35 µg g^{-1} in control to 13.36, 11.16, 8.84, 8.04, 7.06 and 6.16 µg g^{-1} in loamy sand soil and from 13.87 µg g^{-1} in control to 11.15, 9.23, 8.66, 7.76, 7.92 and 6.05 µg g^{-1} in sandy loam soil when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. The corresponding values of per cent decrease in straw Ni concentration over control with these levels of applied Zn were 6.8, 22.2, 38.4, 43.9, 50.8 and 57.0 for loamy sand and 19.6, 33.4, 37.5, 44.0, 42.9 and 56.3 for sandy loam soil, respectively. A linear negative relationship of straw Ni concentration with DTPA-Zn in loamy sand (Fig.4.14a, R^2=0.81) was observed. A quadratic response of straw Ni concentration to DTPA-Zn indicated that in sandy loam (Fig.4.14b, R^2=0.72) straw Ni concentration decreased to the minimum up to level of 11.10 mg DTPA-Zn kg^{-1} soil.

Nickel concentration significantly increased the nickel concentration in rice straw in both the soils. In loamy sand soil its concentration increased from 4.29 µg g^{-1} in control to 6.15, 7.79, 8.60, 14.28 and 18.02 µg g^{-1} and in sandy loam soil it increased from 3.93 µg g^{-1} in control to 6.33, 7.95, 9.77, 11.44 and 15.98 µg g^{-1} when Ni was applied @ 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.33). The corresponding values of per cent increase in straw Ni concentration over control with these levels of applied Ni were 43.3, 81.5, 100.0, 232.8 and 320.0 for loamy sand and 61.0, 102.0, 148.6, 191.0 and 306.6 for sandy loam soil, respectively. A linear positive relationship of straw Ni concentration with DTPA-Ni for loamy sand (Fig.4.14c, R^2=0.80) as well as for sandy loam (Fig.4.14d, R^2=0.92) soil was observed.

A significant interaction effect of Zn and Ni levels on Ni concentration in straw revealed that at each level of applied Zn, it decreased significantly over control when Ni was applied @ 40 mg Ni kg^{-1} soil in loamy sand soil. The content of Ni in rice straw was 22.16, 21.48, 20.46, 16.55, 16.76, 15.42 and 13.29 µg g^{-1} when 0, 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil was combined with 40 mg Ni kg^{-1} soil. In absence of applied Ni in sandy loam soil, the Ni concentration in straw decreased significantly over control when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil (Table 4.31). It increased from 1.42 µg g^{-1} in control to 12.44 µg g^{-1} with the application of 80 mg Zn kg^{-1} soil. Irrespective of the soils, the critical level of straw Ni concentration to produce 90 and 50 per cent of the maximum straw yield as estimated by Mitscherlich and quadratic model was observed to be 1.26 (Table 4.22) and 28.0 (Table 4.23) µg g^{-1}, respectively. Straw Ni concentration to produce 90 per cent of the maximum straw yield was found to be 8.1 µg g^{-1} in loamy sand and 7.3 µg g^{-1} in sandy loam soil (Fig.4.15 e, f). Kumar (1992) observed a significant increase in the content of Ni, Fe and Mn and a significant decrease in Zn content of maize shoot with application of Ni.

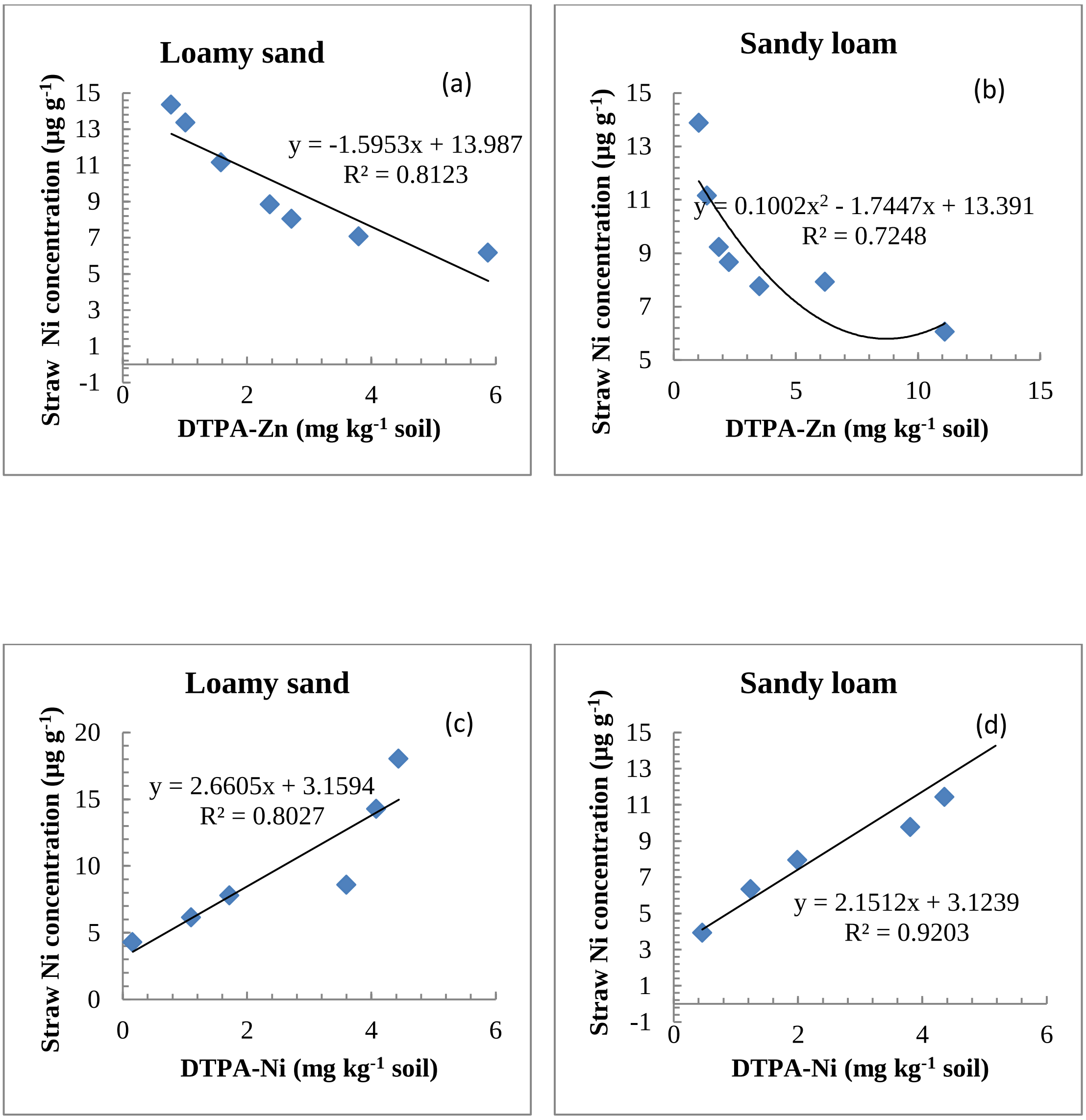


Fig.4.14: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni concentration in straw

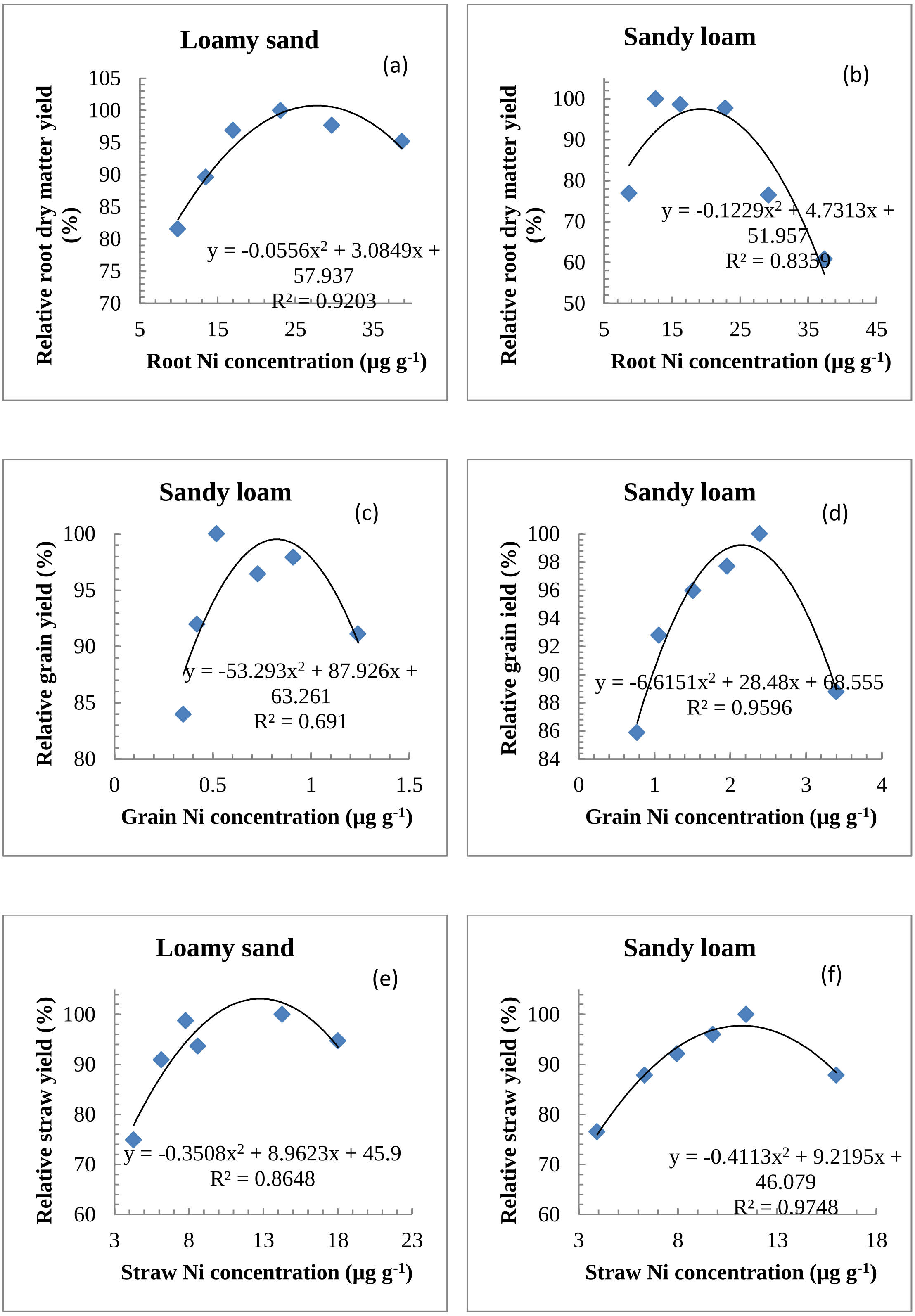


Fig.4.15 Relationship of Ni concentration in root, grain and straw with relative root (a, b), grain (c, d) and straw (e, f)

Table 4.34: Coefficients of correlation of Zn and Ni concentration in root, grain and straw with crop yield

Plant parameter	Loamy sand	Sandy loam
	Root dry matter yield	
Zn concentration	0.840*	0.357
Ni concentration	-0.954**	-0.124
	Grain yield	
Zn concentration	0.945**	0.188
Ni concentration	-0.928**	-0.338
	Straw yield	
Zn concentration	0.769*	0.138
Ni concentration	-0.910**	-0.272

**Significant at 1% level
* Significant at 5% level

Table: 4.35: Coefficients of correlation of Zn and Ni concentration in root, grain and straw with chemical pools of Zn

	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Loamy sand					
EXCH-Zn	0.969**	0.771*	0.943**	-0.836*	-0.912**	-0.830*
SAD-Zn	0.955**	0.799*	0.882**	-0.876**	-0.933**	-0.849*
MnOX-Zn	0.989**	0.828*	0.964**	-0.888**	-0.944**	-0.881**
AMPOX-Zn	0.976**	0.822*	0.962**	-0.867*	-0.931**	-0.859*
CRYOX-Zn	0.962**	0.906**	0.947**	-0.957**	-0.976**	-0.976**
OM-Zn	0.955**	0.942**	0.947**	-0.975**	-0.978**	-0.986**
RES-Zn	0.930**	0.694	0.874*	-0.781*	-0.872*	-0.764*
DTPA-Ni	-0.876**	-0.649	-0.892**	0.683	0.780*	0.688
DTPA-Zn	0.981**	0.826*	0.934**	-0.908**	-0.966**	-0.901**
	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Sandy loam					
EXCH-Zn	0.934**	0.897**	0.840*	-0.842*	-0.814*	-0.781*
SAD-Zn	0.993**	0.987**	0.944**	-0.938**	-0.937**	-0.879**
MnOX-Zn	0.992**	0.977**	0.939**	-0.943**	-0.921**	-0.884**
AMPOX-Zn	0.993**	0.982**	0.961**	-0.942**	-0.932**	-0.861*
CRYOX-Zn	0.979**	0.970**	0.963**	-0.966**	-0.937**	-0.902**
OM-Zn	0.982**	0.988**	0.975**	-0.971**	-0.976**	-0.917**
RES-Zn	0.912**	0.857*	0.773*	-0.768*	-0.764*	-0.704
DTPA-Ni	-0.989**	-0.962**	-0.913**	0.916**	0.909**	0.856*
DTPA-Zn	0.946**	0.901**	0.827*	-0.825*	-0.819*	-0.763*

**Significant at 1% level
* Significant at 5% level

Table: 4.36 Coefficients of correlation of Zn and Ni concentration in root, grain and straw with chemical pools of Ni

	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Loamy sand					
EXCH-Ni	-0.995**	-0.982**	-0.686	0.977**	0.967**	0.950**
SAD-Ni	-0.985**	-0.969**	-0.794	0.991**	0.984**	0.984**
MnOX-Ni	-0.957**	-0.987**	-0.784	0.975**	0.968**	0.973**
AMPOX-Ni	-0.968**	-0.963**	-0.809	0.994**	0.997**	0.976**
CRYOX-Ni	-0.986**	-0.976**	-0.620	0.948**	0.930**	0.922**
OM-Ni	-0.989**	-0.987**	-0.761	0.996**	0.989**	0.976**
RES-Ni	-0.826*	-0.838*	-0.932**	0.911*	0.932**	0.927**
DTPA-Zn	0.961**	0.968**	0.524	-0.908*	-0.882*	-0.874*
DTPA-Ni	-0.980**	-0.943**	-0.595	0.945**	0.930**	0.896*
	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Sandy loam					
EXCH-Ni	-0.995**	-0.983**	-0.996**	0.992**	0.978**	0.976**
SAD-Ni	-0.993**	-0.984**	-0.997**	0.997**	0.988**	0.987**
MnOX-Ni	-0.978**	-0.992**	-0.987**	0.989**	0.985**	0.989**
AMPOX-Ni	-0.994**	-0.950**	-0.984**	0.988**	0.978**	0.982**
CRYOX-Ni	-0.989**	-0.985**	-0.995**	0.982**	0.980**	0.987**
OM-Ni	-0.996**	-0.948**	-0.989**	0.983**	0.976**	0.978**
RES-Ni	-0.830*	-0.895*	-0.868*	0.908*	0.927**	0.912*
DTPA-Zn	0.973**	0.971**	0.986**	-0.994**	-1.000**	-0.997**
DTPA-Ni	-0.990**	-0.935**	-0.977**	0.978**	0.961**	0.959**

**Significant at 1% level
* Significant at 5% level

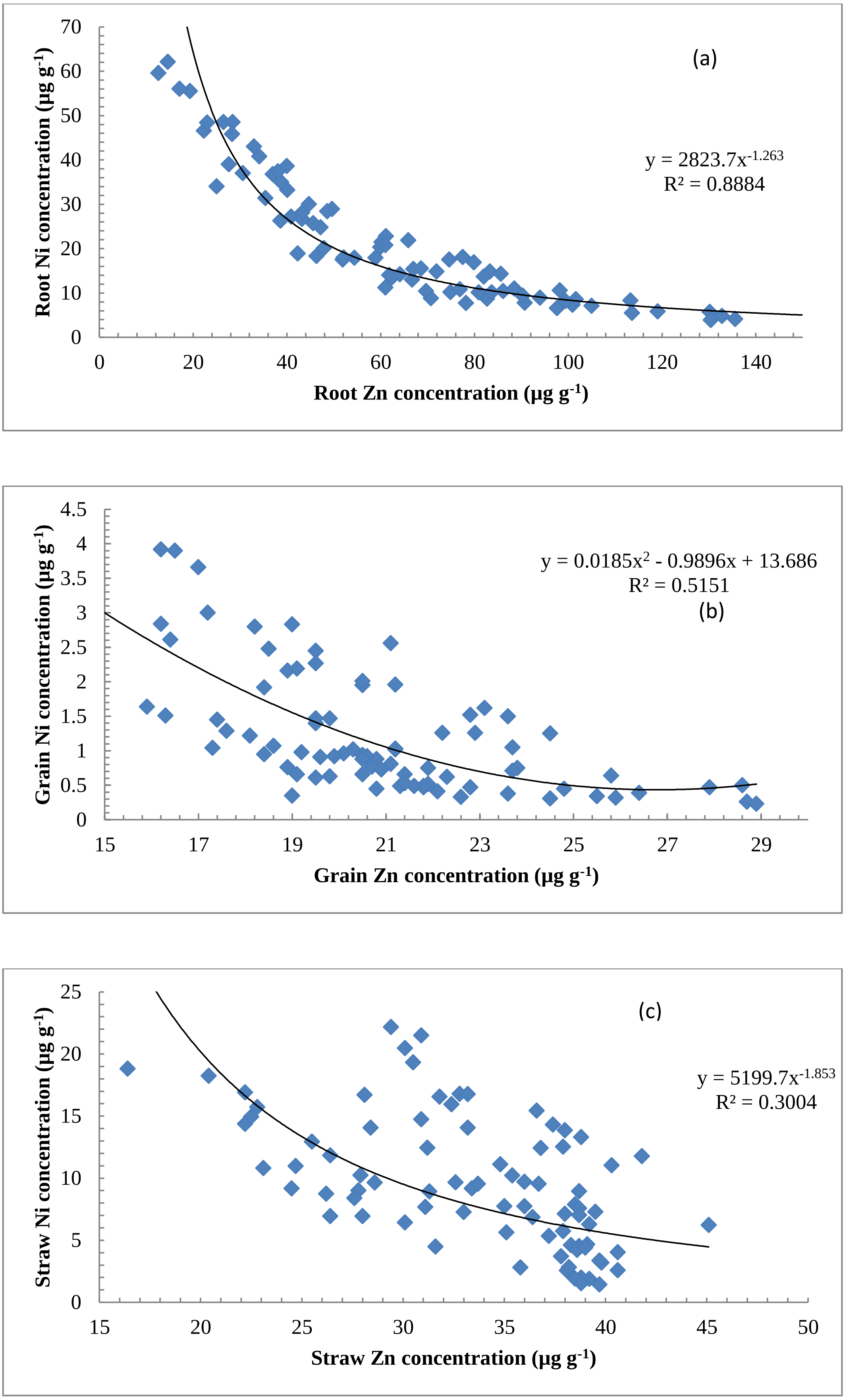


Fig.4.16 Relationship of Zn and Ni concentration in root, grain and straw

Irrespective of the soil used in the study the concentration of Ni in root, grain and straw decreased as the concentration of Zn in these plant parts increased (Fig.4.16)

4.4 Interactive effects Zn and Ni application on their uptake by root, grain and straw.

4.4.1 Zinc uptake by root

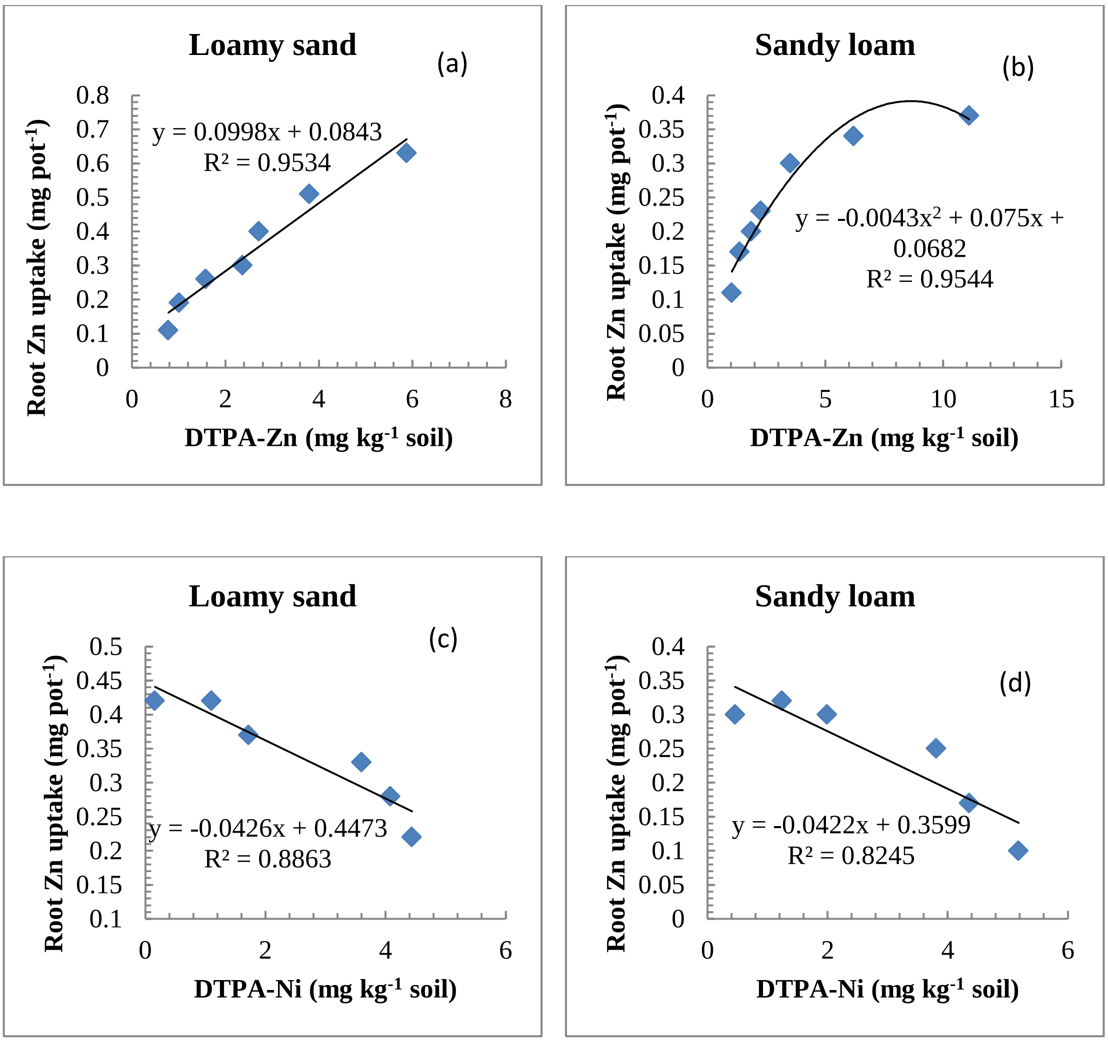
Table 4.37: Effect of Zn and Ni on Zn uptake (mg pot^{-1}) by root

Levels of Zn (mg kg^{-1} soil)	Root Zn uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.12	0.13	0.15	0.12	0.09	0.05	0.11
2.5	0.23	0.27	0.23	0.18	0.15	0.08	0.19
5	0.31	0.33	0.30	0.25	0.21	0.15	0.26
10	0.39	0.37	0.32	0.30	0.24	0.20	0.30
20	0.48	0.47	0.46	0.40	0.33	0.26	0.40
40	0.66	0.60	0.54	0.47	0.44	0.34	0.51
80	0.77	0.75	0.70	0.59	0.52	0.46	0.63
Mean	0.42	0.42	0.39	0.33	0.28	0.22	
CD (5%)	Zn- 0.05			Ni-0.04		Zn x Ni- NS	
Sandy loam							
0	0.14	0.16	0.13	0.09	0.07	0.04	0.11
2.5	0.22	0.23	0.22	0.18	0.09	0.05	0.17
5	0.28	0.30	0.25	0.21	0.09	0.06	0.20
10	0.28	0.34	0.32	0.22	0.12	0.07	0.23
20	0.32	0.43	0.41	0.31	0.23	0.12	0.30
40	0.42	0.43	0.36	0.37	0.32	0.16	0.34
80	0.45	0.52	0.41	0.34	0.25	0.23	0.37
Mean	0.30	0.32	0.30	0.25	0.17	0.10	
CD (5%)	Zn-0.04			Ni-0.03		Zn x Ni- NS	

The data on zinc uptake by root as influenced by graded levels of applied zinc and nickel is presented in Table 4.37. In loamy sand soil, mean Zn uptake by root increased by 0.72, 1.36, 1.72, 2.63, 3.63 and 4.72 times over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. It increased significantly from 0.11 mg pot^{-1} in control to a maximum of 0.63 mg pot^{-1} when Zn was applied @ 80 mg Zn kg^{-1} soil. In sandy loam soil, Zn uptake by root increased significantly by 0.54, 0.81, 1.09, 1.72, 2.09 and 2.36 times over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. It increased from 0.11 mg pot^{-1} in control to maximum of 0.37 mg pot^{-1} when Zn was applied @ 80 mg Zn kg^{-1} soil. A significant positive coefficient of correlation of Zn uptake by root with root dry matter yield in loamy sand (r=0.868*) was observed (Table 4.43). The linear response of root Zn uptake to DTPA-Zn was observed for loamy sand (Fig.4.17a, R^2=0.95) whereas in sandy loam (Fig.4.17b, R^2=0.95) soil maximum root Zn uptake was observed up to a level of about 6 mg

DTPA-Zn kg^{-1} soil, respectively and then levelled off. Khan *et al* (2003) observed that application of Zn increased Zn uptake in root significantly over control.

Nickel application @ 10, 20 and 40 mg kg^{-1} soil significantly decreased Zn uptake by root in both the soils. In loamy sand soil, Zn uptake by root decreased significantly from 0.42 mg pot^{-1} in control to 0.33, 0.28 and 0.22 mg pot^{-1} thereby resulting in decrease of 21.4, 33.3 and 47.6 per cent over control when Ni was applied @ 10, 20 and 40 mg kg^{-1} soil, respectively. In sandy loam soil, it decreased significantly from 0.30 mg pot^{-1} in control to 0.25, 0.17, 0.10 mg pot^{-1} thereby resulting in decrease of 16.6, 43.3 and 66.6 per cent over control when Ni was applied @ 10, 20 and 40 mg kg^{-1} soil, respectively (Table 4.37). Root Zn uptake decrease linearly with increasing level of applied Ni in both the soils (Fig.4.17c, R^2=0.88 and Fig. 4.17d, R^2=0.82). A non-significant interaction effect of Zn and Ni levels on Zn uptake by root was observed in both the soils. Palacious *et al* (1998) observed that high concentration of Ni significantly decreased the uptake of other divalent cations such as Mg^{+2}, Fe^{+2}, Mn^{+2}, Cu^{+2} and Zn^{+2}. Jain *et al* (2000) reported inhibitory effect of nickel on sugarcane root growth and destruction of the integrity of the root meristems which led to alterations in mineral nutrition.



.Fig.4.17: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn uptake by root

4.4.2 Zinc uptake by grain

Table 4.38: Effect of Zn and Ni on Zn uptake (mg pot^{-1})by grain

Levels of Zn (mg kg^{-1} soil)	Grain Zn uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.40	0.51	0.59	0.59	0.48	0.42	0.50
2.5	0.55	0.59	0.67	0.62	0.64	0.50	0.59
5	0.68	0.63	0.80	0.59	0.56	0.45	0.62
10	0.77	0.76	0.77	0.73	0.64	0.53	0.70
20	0.82	0.78	0.77	0.68	0.74	0.62	0.73
40	0.90	0.85	0.79	0.81	0.71	0.68	0.79
80	0.89	0.87	0.71	0.75	0.74	0.67	0.77
Mean	0.71	0.71	0.73	0.68	0.65	0.55	
CD (5%)	Zn- 0.08			Ni-0.07		Zn x Ni- NS	
Sandy loam							
0	0.46	0.56	0.61	0.61	0.51	0.40	0.52
2.5	0.61	0.62	0.65	0.64	0.55	0.49	0.60
5	0.69	0.72	0.67	0.67	0.55	0.55	0.64
10	0.69	0.74	0.68	0.71	0.69	0.52	0.67
20	0.73	0.77	0.79	0.81	0.69	0.54	0.72
40	0.83	0.79	0.72	0.80	0.74	0.58	0.74
80	0.81	0.79	0.78	0.74	0.71	0.61	0.74
Mean	0.69	0.71	0.70	0.71	0.64	0.53	
CD (5%)	Zn- 0.06			Ni-0.06		Zn x Ni- NS	

The data on zinc uptake by grain is presented in Table 4.38. With the increasing levels of applied Zn, its uptake by grain increased significantly over control in both the soils. In loamy sand soil Zn uptake by grain increased significantly from 0.50 mg pot^{-1} in control to 0.59, 0.62, 0.70, 0.73, 0.79 and 0.77 mg pot^{-1} resulting in an increase of 18.0, 24.0, 40.0, 46.0, 58.0 and 54.0 per cent over control with the zinc application @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil, respectively. Similarly, in sandy loam soil Zn uptake was increased significantly from 0.52 mg pot^{-1} in control to 0.60, 0.64, 0.67, 0.72, 0.74 and 0.74 mg pot^{-1} which produced an increase of 15.3, 23.0, 28.8, 38.4, 42.3 and 42.3 per cent over control when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil, respectively. A significant positive coefficient of correlation of Zn uptake by grain with grain yield in loamy sand (r=0.988**) was observed (Table 4.42). The quadratic response of grain Zn uptake to DTPA-Zn indicated that in loamy sand (Fig.4.18a, R^2=0.97) Zn uptake by grain reached a maximum level at 4 mg DTPA-Zn kg^{-1} soil and then became constant. In sandy loam (Fig.4.18b, R^2=0.86) grain Zn uptake increased with increasing DTPA-Zn up to level of 7 mg DTPA-Zn kg^{-1} soil and then became constant. Shivay *et al* (2008) reported that 1.0% coating of urea either with zinc sulphate or zinc oxide increased Zn uptake by rice grain. Sharma *et al* (1982) studied that soil applied Zn was significantly correlated with yield of rice (r = 0.80**) and zinc uptake (r = 0.89**).

In both soils, significant decrease in mean Zn uptake by grain was observed only at the highest level of applied Ni. Application of 40 mg Ni kg^{-1} soil significantly decreased the mean Zn uptake by grain from 0.71 mg pot^{-1} in control to 0.55 mg pot^{-1} resulting in a decrease of 22.5 per cent over control in loamy sand soil and in sandy loam soil, it decreased from 0.69 mg pot^{-1} in control to 0.53 mg pot^{-1} (Table 4.38), resulting in decrease of 23.1 per cent over control with the application of 40 mg Ni kg^{-1} soil. A negative relationship of Zn uptake by grain with DTPA-Ni in loamy sand (Fig.4.18c, R^2=0.88) was observed. In sandy loam soil (Fig.4.18d, R^2=0.82) Zn uptake by grain reached maximum level at 2 mg DTPA-Ni kg^{-1} soil and then declined. Kumar *et al* (2018) observed that foliar spray of Ni (>0.2% $NiSO_4 \cdot 7H_2O$), significantly reduced the uptake of Fe, Zn, Mn and Cu in barley grain because of toxic effect on plant growth which decreased grain yield. However, uptake of the Ni in grain increased with the increasing concentration of Ni spray. A non-significant interaction effect of Zn and Ni levels on grain Zn uptake was observed in both the soils.

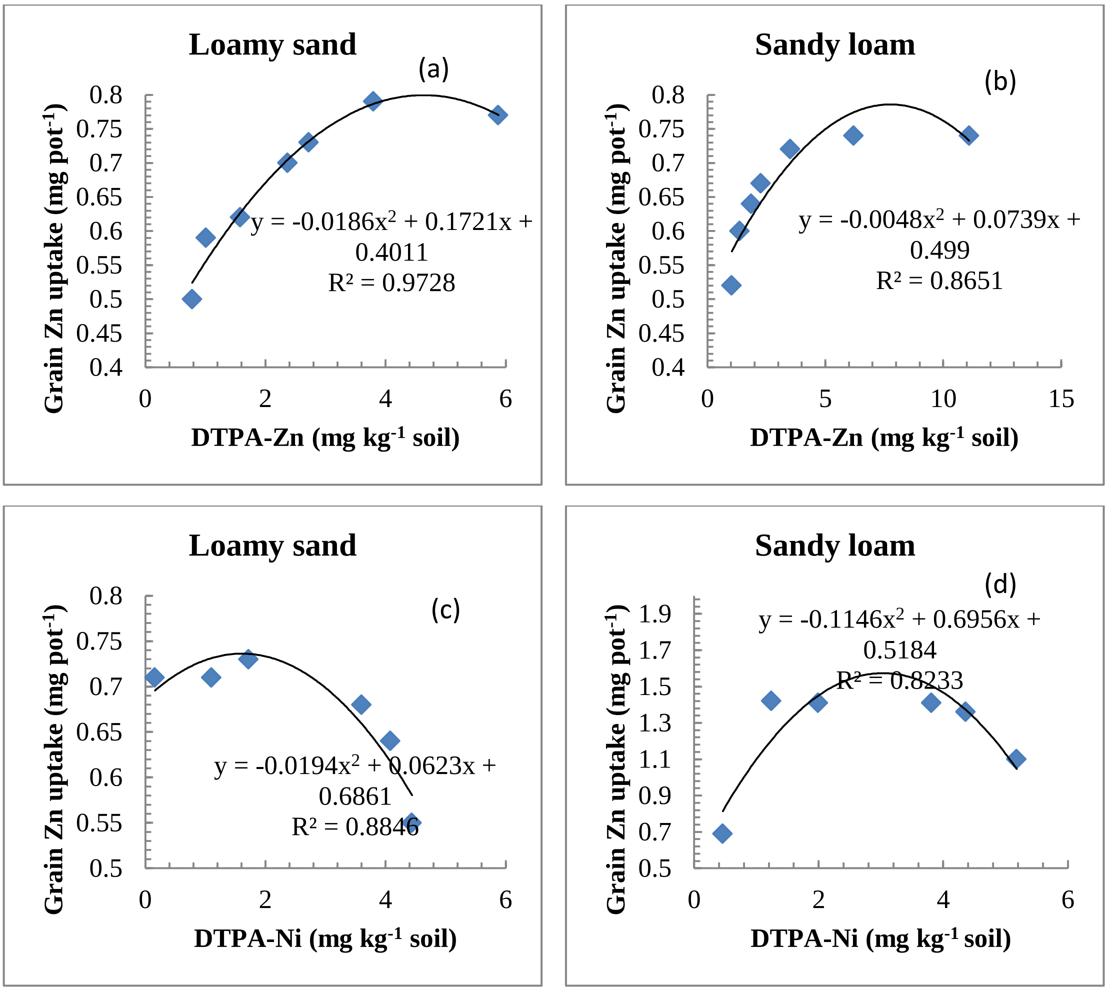


Fig.4.18: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn uptake by grain

4.4.3 Zinc uptake by straw

Table 4.39: Effect of Zn and Ni on Zn uptake (mg pot^{-1}) by straw

Levels of Zn (mg kg^{-1} soil)	Straw Zn uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.88	1.23	1.42	1.37	1.02	0.94	1.14
2.5	1.19	1.29	1.53	1.43	1.53	1.32	1.38
5	1.25	1.42	2.12	1.49	1.53	1.22	1.50
10	1.50	1.78	1.88	2.03	1.61	1.44	1.71
20	1.50	1.86	1.92	1.83	1.88	1.67	1.78
40	1.56	2.02	1.91	2.26	2.00	1.97	1.95
80	1.48	1.97	1.87	1.99	2.19	1.94	1.91
Mean	1.34	1.65	1.81	1.77	1.68	1.50	
CD (5%)	Zn- 0.13			Ni-0.12		Zn x Ni-0.32	
Sandy loam							
0	0.84	1.02	1.08	1.05	1.11	0.69	0.97
2.5	1.16	1.15	1.19	1.09	1.06	0.88	1.09
5	1.36	1.25	1.24	1.23	1.13	1.07	1.21
10	1.45	1.71	1.51	1.51	1.42	1.19	1.47
20	1.53	1.75	1.57	1.61	1.47	1.28	1.53
40	1.44	1.78	1.57	1.86	1.76	1.33	1.62
80	1.39	1.53	1.72	1.53	1.60	1.25	1.50
Mean	1.31	1.46	1.43	1.41	1.36	1.10	
CD (5%)	Zn-0.11			Ni-0.10		Zn x Ni- NS	

In loamy sand soil, Zn uptake by straw increased significantly from 1.14 mg pot^{-1} in control to 1.38, 1.50, 1.71, 1.78, 1.95 and 1.91 mg pot^{-1} whereas in sandy loam soil it increased significantly from 0.97 mg pot^{-1} in control to 1.09, 1.21, 1.47, 1.53, 1.62 and 1.50 mg pot^{-1} when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively (Table 4.39). The corresponding values of per cent increase in straw Zn uptake over control with these levels of applied Zn were 21.0, 31.5, 50.0, 56.1, 71.0 and 67.5 per cent for loamy sand and 12.3, 24.7, 51.5, 57.7, 67.0 and 54.6 per cent for sandy loam soil, respectively. A significant positive coefficient of correlation of Zn uptake by straw with straw yield in loamy sand (r=0.948**) was observed (Table 4.43). The quadratic response of straw Zn uptake to DTPA-Zn indicated that in loamy sand (Fig.4.19a, R^2=0.97) and in sandy loam (Fig.4.19b, R^2=0.86) Zn uptake by straw increased maximum up to a level of 5 mg DTPA-Zn kg^{-1} soil and thereafter it declined. Denre *et al* (2017) observed that the zinc uptake was significantly influenced by various levels of zinc applications as compared to no zinc application.

In loamy sand soil mean Zn uptake by straw increased significantly by 23.1 and 35.0 per cent over control with application of nickel of 2.5 and 5 mg Ni kg^{-1} soil and thereafter it decreased significantly by 15.2 per cent over the application of Ni @ 5 mg Ni kg^{-1} soil, with the application of 40 mg Ni kg^{-1} soil. Similarly in sandy loam soil mean Zn uptake by straw increased significantly by 11.4 and 9.1 per cent over control with the application of nickel @ 2.5 and 5 mg Ni kg^{-1} soil and thereafter it decreased significantly by 23.0 per cent over the application of Ni @ 5 mg Ni kg^{-1} soil, with the application of 40 mg Ni kg^{-1} soil. A significant interaction effect of Zn and Ni levels on straw uptake in both the soils revealed that maximum Zn uptake by straw was observed when 40 mg Zn kg^{-1} was applied in combination with 10 mg Ni kg^{-1} soil. Zinc uptake by straw decreased steeply beyond a level of 2.0 mg DTPA-Ni kg^{-1} soil in loamy sand (Fig.4.19c, R^2=0.98) and sandy loam (Fig.4.19d, R^2=0.90), respectively. A non-significant interaction effect of Zn and Ni levels on straw Zn uptake was observed in sandy loam soil. Singh (1994) observed that Ni had an antagonistic effect on uptake of Zn by wheat straw. This is due to antagonistic effect of Ni and Zn absorption due to competition at absorption sites on plant roots. Both Ni^{+2} and Zn^{+2} have similar ionic charge and possibly same carrier sites, and hence antagonistic effect of Ni on Zn in plants.

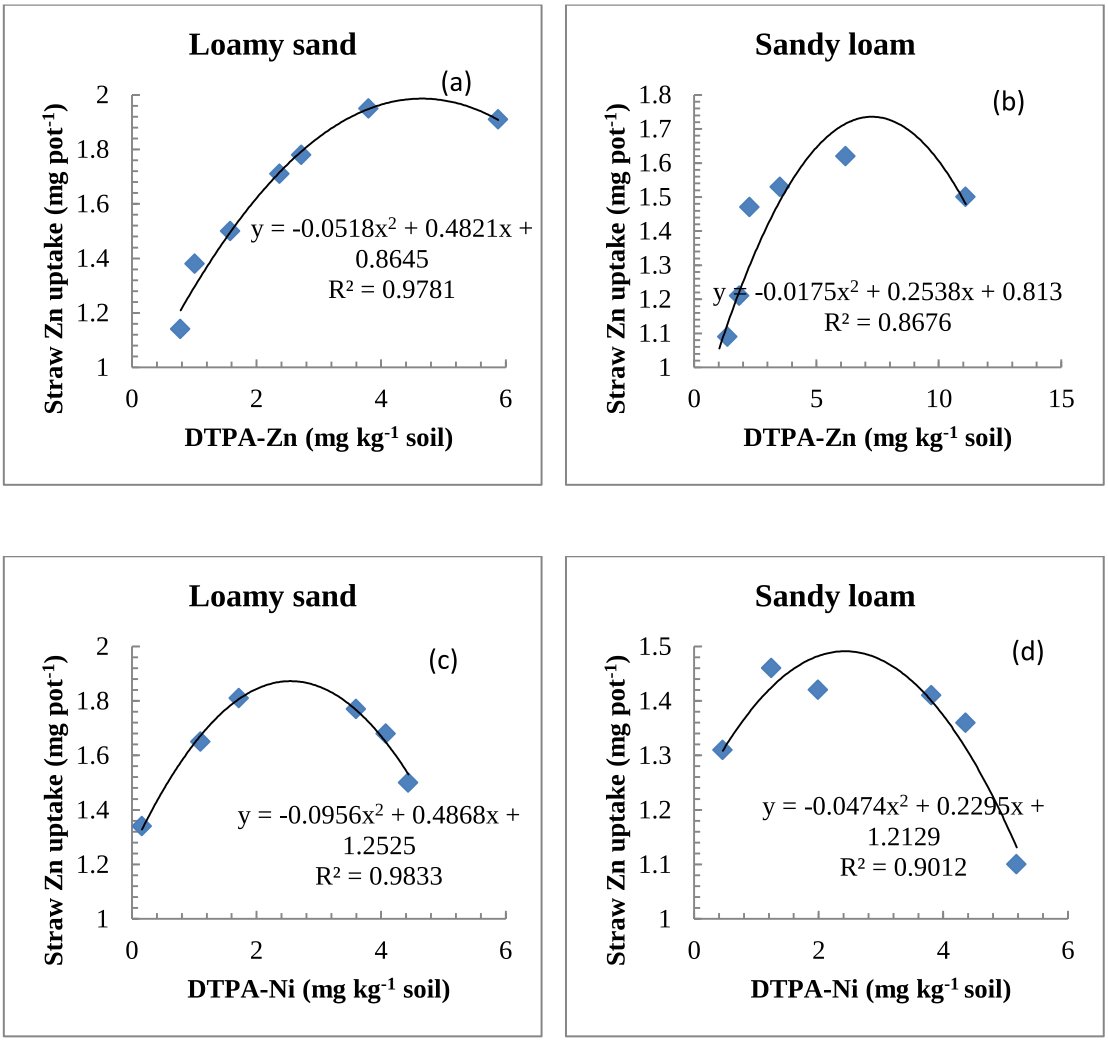


Fig.4.19: Relationship of DTPA-Zn and DTPA-Ni in soil with Zn uptake by straw

4.4.4 Nickel uptake by root

Table 4.40: Effect of Zn and Ni on Ni uptake (mg pot^{-1}) by root

Levels of Zn (mg kg^{-1} soil)	Root Ni uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand						
0	0.05	0.09	0.12	0.15	0.17	0.21	0.13
2.5	0.05	0.08	0.12	0.16	0.19	0.23	0.14
5	0.04	0.07	0.10	0.15	0.20	0.24	0.13
10	0.04	0.05	0.07	0.10	0.14	0.19	0.10
20	0.04	0.04	0.05	0.09	0.12	0.15	0.08
40	0.03	0.04	0.06	0.08	0.10	0.12	0.07
80	0.02	0.02	0.03	0.05	0.06	0.09	0.04
Mean	0.04	0.06	0.08	0.11	0.14	0.18	
CD (5%)	Zn-0.01		Ni- 0.01		Zn x Ni- 0.02		
Sandy loam							
0	0.06	0.11	0.11	0.13	0.15	0.17	0.12
2.5	0.04	0.08	0.12	0.18	0.15	0.16	0.12
5	0.03	0.07	0.09	0.13	0.11	0.13	0.09
10	0.03	0.05	0.06	0.09	0.09	0.09	0.07
20	0.02	0.04	0.05	0.07	0.08	0.07	0.06
40	0.02	0.03	0.04	0.06	0.07	0.06	0.05
80	0.01	0.02	0.02	0.03	0.03	0.04	0.02
Mean	0.03	0.06	0.07	0.10	0.10	0.10	
CD (5%)	Zn- 0.02		Ni-0.01		Zn x Ni- NS		

The data on Ni uptake by root is presented in Table 4.40. Zinc application significantly decreased the mean Ni uptake by root in both the soils. In loamy sand soil it decreased significantly from 0.13 mg pot^{-1} in control to 0.10, 0.08, 0.07 and 0.05 mg pot^{-1} which represented a decrease of 23.4, 37.1, 43.9 and 63.6 per cent over control with the application of 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. In sandy loam soil, it decreased significantly from 0.122 mg pot^{-1} in control to 0.09, 0.07, 0.06, 0.05 and 0.02 mg pot^{-1} which represented a decrease of 24.5, 45.0, 54.9, 62.2 and 81.1 per cent over control with the application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. A linear relationship of DTPA-Zn with root Ni uptake revealed that Ni uptake by root decreased with increasing levels of applied Zn in both the soils (Fig.4.20a, R^2=0.91 and Fig.20b, R^2= 0.72). Kochian (1991) observed that increasing soil Zn reduces root uptake by nickel. Palacious *et al* (1998) observed that adsorption of Ni by soybean root was inhibited by presence of Zn due to competition kinetics. It was observed that presence of Zn inhibit Ni absorption competitively, suggesting that Ni and Zn are adsorbed by using the same carrier sites.

Nickel uptake by root increased significantly over control with increasing levels of applied nickel in both the soils. It increased from 0.04 mg pot^{-1} in control to 0.06, 0.08, 0.11, 0.14 and 0.18 mg pot^{-1} in loamy sand soil and from 0.03 mg pot^{-1} in control to 0.06, 0.07, 0.10, 0.10 and 0.10 mg pot^{-1} in sandy loam soil with nickel application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.40). This increase in Ni uptake by root over control was of order of 0.5, 1.13, 1.94, 2.73 and 3.73 times in loamy sand and 0.86, 1.36, 2.3, 2.26 and 2.36 times in sandy loam with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. The linear relationship of DTPA-Ni with root Ni uptake indicated that Ni uptake by root increased with increasing levels of applied Ni in both the soils (Fig.4.20c, R^2=0.92 and Fig.4.20d, R^2=0.91). Dalir and Khoshgoftarmanesh (2015) studied that Ni uptake per unit root biomass increased with increasing Ni concentration in nutrient solution. A significant interaction effect of Zn and Ni levels on Ni uptake by root was observed in loamy sand soil. Nickel uptake by root decreased sequentially when each level of applied Ni was combined with 10, 20, 40 and 80 mg Zn kg^{-1} soil. In sandy loam soil non-significant effect of Zn and Ni levels on Ni uptake by root was observed.

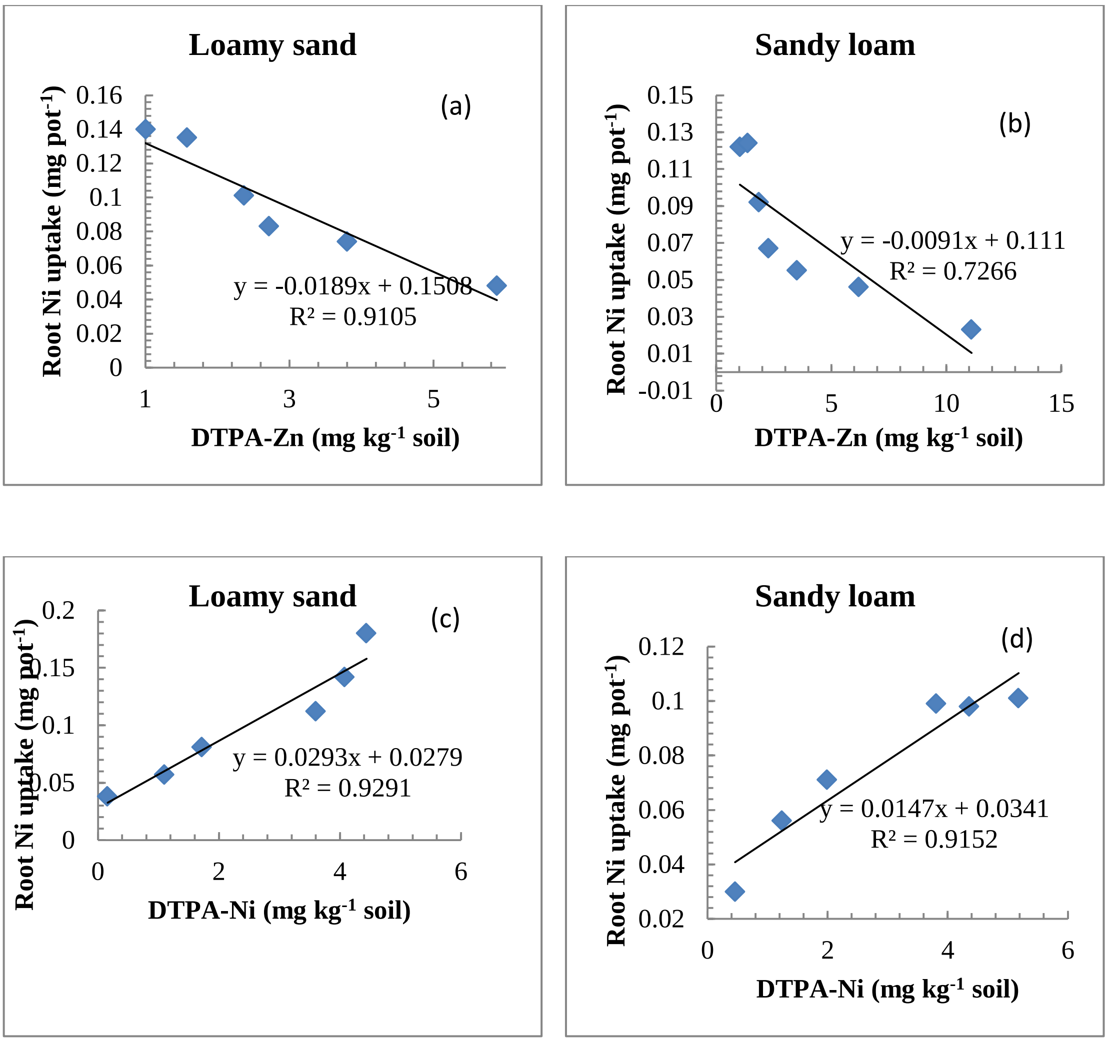


Fig.4.20: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni uptake by root

4.4.5 Nickel uptake by grain

Table 4.41: Effect of Zn and Ni on Ni uptake (mg pot^{-1}) by grain

Levels of Zn (mg kg^{-1} soil)	Grain Ni uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand (Bhaowal)						
0	0.007	0.018	0.018	0.027	0.030	0.043	0.024
2.5	0.012	0.013	0.021	0.026	0.034	0.045	0.025
5	0.012	0.014	0.019	0.022	0.027	0.038	0.022
10	0.010	0.011	0.016	0.025	0.030	0.039	0.022
20	0.012	0.013	0.014	0.022	0.033	0.036	0.022
40	0.008	0.011	0.016	0.022	0.032	0.035	0.021
80	0.007	0.011	0.016	0.019	0.023	0.027	0.017
Mean	0.010	0.013	0.017	0.023	0.030	0.038	
CD (5%)	Zn- NS			Ni- 0.004		Zn x Ni- NS	
Sandy loam (PAU)							
0	0.032	0.057	0.081	0.095	0.090	0.118	0.079
2.5	0.027	0.032	0.049	0.074	0.097	0.119	0.066
5	0.027	0.034	0.050	0.076	0.087	0.133	0.068
10	0.023	0.035	0.048	0.069	0.087	0.112	0.062
20	0.023	0.034	0.044	0.058	0.080	0.094	0.056
40	0.015	0.023	0.041	0.054	0.073	0.085	0.048
80	0.014	0.020	0.039	0.046	0.066	0.073	0.043
Mean	0.023	0.034	0.050	0.068	0.083	0.105	
CD (5%)	Zn- 0.014			Ni- 0.013		Zn x Ni- NS	

The data on nickel uptake by grain is presented in Table 4.41. Application of Zn had no significant effect on nickel uptake by grain, in loamy sand soil. Whereas in sandy loam soil, application of 10, 20, 40 and 80 mg Zn kg^{-1} soil significantly decreased the mean nickel uptake by grain from 0.079 mg pot^{-1} in control to 0.062, 0.056, 0.048 and 0.043 mg pot^{-1} resulting in decrease of 21.5, 29.1, 39.2 and 45.5 per cent over control, respectively. Nickel uptake by grain decreased with increasing levels of applied Zn in both the soils (Fig.4.21a, R^2= 0.90 and Fig.4.21b, R^2=0.78).

With the increasing levels of applied nickel, its uptake by grain increased significantly over control in both the soils. In loamy sand soil nickel uptake by grain increased significantly from 0.010 mg pot^{-1} in control to 0.017, 0.023, 0.030 and 0.038 mg pot^{-1} resulting in an increase of 0.7, 1.3, 2.0 and 2.8 times over control with nickel application @ 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.41). Similarly, in sandy loam soil nickel uptake by grain increased significantly from 0.023 mg pot^{-1} in control to 0.050, 0.068, 0.083 and 0.105 mg pot^{-1} which produced an increase of 1.17, 1.95, 2.6 and 3.56 times over control when nickel was applied @ 5, 10, 20 and 40 mg Ni kg-1 soil, respectively. A linear response of grain Ni uptake to DTPA-Ni indicated that in both the soils Ni uptake by grain increased with increasing levels of applied (Fig.4.21c, R^2=0.90 and Fig.4.21d, R^2=0.97). Kumar *et al* (2018) observed that the uptake of micronutrients (Fe, Mn, Cu and Zn) in grain significantly varied with graded application of Ni from 0 to 60 mg Ni kg^{-1}. A significant reduction in uptake of Fe, Mn, Cu and Zn was observed with application of higher levels of Ni, when Ni supply exceeds 10, 15, 5 and 10 mg Ni kg^{-1} soil. However, it has been noticed that uptake of Ni increased with increasing levels of Ni supply in soil. A non-significant interaction effect of Zn and Ni levels on grain nickel uptake was observed.

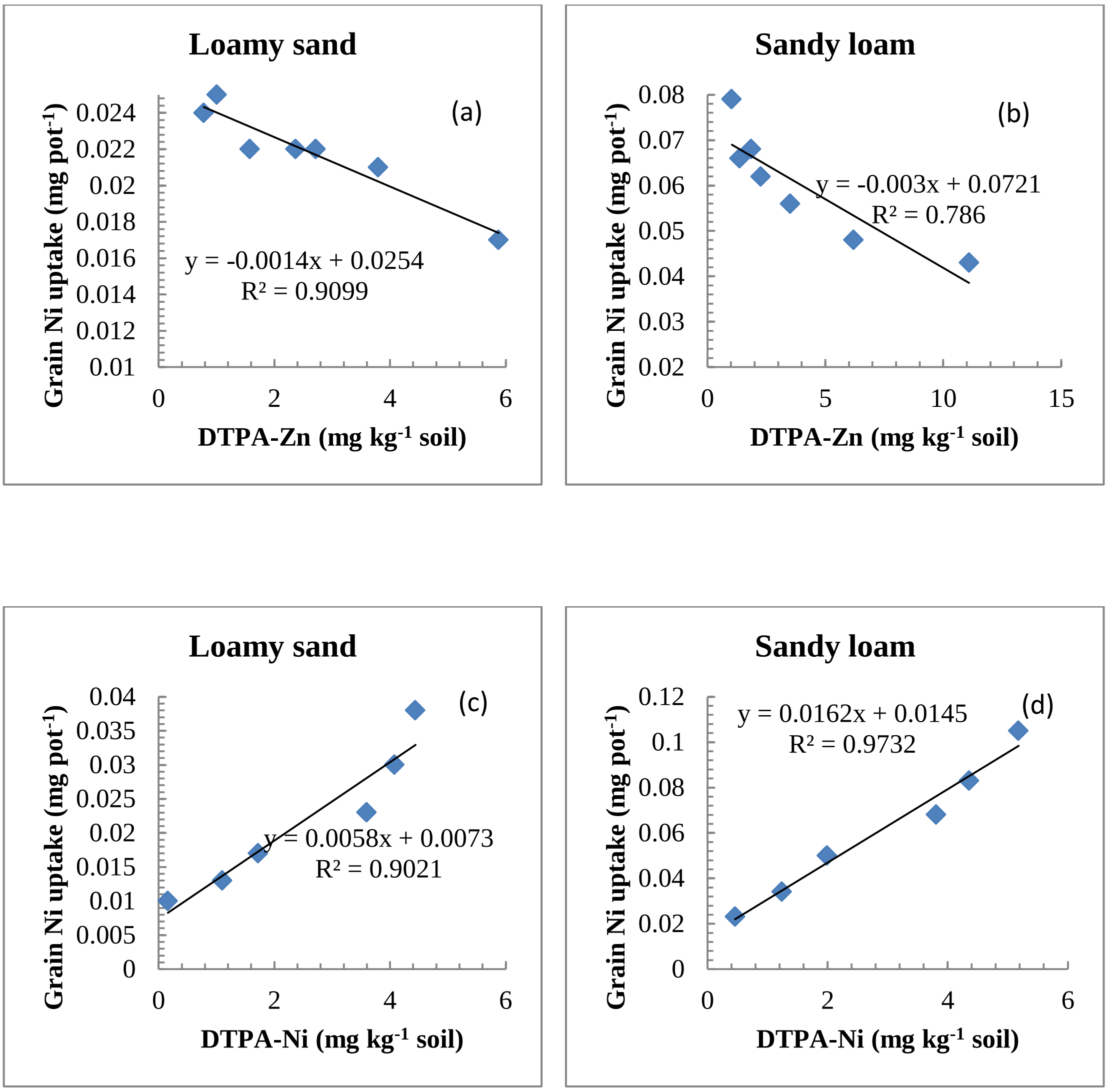


Fig4.21: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni uptake by grain

4.4.6 Nickel uptake by straw

Table 4.42:Effect of Zn and Ni on Ni uptake (mg pot^{-1}) by straw

Levels of Zn (mg kg^{-1} soil)	Straw Ni uptake (mg pot^{-1})						
	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Loamy sand (Bhaowal)						
0	0.19	0.35	0.48	0.52	0.64	0.70	0.48
2.5	0.22	0.33	0.50	0.52	0.74	0.92	0.52
5	0.18	0.29	0.49	0.29	0.78	0.83	0.47
10	0.14	0.21	0.35	0.37	0.68	0.75	0.42
20	0.10	0.20	0.30	0.33	0.60	0.84	0.40
40	0.07	0.16	0.22	0.31	0.54	0.82	0.35
80	0.07	0.16	0.11	0.19	0.61	0.66	0.30
Mean	0.14	0.24	0.35	0.36	0.66	0.79	
CD (5%)	Zn- 0.04			Ni-0.03		Zn x Ni-0.09	
Sandy loam (PAU)							
0	0.27	0.46	0.55	0.70	0.76	0.80	0.59
2.5	0.25	0.35	0.40	0.51	0.69	0.78	0.50
5	0.19	0.31	0.32	0.46	0.50	0.81	0.43
10	0.11	0.27	0.37	0.43	0.52	0.70	0.40
20	0.08	0.21	0.35	0.45	0.50	0.64	0.37
40	0.06	0.20	0.34	0.50	0.52	0.64	0.38
80	0.05	0.12	0.20	0.23	0.45	0.50	0.26
Mean	0.14	0.27	0.36	0.47	0.56	0.69	
CD (5%)	Zn- 0.04			Ni-0.04		Zn x Ni- NS	

The data on nickel uptake by straw is presented in Table 4.42. Nickel uptake by straw decreased significantly over control with increasing levels of applied zinc in both the soils. In loamy sand soil it decreased significantly from 0.48 mg pot^{-1} in control to 0.42, 0.40, 0.36 and 0.31 mg pot^{-1} with zinc application @ 10, 20, 40 and 80 mg Zn kg^{-1} soil which represented a decrease of 13.2, 17.3, 26.0 and 36.5 per cent over control, respectively. In sandy loam soil, nickel uptake by straw decreased significantly from 0.59 mg pot^{-1} in control to 0.49, 0.43, 0.40, 0.37, 0.38 and 0.26 mg pot^{-1} with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil resulting in decrease of 15.9, 26.8, 31.9, 37.5, 36.1 and 56.5 per cent over control, respectively. A linear negative relationship of Ni uptake by straw with DTPA-Zn in loamy sand (Fig.4.22a, R^2=0.92) and in sandy loam (Fig.4.22b, R^2=0.71) was observed. Palacious *et al* (1998) observed that uptake of Ni by soybean shoots was inhibited by presence of Zn due to competition kinetics. Kumar *et al* (2018) observed that the uptake of Fe, Mn, Cu and Zn in straw declined with higher concentration of $NiSO_4 \cdot 7H_2O$ spray (> 0.2%) because of decrease in dry matter yield.

Nickel application significantly increased nickel uptake by straw over control in both the soils. In loamy sand soil it increased from 0.14 mg pot^{-1} in control to 0.25, 0.35, 0.36, 0.66 and 0.79 mg pot^{-1} and in sandy loam soil it increased from 0.14 mg pot^{-1} in control to 0.27, 0.36, 0.47, 0.56 and 0.69 mg pot^{-1} with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively (Table 4.42). The corresponding values of per cent increase in straw nickel uptake over control with these levels of applied Ni were 74.6, 150.0, 157.0, 364.7 and 456.3 for loamy sand and 88.8, 150.0, 224.3, 290.9 and 381.9 for sandy loam soil, respectively. A linear positive relationship of Ni uptake by straw with DTPA-Ni in loamy sand (Fig.4.22c, R^2=0.81) and in sandy loam (Fig.4.22d, R^2=0.97) was observed.

A significant interaction effect of zinc and nickel levels on straw nickel uptake was observed in loamy sand soil. It was observed that straw nickel uptake decreased significantly at each level of applied Zn in both the soils. Effect of applied Zn and Ni on Ni uptake by straw was non-significant in sandy loam soil.

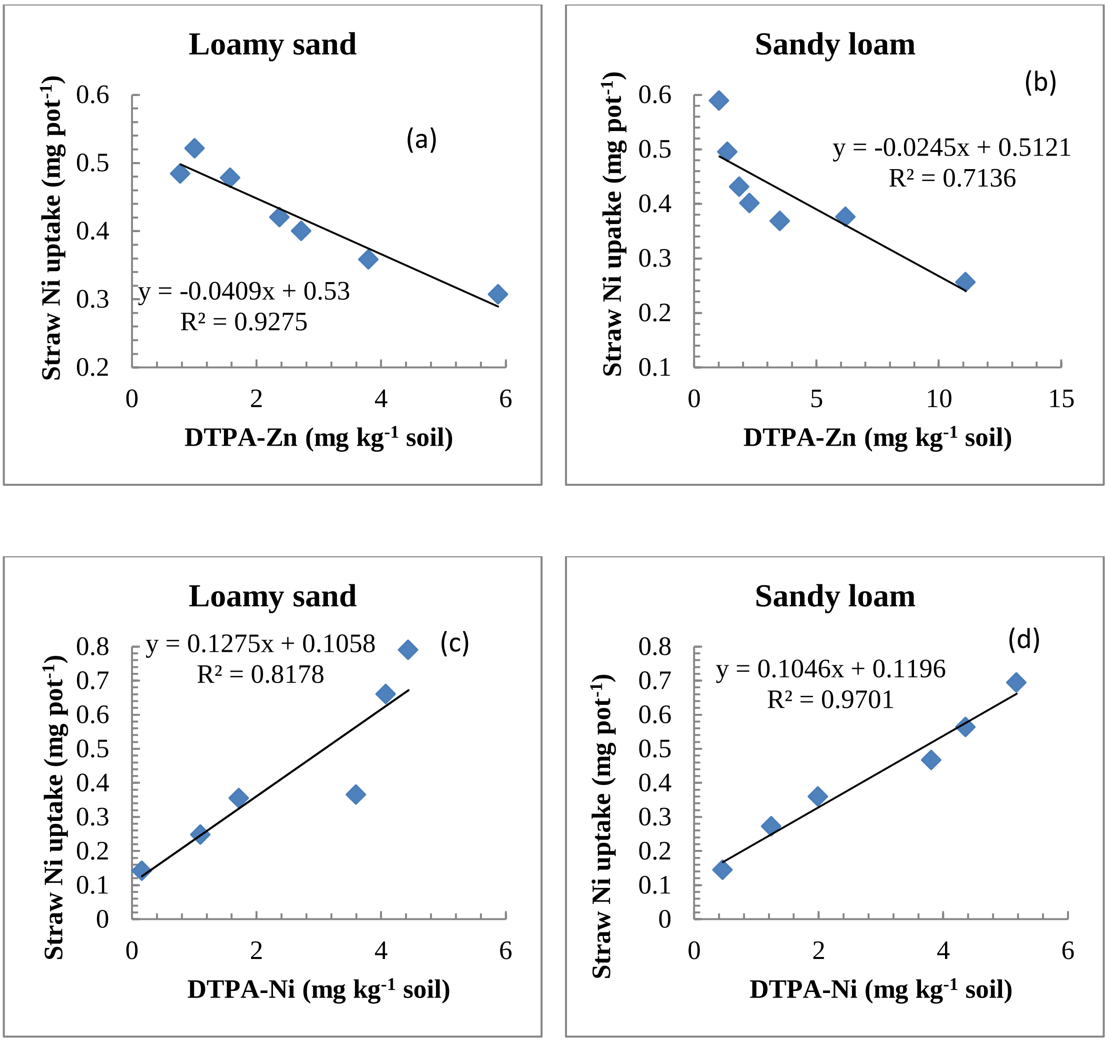


Fig.4.22: Relationship of DTPA-Zn and DTPA-Ni in soil with Ni uptake by straw

Table 4.43: Coefficients of correlation of Zn and Ni uptake in root, grain and straw with crop yield

Plant parameter	Loamy sand	Sandy loam
	Root dry matter yield	
Zn uptake	0.868^{*}	0.173
Ni uptake	-0.768^{*}	-0.246
	Grain yield	
Zn uptake	0.988^{**}	0.467
Ni uptake	-0.684	-0.185
	Straw yield	
Zn uptake	0.948^{**}	0.420
Ni uptake	-0.713^{*}	-0.112

**Significant at 1% level
* Significant at 5% level

Table 4.44: Coefficients of correlation of Zn and Ni uptake by root, grain and straw with chemical pools of Zn

	Zn uptake			Nickel uptake		
	Root	Grain	Straw	Root	Grain	Straw
	Loamy sand					
EXCH-Zn	0.957^{**}	0.794^{*}	0.797^{*}	-0.916^{**}	-0.329	-0.929^{**}
SAD-Zn	0.950^{**}	0.793^{*}	0.799^{*}	-0.900^{**}	-0.290	-0.900^{**}
MnOX-Zn	0.980^{**}	0.855^{*}	0.855^{*}	-0.951^{**}	-0.348	-0.947^{**}
AMPOX-Zn	0.969^{**}	0.832^{*}	0.837^{*}	-0.907^{**}	-0.319	-0.923^{**}
CRYOX-Zn	0.967^{**}	0.935^{**}	0.944^{**}	-0.949^{**}	-0.559	-0.955^{**}
OM-Zn	0.965^{**}	0.959^{**}	0.968^{**}	-0.933^{**}	-0.505	-0.929^{**}
RES-Zn	0.915^{**}	0.709	0.713	-0.873^{*}	-0.274	-0.893^{**}
DTPA-Ni	-0.857^{*}	-0.670	-0.672	0.791^{*}	0.276	0.828^{*}
DTPA-Zn	0.976^{**}	0.850^{*}	0.856^{*}	-0.948^{**}	-0.390	-0.959^{**}
	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Sandy loam					
EXCH-Zn	0.863^{*}	0.742	0.655	-0.905^{**}	-0.933^{**}	-0.859^{*}
SAD-Zn	0.976^{**}	0.899^{**}	0.826^{*}	-0.952^{**}	-0.960^{**}	-0.911^{**}
MnOX-Zn	0.966^{**}	0.885^{**}	0.815^{*}	-0.972^{**}	-0.965^{**}	-0.921^{**}
AMPOX-Zn	0.978^{**}	0.902^{**}	0.857^{*}	-0.957^{**}	-0.951^{**}	-0.884^{**}
CRYOX-Zn	0.969^{**}	0.914^{**}	0.876^{**}	-0.984^{**}	-0.977^{**}	-0.921^{**}
OM-Zn	0.989^{**}	0.950^{**}	0.909^{**}	-0.963^{**}	-0.984^{**}	-0.924^{**}
RES-Zn	0.819^{*}	0.673	0.566	-0.843^{*}	-0.890^{**}	-0.790^{*}
DTPA-Ni	-0.950^{**}	-0.861^{*}	-0.784^{*}	0.953^{**}	0.962^{**}	0.894^{**}
DTPA-Zn	0.870^{*}	0.740	0.640	-0.889^{**}	-0.924^{**}	-0.836^{*}

**Significant at 1% level
* Significant at 5% level

Table 4.45: Coefficients of correlation of Zn and Ni uptake by root, grain and straw with chemical pools of Ni

	Zn uptake			Nickel uptake		
	Root	Grain	Straw	Root	Grain	Straw
	Loamy sand					
EXCH-Ni	-0.979**	-0.841*	0.256	0.985**	0.970**	0.957**
SAD-Ni	-0.995**	-0.893*	0.121	0.992**	0.987**	0.987**
MnOX-Ni	-0.950**	-0.899*	0.156	0.975**	0.956**	0.971**
AMPOX-Ni	-0.986**	-0.947**	0.039	0.990**	0.975**	0.963**
CRYOX-Ni	-0.952**	-0.769	0.367	0.961**	0.946**	0.942**
OM-Ni	-0.982**	-0.907*	0.159	0.998**	0.964**	0.974**
RES-Ni	-0.900*	-0.983**	-0.279	0.891*	0.912*	0.891*
DTPA-Zn	0.894*	0.703	-0.494	-0.926**	-0.879*	-0.900*
DTPA-Ni	-0.941**	-0.793	0.316	0.958**	0.892*	0.907*
	Zn concentration			Nickel concentration		
	Root	Grain	Straw	Root	Grain	Straw
	Sandy loam					
EXCH-Ni	-0.938**	-0.783	-0.648	0.910*	0.984**	0.993**
SAD-Ni	-0.948**	-0.813*	-0.680	0.895*	0.990**	0.994**
MnOX-Ni	-0.945**	-0.850*	-0.700	0.857*	0.974**	0.983**
AMPOX-Ni	-0.914*	-0.754	-0.616	0.936**	0.989**	0.996**
CRYOX-Ni	-0.912*	-0.796	-0.637	0.895*	0.981**	0.993**
OM-Ni	-0.905*	-0.738	-0.607	0.940**	0.993**	0.996**
RES-Ni	-0.956**	-0.984**	-0.915*	0.606	0.882*	0.847*
DTPA-Zn	0.957**	0.870*	0.751	-0.845*	-0.992**	-0.981**
DTPA-Ni	-0.908*	-0.713	-0.594	0.948**	0.982**	0.986**

**Significant at 1% level
* Significant at 5% level

4.5 Interactive effects of Zn and Ni application on activity of urease in soil at maximum tillering and harvesting stage.

4.5.1 Urease enzyme at maximum tillering stage

Table 4.46: Effect of Zn and Ni on urease enzyme at maximum tillering stage

Levels of Zn (mg kg^{-1} soil)	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Soil-I (Bhaowal)						
0	1.26	2.20	2.88	4.37	2.25	1.71	2.44
2.5	1.25	2.18	2.48	3.45	1.61	0.88	1.98
5	0.95	1.81	2.30	3.11	1.45	0.83	1.74
10	0.93	1.78	2.20	2.51	1.44	0.79	1.61
20	0.86	1.42	2.13	2.46	1.20	0.61	1.45
40	0.75	1.35	2.05	2.40	0.79	0.53	1.31
80	0.51	0.84	1.50	1.96	0.62	0.41	0.97
Mean	0.93	1.65	2.22	2.89	1.34	0.81	
CD (5%)	Zn- 0.12			Ni- 0.10		Zn x Ni- 0.33	
Soil-II (PAU)							
0	2.35	2.70	3.63	4.55	1.96	1.20	2.73
2.5	2.26	2.48	3.53	4.28	1.87	1.08	2.58
5	2.17	2.22	2.88	3.30	1.76	0.94	2.21
10	1.60	2.18	2.55	2.87	1.42	0.92	1.92
20	1.46	1.95	2.08	2.72	1.31	0.84	1.73
40	1.41	1.83	1.99	2.61	1.19	0.62	1.61
80	0.82	1.26	1.64	2.49	1.02	0.54	1.29
Mean	1.72	2.09	2.62	3.26	1.51	0.88	
CD (5%)	Zn- 0.16			Ni- 0.15		Zn x Ni- 0.40	

The application of Zn was found to significantly decrease the urease activity of both the soils at all levels of Ni. The mean decrease in urease activity was from 2.44 µg urea/hr/g soil in control to 1.98, 1.74, 1.61, 1.45, 1.31 and 0.97 µg urea/hr/g soil in loamy sand and from 2.73 µg urea/hr/g soil in control to 2.58, 2.21, 1.92, 1.73, 1.61 and 1.29 µg urea/hr/g soil in sandy loam soil with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil (Table 4.46). It produced a decrease of 18.8, 28.6, 34.0, 40.5, 46.3 and 60.2 per cent over control in loamy sand soil and a decrease of 5.4, 19.0, 29.6, 36.6, 41.0 and 52.7 per cent over control in sandy loam soil, when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil, respectively. A negative linear relationship of urease activity with applied Zn in both the soils (Fig.4.23a, R^2= 0.72 and Fig.4.23b, R^2=0.73) soil was observed.

Data in the Table 4.46 showed that activity of urease enzyme in soil at maximum tillering stage of rice significantly increased with increase in the level of applied but upto 10 mg Ni kg^{-1} in both soils. Thereafter it decreased significantly. The mean activity of urease increased significantly from 0.93 µg urea/hr/g soil in control to 1.65, 2.22 and 2.89 µg urea/hr/g soil when Ni was applied @ 2.5, 5 and 10 mg kg^{-1} soil respectively in loamy sand soil, resulting in an increase of 77.4, 138.7 and 210.7 per cent over control respectively. In sandy loam soil, the mean urease activity increased from 1.72 µg urea/hr/g soil in control to 2.09, 2.62, 3.26 µg urea/hr/g soil when Ni was applied @ 2.5, 5 and 10 mg kg^{-1} soil resulting in an increase of 21.5, 52.3, 89.5 per cent over control respectively. Further addition of Ni beyond these levels reduced the activity of urease In loamy sand soil. Urease activity was reduced significantly by 12.9 per cent over control when Ni was applied @ 40 mg Ni kg^{-1} soil, whereas in sandy loam soil it declined significantly by 12.2 and 48.8 per cent over control with the application of 20 and 40 mg Ni kg^{-1} soil, respectively. The quadratic response of urease activity to applied Ni in both the soils indicated that urease activity increased up to a level of 10 mg Ni kg^{-1} soil and thereafter it declined (Fig.4.23c, R^2=0.44 and Fig.4.23d, R^2=0.54). The interaction effect of applied Zn and Ni on urease activity was also significant for both soils. Urease activity was more in medium textured soil than light textured soil.

Reduction in the urease activity with increase in level of Zn was due to the fact that heavy metals like Zn, Cd, Pb have an inhibitory effects on activity of urease present in soil (Sandaa *et al* 2001, Akmal *et al* 2005). Heavy metals may directly inhibit urease activity by interacting with protein SH-groups; in this way protein conformation is changed, and enzymes are inactivated (Seregin and Kozhevnikova 2005). Ofoegbu *et al* (2013) indicated that the activities of urease showed significant negative correlation with increase in heavy metal content such as Zn. Tabatabai (1976) studied the effect of trace elements on urease activity in soil and found that all the trace elements such as Zn^{+2}, Cu^{+2}, Hg^{+2}, Ni^{+2}, Al^{+3} etc. inhibit the activity of urease in soil**.** But increase in the activity of urease with increase in the level of Ni is due to its role in N metabolism and being a constituent of urease enzyme. Hence, Ni is essential for urease enzyme metabolism (Eskew *et al* 1983, Brown *et al* 1990, Gerendás and Sattelmacher 1997) but at low concentration of Ni. Barcelos *et al* (2017) observed that urease activity increased proportionally up to 20 g Zn ha^{-1}, thereafter it decreased.

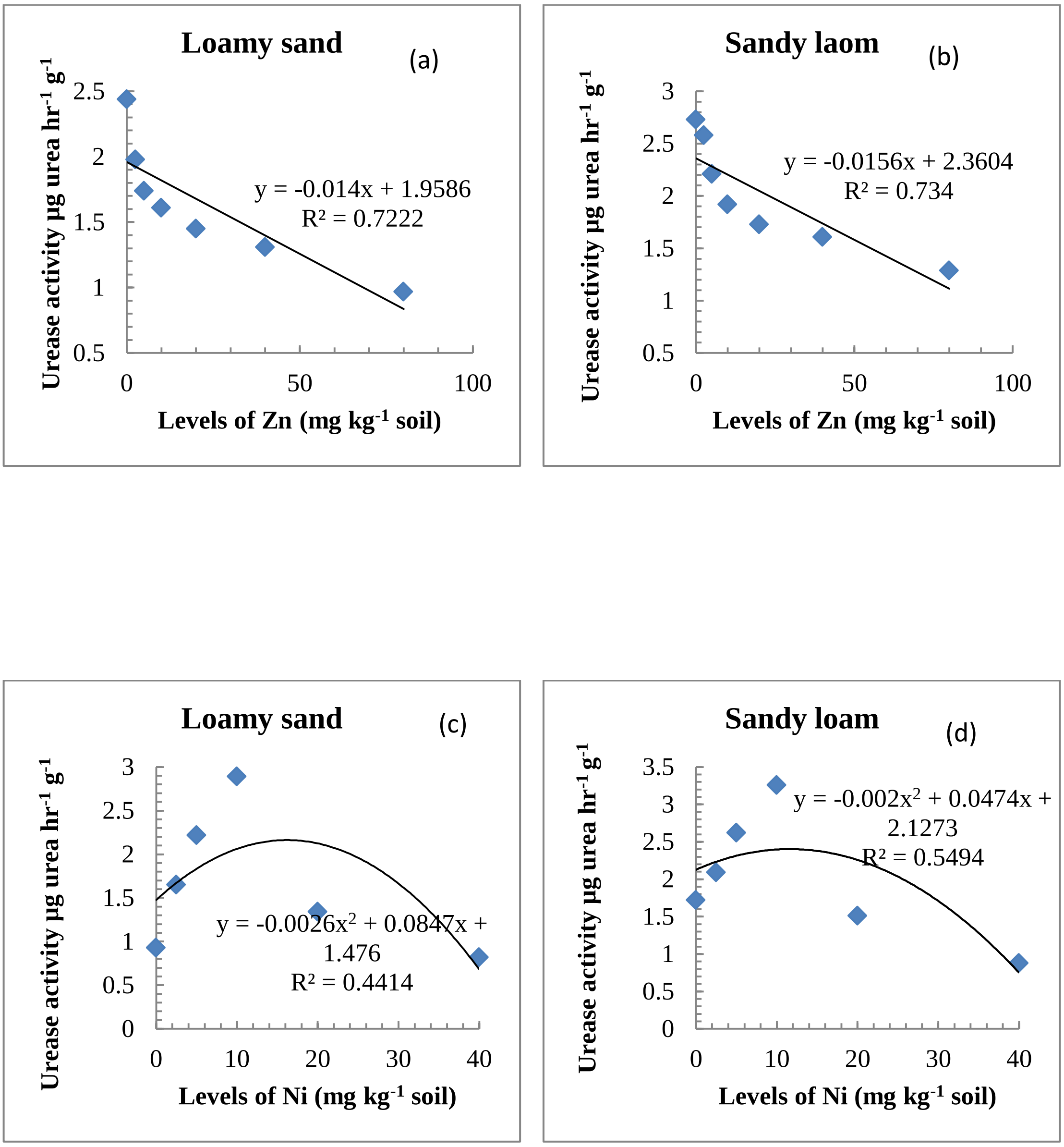


Fig.4.23: Effect of levels of Zn and Ni on urease activity in soil at maximum tillering stage

4.5.2 Urease enzyme at harvesting stage

Table 4.47: Effect of Zn and Ni on urease enzyme at harvesting stage

Levels of Zn (mg kg^{-1} soil)	Levels of Ni (mg kg^{-1} soil)						
	0	2.5	5	10	20	40	Mean
	Soil-I (Bhaowal)						
0	1.19	2.10	2.63	3.84	2.17	1.62	2.26
2.5	1.07	1.87	2.34	3.26	1.53	0.86	1.82
5	0.96	1.76	2.17	2.90	1.41	0.78	1.67
10	0.89	1.58	1.96	2.41	1.32	0.70	1.48
20	0.75	1.35	1.90	2.20	1.10	0.57	1.31
40	0.60	1.15	1.78	2.15	0.83	0.50	1.17
80	0.54	0.82	1.26	1.80	0.53	0.32	0.88
Mean	0.86	1.52	2.01	2.65	1.27	0.74	
CD (5%)	Zn- 0.12		Ni- 0.11		Zn x Ni- 0.31		
Soil-II (PAU)							
0	2.30	2.64	3.50	4.41	1.89	1.13	2.65
2.5	2.14	2.35	3.45	4.24	1.80	1.03	2.50
5	2.04	2.15	2.87	3.19	1.64	0.89	2.13
10	1.45	2.07	2.52	2.71	1.35	0.83	1.82
20	1.34	1.86	1.98	2.58	1.22	0.77	1.62
40	1.27	1.63	1.86	2.43	1.19	0.60	1.50
80	0.80	1.11	1.52	2.25	0.90	0.52	1.18
Mean	1.62	1.97	2.53	3.12	1.43	0.82	
CD (5%)	Zn- 0.14		Ni- 0.13		Zn x Ni- 0.34		

Data in the Table 4.47, the application of Zn was found to significantly decrease the urease activity of both the soils at all levels of Ni. The mean decrease in urease activity was from 2.26 µg urea/hr/g soil in control to 1.82, 1.67, 1.48, 1.31, 1.17 and 0.88 µg urea/hr/g soil in loamy sand and from 2.65 µg urea/hr/g soil in control to 2.50, 2.13, 1.82, 1.62, 1.50 and 1.18 µg urea/hr/g soil in sandy loam when Zn was applied @ 2.5, 5, 10, 20, and 80 mg kg^{-1} soil. In loamy sand soil urease activity decreased significantly by 19.4, 26.1, 34.5, 42.0, 48.2 and 61.0 per cent over control and in sandy loam soil it decreased by 5.6, 19.6, 31.3, 38.8, 43.4 and 55.4 per cent over control with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively. A negative linear relationship of urease activity with applied Zn in both the soils (Fig.4.24a, R^2=0.73 and Fig.4.24b, R^2=0.73)

Data in the Table 4.47 showed that activity of urease enzyme at harvesting stage of rice significantly increased with increase in the level of applied Ni up to 10 mg Ni kg^{-1} in both soils. Thereafter it decreased significantly. In loamy sand soil, the mean activity of urease increased significantly from 0.93 µg urea/hr/g soil in control to 1.52, 2.01 and 2.65 µg urea/hr/g soil when Ni was applied @ 2.5, 5 and 10 mg kg^{-1} soil resulting in an increase of 76.7, 133.7 and 208.1 per cent over control, respectively. In sandy loam, the mean urease activity increased from 1.62 µg urea/hr/g soil in control to 1.97, 2.53, 3.12 µg urea/hr/g soil resulting in an increase of 21.6, 56.1 and 92.5 percent over control with the application of 2.5, 5 and 10 mg Ni kg^{-1} soil, respectively. But when Ni was applied @ 40 mg kg^{-1} soil, urease activity significantly reduced by 10.4 per cent over control, in loamy sand soil. Whereas in loamy sand soil, urease activity declined significantly by 11.7 and 49.4 per cent over control with the application of 20 and 40 mg Ni kg^{-1} soil, respectively. The quadratic response of urease activity to applied Ni in both soils (Fig.4.24c, R^2=0.73 and Fig.4.24d, R^2=0.73) indicated that urease activity increased up to a level of 10 mg Ni kg^{-1} soil and thereafter it declined. The interaction effect of applied Zn and Ni on urease activity was also significant for both soils. Urease activity was more in medium textured soil than light textured soil. Urease activity was lower at harvesting stage as compared to maximum tillering stage because at harvesting stage very less amount of urea is available due to hydrolysis of urea in soils.

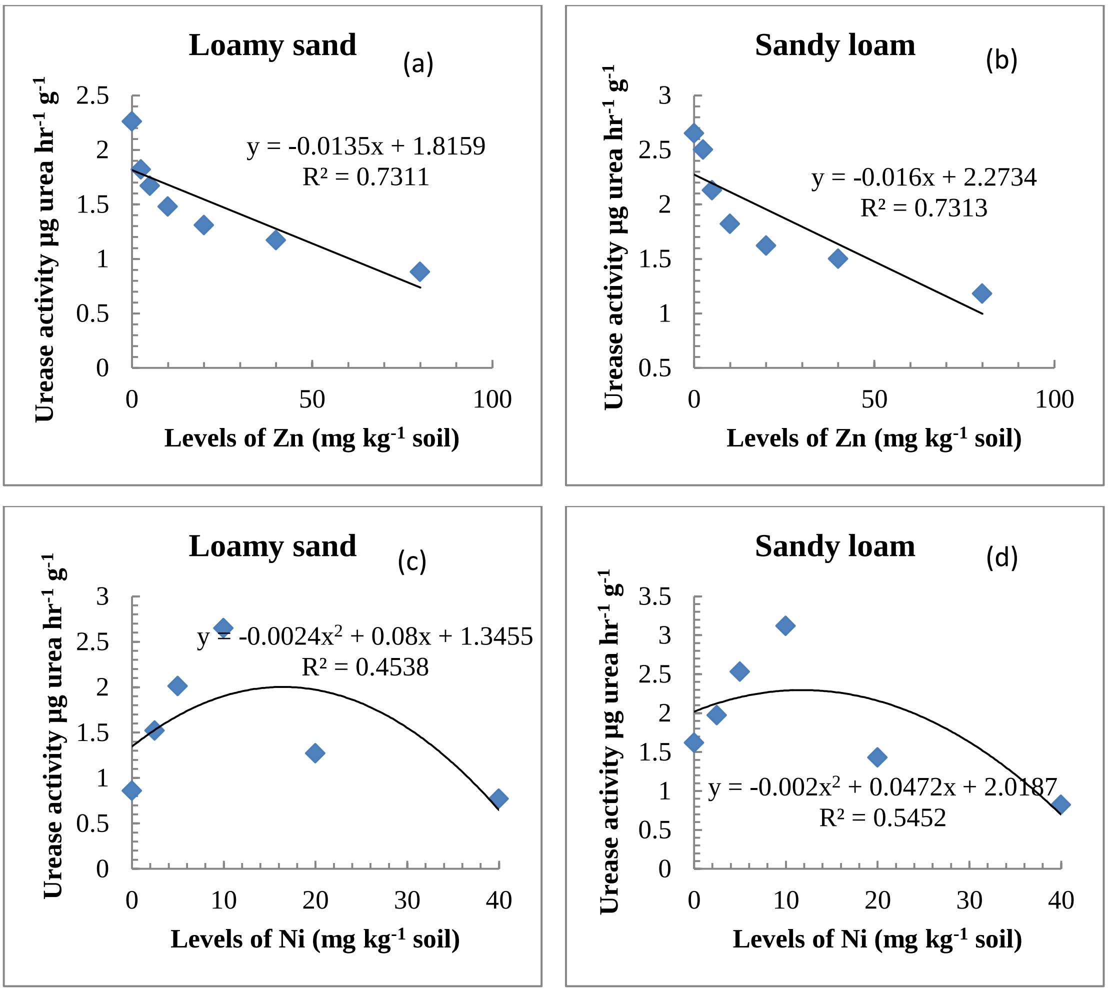


Fig.4.24: Effect of levels of Zn and Ni on urease activity in soil at harvesting stage

Zinc management appears to be an especially important component of an effective strategy to prevent Ni deficiency because Zn is an competitive inhibitor of Ni uptake by roots, soil Zn levels should not be allowed to increase in low CEC soils that are already low in Ni. In the present investigation also the content of DTPA-Ni remained higher in medium textured soil (PAU) as compared to light textured soil (Bahowal) at any level of applied Zn. Thus, indicating a high antagonistic effect of applied Zn on availability of Ni in light textured soil. This is also evidenced by a more decrease of the activity of urease enzyme at maximum tillering stage in loamy sand as compared to medium textured soil because Ni involved in the activity of urease enzyme during hydrolysis of urea in soils.

CHAPTER V

SUMMARY

The interactions between nutrients can either induce deficiencies and/or toxicities which can modify the growth and nutrition of crops. In present investigation, a pot experiment was conducted to study the interactive effects of Zn and Ni on growth and nutrition of rice. The soils used in the study were i) loamy sand (ls) Typic Ustipssament (pH 7.9, EC 0.25 dS m^{-1}, OC 0.15%, $CaCO_3$ 0.13%, DTPA-Zn 1.00 and DTPA-Ni 0.19 mg kg^{-1} soil) and ii) sandy loam (sl) Typic Haplustept (pH 8.1, EC 0.35 dS m^{-1}, OC 0.32%, DTPA-Zn 1.20 and DTPA-Ni 0.46 mg kg^{-1} soil). Seven levels of Zn (0, 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil) as zinc sulfate heptahydrate and six levels of Ni (0, 2.5, 5, 10, 20 and 40) as nickel chloride were applied in all possible combinations to eight kg of soil per pot with three replications. Rice (cv PR-126) was grown till maturity and soil, root, grain and straw samples were collected. Soil and plant samples were processed and analysed for DTPA-Zn, DTPA-Ni, various pools of Zn and Ni (exchangeable, specifically adsorbed, manganese oxide bound, amorphous Fe and Al oxides bound, organically bound and residual mineral fraction) and Zn and Ni concentration in root, grain and straw. The activity of urease enzyme in soil was estimated at maximum tillering and harvesting stage. Mean DTPA-Zn decreased significantly from 3.55 mg kg^{-1} soil in control to 1.98 mg kg^{-1} soil in loamy sand and from 4.76 mg kg^{-1} soil in control to 2.68 mg kg^{-1} soil in sandy loam with application of 40 mg Ni kg^{-1} soil. Application of Zn significantly increased DTPA-Zn in both the soils. The interaction effect of Zn and Ni levels on DTPA-Zn was also significant. It was observed that DTPA-Zn decreased significantly by 45 and 34 per cent when 40 mg Ni kg^{-1} soil was applied along with 80 mg Zn kg^{-1} soil as compared to when only 80 mg Zn kg^{-1} soil was applied in loamy sand and sandy loam soil, respectively. DTPA-Ni decreased significantly from 2.65 mg kg^{-1} soil in control to 2.19 and 2.09 mg kg^{-1} soil when Zn was applied @ 40 and 80 mg Zn kg^{-1} soil, respectively in loamy sand. In sandy loam soil, DTPA-Ni decreased significantly from 2.99 mg kg^{-1} soil in control to 2.83, 2.71 and 2.60 mg kg^{-1} when Zn was applied @ 20, 40 and 80 mg Zn kg^{-1} soil, respectively. Application of Ni significantly increased DTPA-Ni in both the soils.

When a nutrient is applied to soil through external sources many chemical reactions like adsorption, precipitation and complexation take place. The per cent recovery of added Zn @ 80 mg kg^{-1} soil at different levels of applied Ni in a particular fraction was calculated by taking the difference of content of that fraction in Zn treated pot and the corresponding no Zn pot. Soil Zn was largely found in unavailable forms and it was observed that in loamy sand soil only 1.11 and 1.82 per cent, and in sandy loam soil 0.81 and 1.72 per cent of applied Zn @ 80 mg kg^{-1} soil entered in exchangeable and specifically adsorbed fraction, respectively which are considered to be the most plant available forms. A major portion of added Zn

entered in to residual mineral fraction followed by amorphous Fe and Al oxides and crystalline Fe and Al oxides in both the soils. Only 2.52 and 3.35 per cent of added Zn entered in to organic matter bound Zn in loamy sand and sandy loam soils, respectively. Soil Ni was largely found in unavailable forms and it was observed that in loamy sand soil only 1.25 and 1.55 per cent and in sandy loam 1.55 and 1.75 per cent of applied nickel @ 40 mg kg^{-1} soil entered in to exchangeable and specifically adsorbed fractions, respectively which are considered to be the most plant available forms. A major portion of the added Ni entered in to residual mineral fraction followed by amorphous Fe and Al oxides and organically bound Ni in loamy sand whereas in sandy loam, a major portion of the added Ni entered in to residual mineral fraction followed by crystalline and amorphous oxides. Only 2.75 and 3.5 per cent of added Ni entered in to manganese oxides bound-Ni in loamy sand and sandy loam soil, respectively.

In loamy sand, Zn application @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil significantly increased the mean root dry matter yield (RDMY) by 33.7, 47.7, 57.1, 61.0, 65.6 and 71.1 per cent over control. However, the differences in RDMY produced with application of 20, 40 and 80 mg Zn kg^{-1} soil, were not significant. In sandy loam soil, the mean RDMY increased by 18.2, 16.5, 16.8, 18.2 per cent over control with the application of 2.5, 5, 10 and 20 mg Zn kg^{-1} soil, respectively. The differences in RDMY produced with application of 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil were not significant, which may be due to higher soil test value of Zn (DTPA-Zn 1.20 mg kg^{-1} soil) in sandy loam as compared to loamy sand (1.0 mg DTPA-Zn kg^{-1} soil). The mean grain yield increased significantly from 26.8 g pot^{-1} in control to 29.7, 29.2, 32.7, 33.7, 35.0 and 34.3 g pot^{-1} when Zn was applied @ 2.5, 5, 10, 20, 40 and 80 mg kg^{-1} soil, respectively in loamy sand soil whereas in sandy loam soil, the mean grain yield increased significantly from 31.0 g pot^{-1} over control to 33.7, 33.6 and 33.2 g pot^{-1} when Zn was applied @ 5, 10 and 20 mg Zn kg^{-1} soil. Zinc application significantly increased the straw yield from 33.4 g pot^{-1} in control to 39.2, 41.9, 47.0, 47.9, 48.7 and 45.5 g pot^{-1} with the application of 2.5, 5, 10, 20, 40 and 80 mg Zn kg^{-1} soil, respectively in loamy sand soil. In sandy loam soil, straw yield increased significantly from 41.5 g pot^{-1} in control to 46.3, 46.4, 46.2 and 46.0 g pot^{-1} with the application of 5, 10, 20 and 40 mg Zn kg^{-1} soil, respectively. A significant decrease in straw yield was observed in both soils when Zn was applied @ 80 mg kg^{-1} soil over the application of 40 mg kg^{-1} soil.

Growth of crop was improved with graded levels of applied Ni in both the soils. Mean RDMY increased significantly from 4.25 g pot^{-1} in control to a maximum of 5.21 g pot^{-1} when Ni was applied @ 10 mg kg^{-1} soil in loamy sand. Thereafter, it deceased up to a level of 40 mg Ni kg^{-1} soil. However, in sandy loam soil mean RDMY increased significantly from 3.40 g pot^{-1} in control to a maximum of 4.42 g pot^{-1} with the lowest level of applied Ni and thereafter it decreased significantly. Mean grain yield of rice increased significantly from 28.3

g pot^{-1} in control to 31.0, 33.7, 32.5 and 33.0 g pot^{-1} with the application of 2.5, 5, 10 and 20 mg Ni kg^{-1} soil, respectively in loamy sand. The differences in grain yield observed with the application of 5, 10 and 20 mg Ni kg^{-1} soil were not significant. In sandy loam soil, grain yield increased significantly from 29.8 g pot^{-1} in control to 32.2, 33.3, 33.9 and 34.7 g pot^{-1}when Ni was applied @ 2.5, 5, 10 and 20 mg kg^{-1} soil, respectively. The increase in grain yield was observed only up to a level of 20 mg Ni kg^{-1} soil and thereafter it declined. In loamy sand soil, straw yield increased from 35.5 g pot^{-1} in control to 43.1, 46.8, 44.4 and 47.4 g pot^{-1} and in sandy loam soil it increased from 37.8 g pot^{-1} in control to 43.4, 45.5, 47.4 and 49.4 g pot^{-1} with the application of 2.5, 5, 10, 20 and 40 mg Ni kg^{-1} soil, respectively. A significant decreased in straw yield was observed in both soils when Ni was applied @ 40 mg kg^{-1} soil over the application of 20 mg kg^{-1} soil. The interactive effects of Zn and Ni application on RDMY, grain and straw yield was not significant.

Upper critical levels of Zn and Ni associated with 50 per cent reduction from maximum yield, which are generally considered to be toxic for plants were determined by using data of all the 42 treatment combinations for both the soils taken together (n=84). Irrespective of the soil used, about 12.0, 16.5 and 14.5 mg DTPA-Zn kg^{-1} soil and 5.37, 7.45 and 7.10 mg DTPA-Ni kg^{-1} soil produced 50 per cent reduction from maximum yield of root, grain and straw, respectively, which may be considered as the upper critical values for rice.

Irrespective of the soil used in the study the concentration of Ni in root, grain and straw decreased as the concentration of Zn in these plant parts increased. Thus indicating their antagonism with each other. Also, Ni uptake by each plant part decreased with increase in DTPA-Zn. With increase in level of applied Zn activity of urease enzyme significantly decreased at both the stages (Maximum tillering and harvesting stage). With the application of Ni urease activity significantly increased up to a level of 10 mg Ni kg^{-1} soil and thereafter it decreased in both the soils at both the stages. Hence Zn management appears to be an especially important component of an effective strategy to prevent Ni deficiency because Zn is an competitive inhibitor of Ni uptake by roots, soil Zn levels should not be allowed to increase in low CEC soils that are already low in Ni. In the present investigation also the content of DTPA-Ni remained higher in medium textured soil (PAU) as compared to light textured soil (Bahowal) at any level of applied Zn. Thus, indicating an antagonistic effect of applied Zn on availability of Ni in light textured soil. This is also evidenced by a more decrease of the activity of urease enzyme at maximum tillering stage in loamy sand as compared to medium textured soil because Ni involved in the activity of urease enzyme during hydrolysis of urea in soils. So, the farmers should apply Zn to the soils only, if the soil test value is below the critical deficiency level to avoid Zn induced Ni deficiency due to build up of Zn in the soils.

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