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Pedological Characteristics and Heavy Metals Contamination of the Paddy Soils in Taiwan

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Abstract

Extensive rice production on numerous alluviums and terraces in Taiwan has been done by the complete irrigation systems since the early and mid stages of the 20th century. Irrigation water and the fluctuation of groundwater play important roles in controlling the soil hydrology and redoximorphology. Redoximorphic features are consequently formed by the alternative wet and dry cycles, such as Fe soft masses, Fe and clay depletions and Fe-Mn nodules through the profiles of paddy soils. The saturated and reducing durations were specified associated with the definite redoximorphic features in the soils under a landscape unit. In the case studies of rice-growing Ultisols on red earth terrace in northwestern Taiwan, the optimum durations of saturation and reduction were about 50% of the year in the formation of redoximorphic features. This anthraquic condition could promote the formation of diverse redoximorphic features associated with plinthites. In the paddy soils of Taiwan, Entisols, Inceptisols, Alfisols, Ultisols, Mollisols and Oxisols are main Soil Orders based on *Soil Taxonomy*. On one hand considering by soil quality and food security of rice, heavy metal contamination is the main issue in rice production of Taiwan. On the other hand by rice market liberalization, changing the land use from paddy soils into non-waterlogged cropping has some problems in initial soil properties such as poor drainage and impeded root growth by the subsurface compacted layers for upland crops. Irrigation water for rice production in Taiwan has been contaminated by illegal discharges of industrial and livestock wastewater affecting the paddy soil qualities by heavy metals. According to the regulation for pollutants in Soil and Groundwater Pollution Remediation Act of Taiwan, the total seriously contaminated area by heavy metals is more than 300 ha, especially by Cd, Cr, Cu, Ni and Pb contamination of rice in Taiwan. Due to the special profile morphology and hydrology of paddy soils, dilution by deep plowing and mixing, acid washing, chemical stabilization, and phytoremediation are major remediation technologies applied on the contaminated sites with pilot or field scales. However, the recovery of soil fertilities and ecological functions is needed to be evaluated after remediation.

1. Introduction

1.1. Soil Survey of Paddy Soils in Taiwan

Detailed soil surveys of rural soils in the western, northern and eastern plains of Taiwan were conducted by National Chung-Hsing University and Taiwan Agricultural Research Institute, from 1962 to 1973, and from 1974 to 1976, respectively. Total 178 field sheets of the soil survey on a scale of 1:25,000 have been published. From 1979 to 1987, the detailed soil surveys of the slope lands with elevation lower than 1,000 m above sea level were also conducted by the former Taiwan Provincial Mountain Agriculture and Pasture Development Bureau which has been reformed as Taiwan Soil and Water Conservation Bureau, Council of Agriculture, Taiwan. However, 215 field sheets of the soil maps were consequently published on a scale of 1:25,000. The mapping units were soil types in the rural regions and soil phases in the slope regions. Additionally, 106 map units were republished on the same scale in 1988. Paddy fields occupied approximately 50% (450,000 ha) of the agricultural lands in Taiwan in last decade, and the history of planting lowland rice ranged from 50 to 350 years, particularly on the numerous alluviums and terraces followed by the complete irrigation systems since the early and mid stages of the 20th century. Because of the worldwide liberalization of rice marketing, the government of Taiwan therefore changed the policy of land use in decreasing the production of rice and into increasing upland crop production in original paddy fields.

There are nearly 1,000 soil series in Taiwan. According to the land use and different parent materials, these soils were classified as 34 major soil groups based on the classification system of Taiwan, and 106 soil units in the soil map of Taiwan on a scale of 1:250,000 (Sheh and Wang, 1989). The properties of paddy soils in Taiwan can be approximately divided into five alluvial soil groups: (1) slate alluvial soils, (2) sandstone and shale alluvial soils, (3) schist alluvial soils, (4) slate, sandstone and shale mixed alluvial soils, and (5) Quaternary aged alluvial soils. However, most of them are on the western part of Taiwan and on the alluvial fans of some main rivers.

1.2. Soil Hydrology of the Paddy Soils

Seasonal flooding and drainage cycles control the durations of saturation and reduction of paddy soils. Saturation and reduction are the common characteristics of paddy soils in Taiwan, and various redoximorphic features occur with anthraquic or oxyaquic conditions (Hseu and Chen, 1995, 1996, 1999, and 2001; Jien et al., 2004). The concept of aquic conditions was introduced in the *Keys to Soil Taxonomy* to assess seasonal wetness throughout the soil profile rather than just using indicators within the upper 50 cm of the pedon for moisture category (Soil Survey Staff, 2006). Alternating cycles of reduction and oxidation in soils over prolonged periods, and the consequent mobility and accumulation or depletion of Fe and Mn, result in the formation of redoximorphic features (Fanning and Fanning, 1989; Vepraskas, 1992). Past studies have tested the application of redoximorphic features as saturation indicators in various pedogenic environments of paddy soils (Hseu and Chen, 1995, 1996, 1999, and 2001; Jien et al., 2004).

1.3. The Objectives of the Present Review

In this article, we will review the general morphology, pedological characteristics and processes, classification, contamination, and remediation of rice production of paddy soils in Taiwan, particularly in the contribution of soil hydrology on the formation of redoximorphic features in Quaternary red earth and in the remediation strategies of heavy metal contamination.

2. Pedological Characteristics of Paddy Soils in Taiwan

2.1. Field morphology

Paddy soils of Taiwan were used in planting lowland rice on the western and eastern alluvial plains and on Quaternary terraces with different histories of paddification, parent materials and topography. Therefore, the above biotic and abiotic factors significantly affect the morphology and soil properties of the paddy soils. The soil series were diversely developed based on the source of parent material, the texture sequence in the profile, the degree of drainage and calcareousness. The main diagnostic epipedons of paddy soils in Taiwan are ochric, umbric and mollic epipedons. Additionally, the diagnostic subsurface horizons are predominantly cambic horizons (Bw or Bg) on the alluvial plains, argillic horizons (Bt, Btg or Btv) on the Quaternary terraces or aged alluvial plains. However, no clearly diagnostic B horizons of the paddy soils have been found in the young alluvial plains. Based on the processes of paddification and on the degrees of drainage, the main morphological characteristics of the epipedons or subsurface horizons in the paddy soils are divided into five sequence groups of profile: Ap-R, Ap-Bg-2Bg-2Cg, Ap-Bw (Bg)-C, Ap-Btv (Btg)-Bt-C, and Ap-Bo-C, respectively. The representative morphology of these groups is listed in Table 1. These morphological attributes are characterized by solum depth, color, texture and structure of plowed layer (Ap). The Ap horizons in the five groups were further characterized by (1) hues of 2.5Y or 5Y and chroma of 2 or less, (2) massive structures, and (3) depth of 15 cm or deeper. The following approach was produced by the pedogenic processes of paddy soils of Taiwan which were mainly affected by irrigation water, groundwater table and dissolved oxygen concentration in water. They are gleyzation of surface soil, formation of compact subsurface layer (plow pan), accumulation of organic matter on the surface soil, formation of redoximorphic features such as Fe/Mn nodules and clay/Fe depletions, chloritization of clay minerals in the surface soils by submergence, redistribution of base cations by irrigation water (Chen, 1984 and 1992).

Table 1. Soil morphological characteristics of five typical groups of paddy soils in Taiwan based on the most frequently occurring attributes (Chen, 1992)

Horizon	Depth (cm)	Color (moist)	Texture*	Structure**	Mottle
Ap-R (6 soil pedons)					
Ap	0-14	5Y 4/1	L	massive	2.5Y 3/1
R					
Ap-Bg-2Bg-2C (41 soil pedons)					
Ap	0-21	5Y 4/1	L	massive	2.5Y 4/6
Bg	21-53	2.5Y 4/1	SiL	massive	10Y 6/6
B	53-116	2.5Y 5/4	SiL	massive	5Y 4/3
C	>116				
Ap-Bg (Bw)-C					
Ap	0-20	2.5Y 5/2	SiL	massive, 2 sbk	10YR 5/3
Bg1	20-57	2.5Y 5/1	SiL	3 sbk	10YR 7/2
Bg2	57-74	2.5Y 5/3	SiL	2 sbk, massive	10YR 6/4
Bw	74-137	2.5 Y 6/2	SiL	massive	5Y 5/1
C	>137				
Ap-Btg-Bt-C					
Ap	0-28	10YR 5/2	SiCL	massive, 2 sbk	10YR 4/6
Btg/v	40-68	7.5YR 5/2	SiCL	3 sbk	7.5YR 6/6
Bt	68-130	10YR 4/8	SiC	2 sbk	10YR 6/6
C	>130				
Ap-Bo-C					
Ap	0-26	10YR 4/3	SiC	3 sbk	5YR 6/6
Bo	26-148	7.5YR 5/8	SiC	1 sbk	5YR 5/8
C	>148				

*: L=loam, SiC=Silt loam, SiCL=silty clay loam, SiC=silty clay.
**: 3=strong, 2=moderate, 1=weak; sbk=subangular blocky.

2.2. Case Studies in Redoximorphic features implication on Soil Hydrology

Hseu and Chen (2001) have selected three paddy soils from Quaternary terrace along a toposequence of the Chungli Terrace in northern Taiwan for monitoring of water table, matric potential, and redox potential (Eh) at various soil depths in 1996 and 1997. The three soils are Houhu (Typic Plinthaquult) in the toeslope, Hsinwu (Typic Plinthaquult) in the footslope, and Lungchung (Plinthaquic Paleudult) in the lower backslope. Redox concentrations originally occurred as soft masses and concrete nodules associated with seasonally high water levels, but irrigation and drainage processes also influenced the development of redoximorphic features. The studied Fe-Mn concretions and Fe depletions increased with increasing the cycling of oxidation and reduction in rice production (Fig. 1). The durations of saturation and reduction in the Btv horizons (argillic horizons with plinthites) of the Houhu soil in the toeslope position were more than 80% of the year and the soil had about 10% of Fe-Mn concretions. The Btv horizons of the Hsinwu soil in the footslope position were saturated for 50% of the year and reduced for 25% of the year, and the soil had about 20% of Fe-Mn concretions. The Btv horizons of the Lungchung soil in the lower backslope position were saturated for 40% of the year and reduced for only about 10% of the year, and the soil had 15% of Fe-Mn concretions. The Houhu and Hsinwu soils were belonging to the anthraquic condition and the Lungchung soil with less reduction was proposed as having oxyaquic conditions as defined in U.S. soil taxonomy. However, the optimum durations of saturation and reduction were about 50% of the year in the formation of redoximorphic features within the landscape unit, and thus indicating that semi-quantative soil hydrology can be estimated by the above redoximorphic features for the paddy soils.

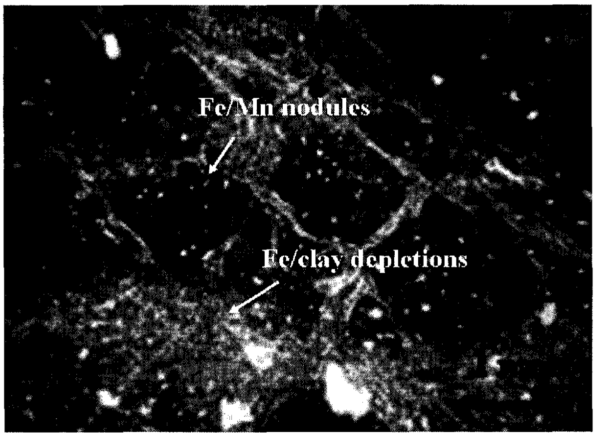

Fig. 1. Photomicrographs of redoximorphic features in the Btv horizons from a paddy soil pedon (Plinthaquults) on Chungli terrace in northwestern Taiwan by plane polarized light, such Fe/Mn nodules and Fe/clay depletions.

Jien et al. (2004) further attempted to establish the relationships between soil morphology-based soil chroma index and soil wetness conditions in the paddy fields, including annual duration of both saturation and reduction along hydrosequences around the Chungli Quaternary terraces in northern Taiwan (Fig. 2). They selected three transects of a toposequence ranging from 20 to 40 m above the sea level. Four soils (Plinthaqualfs and Plinthaquults) were located in the toeslope position (20 m), four soils (Plinthudults and Paleudalfs) in the footslope position (30 m), and three soils (Paleudults and Paleudalfs) in the backslope position (40 m) with different redoximorphic features under a landscape unit (Tables 2 and 3). All

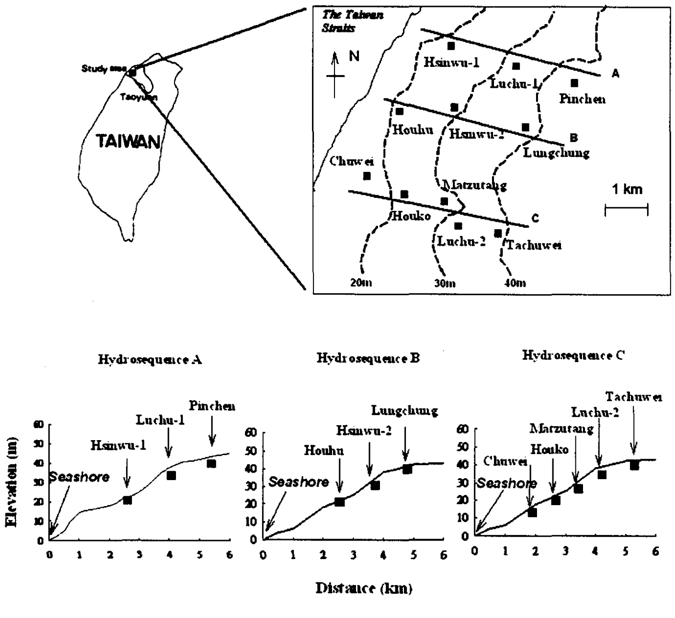

Fig. 2. Sites location and landscapes position of the eleven soils reported by Jien et al. (2004). Dotted line indicates the elevation above the sea level.

these soils are considered anthraquic, since they are seasonally flooded for lowland rice production and have perched water tables from February to October of the year. Seasonally high groundwater levels also occur during the growing season. Hydric soils are defined as soils formed under conditions of sufficient saturation or flooding during the growing season to develop an anaerobic condition in the upper part of the soil (USDA-NRCS, 2003). Ideally, hydric soil states should be confirmed with hydrological and redox potential monitoring data. Because these data are difficult to obtain in paddy soils, the investigation of the relationships between soil chroma and soil wetness were conducted in these soil layers <50 cm, 50-100 cm, and >100 cm.

The chroma index (CI) was used herein from Megonigal et al. (1996) for soil color notations converted into color indices with a single numerical value, respectively. As a result, regression analysis between the CI and soil wetness on Chungli Quaternary terraces in northern Taiwan, including the saturated time (%) and reduced time (%) of the year, demonstrated that the saturation duration of the horizon above 50 cm did not markedly correlate with

Table 2. Identification of hydric soils based on the accumulation days of redox potential, saturation condition of studied soils selected from Chungli Terrace (Jien et al., 2004)

Soil soils#	Classification†	Accumulation days‡				Munsell A horizon	Hydric color of
		1996		1997			
		Eh	SAT	Eh	SAT		
		------------- days -------------					
Toeslope							
Hsinwu-1	Typic Plinthaquults	229	183	244	197	10YR 5/3	Y
Chuwei	Typic Plinthaqualfs	229	183	244	197	7.5YR 4/6	Y
Houhu	Typic Plinthaquults	229	183	244	197	2.5Y 4/2	Y
Houko	Typic Plinthaqualfs	229	183	244	197	10YR 6/2	Y
Footslope							
Luchu-1	Oxyaquic Paleudults	116	79	60	125	2.5Y 7/3	Y
Hsinwu-2	Typic Plinthudults	116	79	60	125	2.5Y 4/3	Y
Matzutang	Plinthaquic Paleudalfs	116	79	60	125	10YR 4/1	Y
Luchu-2	Plinthaquic Paleudalfs	116	79	60	125	10YR 5/8	Y
Backslope							
Pinchen	Oxyaquic Paleudults	216	228	244	216	10YR 4/4	Y
Tachuwei	Plinthitic Paleudalfs	216	228	244	216	10YR 5/6	Y
Lungchung	Plinthaquic Paleudults	216	228	244	216	2.5Y 4/2	Y

† Based on Soil Taxonomy (Soil Survey Staff, 2006)

‡ Accumulation days of rice-growing season (Feb. 1 to Oct. 31) at 25 cm depth which the redox potential (Eh) is ≦ 200mV when soil pH was calibrated to 7, and accumulation days at 25 cm depth which the matrix potential is 0 bar or in saturation condition (SAT) (Hseu and Chen, 2001).

#: Y: meet the definition of hydric soil

Table 3. Morphological features and semi-quantitative of redoximorphic features of paddy soil on Chungli terrace (Jien et al., 2004)

Horizon	Depth	Matrix color	Redoximorphic features Mottles color	Texture	Saturated time	Reduced time
					-----------%-----------	
			Chuwei (Typic Plinthaqualfs)			
Ap	0-35	7.5 YR 4/6	Cp7.5YR 5/8 (10%)† Fp2.5YR 5/8 (<2%)	SiL	55	95
AB	35-65	10 YR 5/4	Cp7.5YR 6/8 (15%)	SiL	60	100
Bt1	65-90	5 G 5/1	Mp10 YR 7/8 (30%)	SiCL	65	100
Bt2	90-105	5 PB 6/1	Cp10 YR 7/8 (10%)	SiCL	70	100
Bt3	105-120	5PB 6/1	Cp2.5Y 7/6 (4%)	SiC	80	100
			Houhu (Typic Plinthaquults)			
Ap	0-34	2.5Y 4/2	Mp 5YR 4/4 (30%)	CL	55	90
AB	34-47	2.5Y 4/1	Cp 7.5YR 5/8 (10%)	SiCL	55	90
Bt1	47-66	10YR 4/3	CP 7.5YR 5/8 (10%)	SiCL	60	100
Btv1	66-82	10YR 5/3	CP7.5YR 5/8 (10%) Cd 10YR 6/1 (10%)	SiC	65	100
Btv2	82-102	10YR 6/1	Mp2.5YR 5/8 (25%)	SiC	70	100
Btv3	102-122	7.5YR 6/1	Mp2.5YR 5/8 (25%) Md10YR 7/1 (10%)	SiC	70	100
Btv4	>122	7.5YR 6/1	Mp5YR 5/8 (30%) Mp 7.5YR 5/6 (20%)	C	80	100
			Houko (Typic Plinthaqualfs)			
Ap	0-25	10YR 6/2	Cp 5YR 5/8 (10%)	SiCL	50	95
Bt1	25-45	2.5Y 4/4	Cp 5YR 5/8 (10%)	SiC	60	90
Bt2	45-70	2.5Y 6/2	Mp 5YR 5/8 (40%)	SiC	65	100
Bt3	70-110	10YR 6/1	Mp 2.5YR 5/8 (40%)	SiC	70	100
Bt4	110-140	5PB 6/1	Mp10YR 5/8 (20%) Mp 2.5YR 5/8 (20%)	SiC	80	100
			Hsinwu-1 (Typic Plinthaquults)			
Ap	0-15	10YR 5/3	Cp7.5YR 5/8 (5%)	SiL	55	95
AB	15-30	2.5Y 5/3	Cp7.5YR 5/8 (5%)	SiL	55	90
Bt1	30-40	10YR 5/6	Cp2.5YR 5/8 (5%)	SiC	55	90
Btv1	40-80	2.5YR 6/4	Cp2.5YR 4/8 (15%)	CL	65	100
Btv2	80-100	2.5YR 5/8	Cp2.5Y 6/8 (15%) Mp2.5YR 7/2 (30%)	C	60	100
Btv3	100-130	5YR 5/8	Cp10YR 4/6 (20%) MP2.5YR 7/2 (30%)	C	65	100
Btv4	130-160	2.5YR 5/8	Cp10YR 6/6 (20%) Mp2.5YR 7/1 (40%)	C	70	100
			Hsinwu-2 (Typic Plinthudults)			
Ap	0-15	2.5Y 4/3	--	SiL	40	10
AB	15-26	2.5Y 4/1	Cf 2.5YR 4/2 (10%)	SiL	40	10
Bt1	26-45	10YR 5/4	Cd 7.5YR 4/4 (10%)	SiC	45	30
Bt2	45-75	10YR 5/6	Cp 5YR 5/8 (15%)	SiC	45	30
Btv1	75-107	10YR 5/2	Mp 2.5YR 4/4 (25%) Cp 10YR 6/1 (5%)	CL	50	25
Btv2	107-133	2.5YR 4/8	Cp10YR 6/3 (5%) Cp10YR 6/2 (5%)	C	50	30
Btv3	>133	2.5YR 4/8	Cp 10YR 6/2 (10%)	C	55	10

§ F= fine, C= coarse, M= medium, p= prominent, d= distinct, f= faint

†: The value in parentheses is amount of redoximorphic features

(continued to next page)

Table 3. (Continued)

Horizon	Depth	Matrix color	Redoximorphic features Mottles color	Texture	Saturated time	Reduced time
					-----------%-----------	
Matzutang (Plinthaquic Paleudalfs)						
Ap	0-10	10YR 4/1	Fp 7.5YR 4/4 (<2%)	SiCL	40	10
AB	10-40	7.5YR 3/2	Fp 10YR 3/6 (<2%)	SiCL	40	30
Bt1	40-60	7.5YR 5/6	Cp5YR 4/6 (5%) Cp 2.5Y 5/1 (5%) CpP2.5Y 5/3 (10%)	SiC	45	30
Bt2	60-100	7.5YR 4/6	Cp 2.5Y 6/1 (20%) Cp2.5Y 6/4 (10%)	SiC	50	25
Bt3	100-135	5YR 4/6	Cp 2.5Y 6/1 (20%)	SiC	50	30
Luchu-1 (Oxyaquic Paleudults)						
Ap	0-30	2.5Y 7/3	Cp10R 4/6 (15%)	SiL	40	30
AB	30-55	2.5Y 5/4	Cp2.5YR 5/8 (15%)	SiL	45	30
Bt1	55-90	2.5YR 4/6	Mp10YR 5/3 (20%)	SiCL	45	25
Bt2	90-140	10R 4/6	Mp10YR 5/3 (20%)	SiCL	50	30
Bt3	140-180	10R4/6	Mp10YR 5/8 (35%) Cp2.5Y 7/6 (5%)	SiC	55	30
Bt4	>180	2.5YR 4/8	Mp10YR 6/8 (30%) MP10R 3/6 (20%) Cp10YR 7/2 (20%)	SiC	65	30
Luchu-2 (Plinthaquic Paleudalfs)						
Ap	0-20	10YR 5/8	Cp2.5YR 4/6 (5%)	SiCL	40	10
AB	20-40	10YR 5/3	Mp2.5YR 5/8 (30%)	SiCL	40	30
Bt1	40-65	10YR 3/2	Cp10YR 6/8 (5%) Mp 5YR 6/8 (25%)	SiCL	35	30
Bt2	65-85	10YR 7/6	Mp2.5YR 4/6 (20%) Cp10YR 6/1 (20%)	SiC	50	25
Bt3	85-105	2.5YR 5/8	Cp10YR 7/1 (30%)	SiC	50	25
Bt4	>105	10R 4/6	Mp10YR 7/2 (40%)	SiC	55	30
Tachuwei (Plinthitic Paleudalfs)						
Ap	0-35	10YR 5/6	Fp10R 4/6 (2%)	L	75	70
AB	35-60	2.5Y 6/6	Mp 10R 4/8 (40%)	L	60	70
Bt1	60-80	2.5YR 4/8	Mp7.5YR 6/8 (25%)	SiL	55	10
Bt2	80-120	10YR 7/8	Mp2.5YR 4/8 (30%)	SiL	40	15
Bt3	120-150	2.5YR 3/6	Mp7.5YR 5/8 (20%) Mp 5YR 7/2 (30%)	SiL	35	5
Lungchung (Plinthaquic Paleudults)						
Ap	0-20	2.5Y 4/2	--	SiCL	75	70
Bw	20-41	10YR 5/2	Cd5YR 5/8 (5%)	SiC	75	70
2A	41-56	10YR 4/2	Cp2.5YR 3/4 (5%)	SiCL	60	70
2Bt	56-85	10YR 4/4	Cd7YR 5/6 (10%)	SiC	55	10
2Btv1	85-100	10YR 5/3	Cd2.5YR 5/8 (30%)	SiC	40	15
2Btv2	100-140	10YR 6/2	Mp2.5YR 5/6 (20%)	SiC	35	5
Pinchen (Oxyaquic Paleudults)						
Ap	0-20	10YR 4/4	Fp5YR 5/8 (15%)	SiCL	75	70
AB	20-40	10YR 4/4	Fp5YR 5/8 (15%)	SiCL	75	70
Bt1	40-60	7.5YR 5/8	Mp5Y 5/3 (15%)	SiC	60	70
Bt2	60-100	10R 3/6	M&Fp5Y 5/3 (<2%) Mp10YR 5/6 (40%)	SiC	55	15
Bt3	100-130	10R 3/6	M&Cp10YR 7/4 (30%)	C	40	5
Bt4	130-160	2.5YR 4/8	M&Cp10YR 7/4 (30%)	C	35	5
Bt5	160-200	2.5YR 4/8	M&Cp10YR 7/4 (30%) Mp 2.5Y 8/2 (20%)	C	35	5

§ F= fine, C= coarse, M= medium, p= prominent, d= distinct, f= faint

†: The value in parentheses is amount of redoximorphic features

the CI values, and soil reduced duration displayed the same pattern (Fig. 3). These results may indicate the disturbance of the surface 50cm soil by rice cultivation during the growing season. The Fe depletions in the Ap horizon were very difficult to see, possibly owing to masking by organic matter, which controls the matrix color. The soil CI values above a depth of 50 cm thus did not predict the soil wetness condition. However, negative significant correlations were found between the CI values and soil saturation duration ($r = -0.43$, $p < 0.01$), and the reduced duration ($r = -0.52$, $p < 0.01$) for the soils at a depth of 50 to 100 cm (Fig. 4). The redoximorphic features at this depth probably were affected more by groundwater table than perched water. The reduction and saturated times at this depth were >25% and >35% of the year, respectively, and the contents of the Fe depletions ranged from 5% to 40%. Some pedons dropped out of the standard deviation at the 95% confidence level, such as Bt1 of Luchu-2, Btv1 of Hsinwu-2, Bt1 and Bt2 of Tachuwei, and Bt1 of Pinchen soils. This study assumed that the main reasons for the saturation condition were abrupt soil texture change, such as Btv1 of the Hsinwu-2 soil, or upper soils being disturbed by plowing and leading to pores being discontinued, resulting in a perched water table, such as Bt1 of the Luchu-2 soil. The perched water was always present, and then leads to the formation of more reduced Fe depletions more quickly than for other horizons with a clayey texture. For the paddy soils below 100 cm depth, the redoximorphic features were affected by groundwater fluctuation. The soil chroma index was significantly correlated with annual soil saturation time ($r = -0.47$, $p < 0.01$) or annual soil reduction time ($r = -0.59$, $p < 0.01$) (Fig. 5). The Bt2 horizon (80-120 cm) of the Tachuwei soil and the 2Btv2 horizon (>140 cm) of Lungchung soil had >30% Fe concentrations and 10-30% reduction time each year. This investigation assumed the Fe concentrations to be a relict during the initial deposition of Quaternary-aged

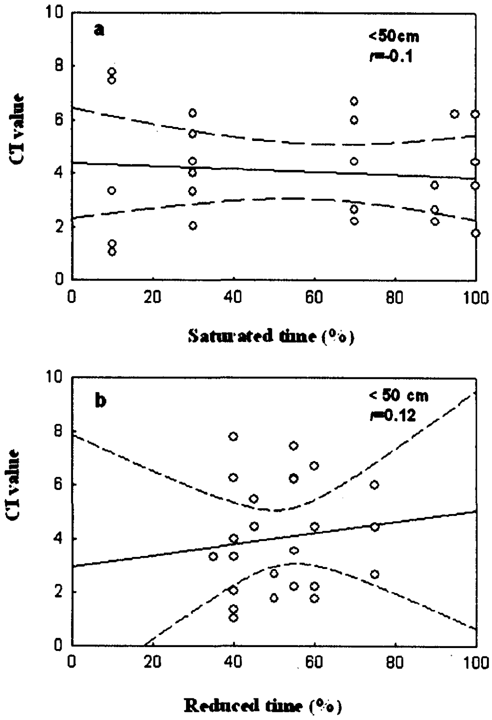

Fig. 3. Relationships between chroma index and (a) soil saturated time (% of a year) (<250 mV, pH 5.5) and (b) reduced time (% of a year) above 50 cm of soil pedon reported by Jien et al. (2004). Solid line is regression line and dash line is the range of 99% confidence level.

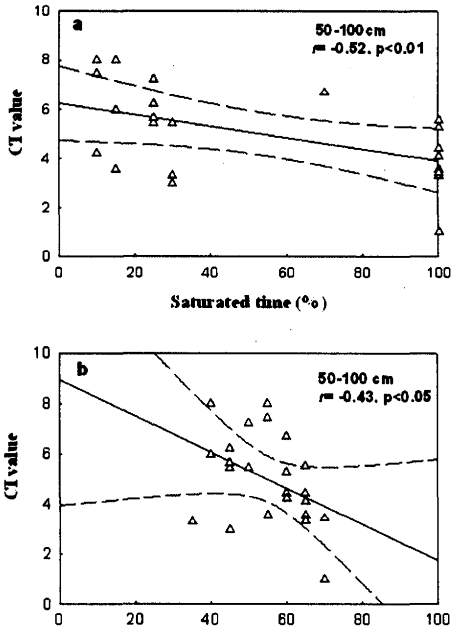

Fig. 4. Relationships between chroma index and (a) soil saturated time (% of a year) (<250 mV, pH 5.5) and (b) reduced time (% of a year) between 50-100 cm of soil pedon reported by Jien et al. (2004). Solid line is regression line and dash line is the range of 99% confidence level.

alluvial red earth, and furthermore assumed it would produce an error in the calculated CI value. On the other hand, soils below the 100 cm depth of Btv3 and Btv4 of Hsinwu-2 soil and the Bt4 of the Luchu-1 soil were saturated with water for 50-65% of the year, with the reduction time comprising just 10-30% of the year.

3. Classification of Paddy soils in Taiwan

Paddy soils in Taiwan are mainly classified into Entisols, Inceptisols, Alfisols and Ultisols, and with minor into Mollisols and Oxisols based on Soil Taxonomy (Soil Survey Staff, 2006). Chen (1984) and Sheh and Wang (1989) have proposed and established the classification system of the cultivated soils in Taiwan, including paddy soils. From the above description in the diagnostic subsurface horizons, typical horizons in the paddy soils of Taiwan included (1) Ap horizon (with ochric, mollic or umbric epipedon), (2) plow-sole (or plow pan Bt or Bg) horizon with relatively high bulk density, (3) argillic horizon (Bt, Btg or Btv) or cambic horizon (Bw or Bg) with various redoximorphic features and with significant translocation of Fe, Al and Mn below the plow-sole horizon, and (4) gleyed horizon with seasonal high water table. The main soil taxa are listed in Table 4 and explained as followings.

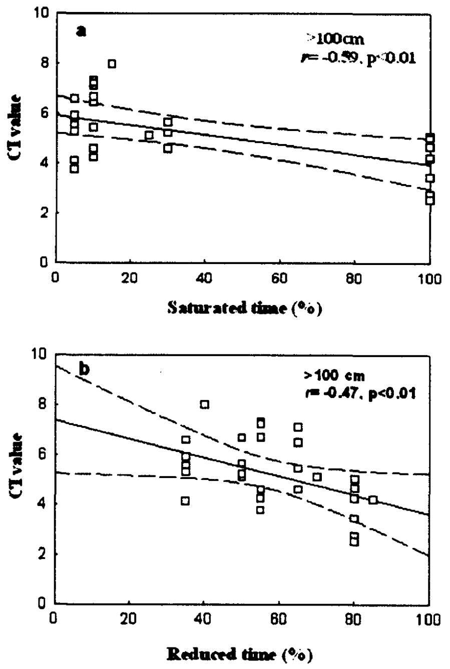

Fig. 5. Relationships between chroma index and (a) soil saturated time (% of a year) (<250 mV, pH 5.5) and (b) reduced time (% of a year) below 100 cm of soil pedon reported by Jien et al. (2004). Solid line is regression line and dash line is the range of 99% confidence level.

3.1. Entisols

Aquents, Fluvents and Psamments are major Soil Suborders in Entisols which were mostly on the young alluvial fans near the coast areas in the western and eastern plains. Additionally, they have no clearly pedogenic features, except for the Ap horizon. The above Soil Suborders are different in moistures, amount and vertical distribution of organic carbon and textures. The total area with Entisols of the paddy soils is roughly 700 km^2 (about 5% of total survey area). Generally, Aquents is much more waterlogged through the profile than Fluvents and Psamments, and thus they are different in soil hydrological conditions such as saturation and reduced durations of the year.

3.2. Inceptisols

Inceptisols are generally on the soils derived from recent alluvium of sandstone, shale and slate in western Taiwan. The Soil Suborders are Aquepts, Ochrepts and Umbrepts with Bwg or Bw horizons. Furthermore, Haplaquepts, Dystrochrepts, Eutrochrepts and Haplumbrepts are the main Great Groups in the alluvial soils of Taiwan. However, the total area of Inceptisols is about 4,400 km^2.

3.3. Alfisols

Alfisols are mainly on the older alluvium from sandstone, shale, and slate in the western part of Taiwan. Argillic horizons (Bt or Btg) are in the lower parts of the pedons. Aqualfs, Udalfs and Ustalfs are the most important Soil Suborders and have different moisture regimes. Ustalfs are locally on the southern part of Taiwan with higher evaporation. Ochraqualfs, Hapludalfs and Haplustalfs are the main Great Groups in such alluvial soils which carbonates are sometimes found herein.

3.4. Ultisols

Ultisols are mainly found in the paddy soils of red earth and aged alluvium from the red earth on Quaternary terraces of northwestern part of Taiwan. These

Table 4. Approximate area of major soil classes in paddy soils of Taiwan (Chen, 1992)

Soil Order	Suborder	Great Group	Area (km^2)	Percentage of total surveyed area
Entisols	Aquents	Haplaquents	20	
		Fluvaquents	150	
	Fluvents	Udifluvents	530	
			(700)	5%
Inceptisols	Aquepts	Haplaquepts	1500	
	Ochrepts	Dystrochrepts	1500	
		Eutrochrepts	1100	
	Umbrepts	Haplumbrepts	300	
			(4400)	30%
Alfisols	Aqualfs	Ochraqualfs	1000	
	Udalfs	Hapludalfs	1600	
	Ustalfs	Haplustalfs	1000	
			(3066)	25%
Ultisols	Aquults	Paleaquults	100	
		Plinthaquults	100	
	Udults	Hapludults	500	
	Humults	Haplhumults	30	
			(730)	5%
Mollisols	Udolls	Hapludolls	110	
	Ustolls	Haplustolls	15	
			(125)	1%
Oxisols	Peroxes	Kandiperoxes	50	
	Udoxes	Hapludoxes	50	
			(100)	<1%
Other soils and upland soils			(5000)	35%
Total surveyed area in Taiwan		14,600	100%	

soils have been used for lowland rice production for over 50 years, and the significant morphological characteristics of the surface epipedon were the color change owing to flooding by irrigation water. The diagnostic subsurface horizon is argillic horizon with plinthites that are iron-rich, humus poor mixtures of clay with quartz and other minerals (Soil Survey Staff, 2006). It commonly occurs as dark red redox concentrations that usually form platy, polygonal or reticulate patterns (Fig. 6). It changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying, especially if it is also exposed to heat from the sun. Therefore, the Great Groups of Aquults are Paleudults and Plinthaquults, respectively. On the other hand, Udults are the dominant Soil Suborders in the paddy

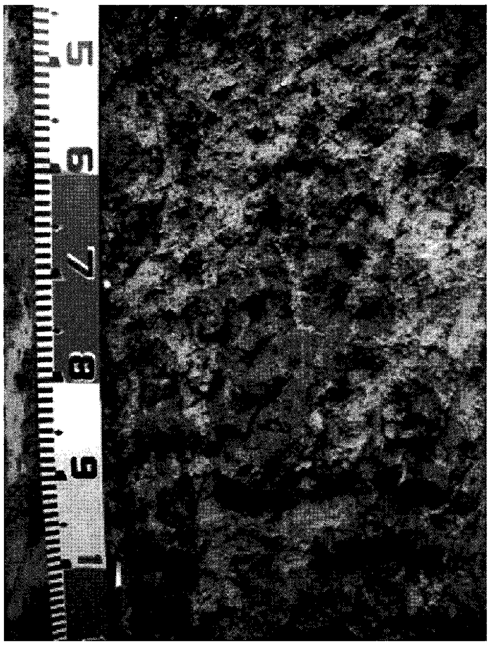

Fig. 6. Plinthites through the Btv horizons from a paddy soil profile (Plinthaquults) on Chungli terrace in northwestern Taiwan. The dark colored zones indicate Fe-rich masses and the light gray zones are redox depletions. The scale unit is 1 cm.

soils of red earth. Hapludults and Paleudults are the main Great Groups. A small area with about 30 km^2 of Haplhumults was only found in local depression farms.

3.5. Mollisols

Mollisols for lowland rice production can be only found in the eastern part of Taiwan, particularly on igneous rock and mudstone alluvial soils or andesite derived soils. The diagnostic horizon is mollic epipedon, but there is no diagnostic subsurface horizon in the Mollisols. The soil depth is generally shallow (<60 cm). However, high organic matter and low color value and chroma in the surface soil are the dominant characteristics in these paddy soils. Udolls are the main soil Suborder, and Hapludolls are the main Great Group.

3.6. Oxisols

Oxisols are mainly on the aged terrace land and have an oxic horizon. They have undergone paddification for about 50 years. Kandiperoxes and Hapludoxes are the main Great Groups in Taiwan.

4. Contamination of Heavy Metals in Paddy Soils of Taiwan

4.1. Soil Pollution Status

Heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) contamination have been found in the paddy soils due to illegal waste water discharged from industrial plants (i.e., chemical, electroplate, pigment) and livestock (i.e., swine). As a result, four stages of soil survey project of the contamination soils in Taiwan were conducted by the Environmental Protection Administration of Taiwan (Taiwan EPA) since 1982. The objectives of the survey are to understand the heavy metal levels in the rural soils of Taiwan. The major results of these stages are illustrated as follows (Taiwan EPA, 2003).

- Stage 1 (1983-1987): The total survey areas were about 1,160,000 ha and each representative survey unit is 1,600 ha. The final report was published by Taiwan EPA in 1987 (Taiwan EPA, 1987).
- Stage 2 (1987-1991): Stage 2 was conducted for 300,000 ha of rural soils selected from stage 1 which have relatively high concentrations of metals and each representative survey unit was 100 or 25 ha. The results showed that about 790 ha of rural soils have higher concentrations of the metals than the regulations of heavy metals announced by Taiwan EPA in 1991 (As 60, Cr 16, Cd 10, Cu 100, Pb 120, Hg 20, Ni 100, Zn 80 mg kg^{-1}) (Taiwan EPA, 1991). However, the soils were extracted by 0.1 M HCl for the measurement of metals, except As and Hg which were extracted by aqua regia.
- Stage 3 (1992-2000): The survey lands were selected according to the results of stage 2 which have relatively high concentration of metals in soil. The total survey area is about 50,000 ha in this stage and each representative survey unit was 1 ha.
- Stage 4 (2000 to now): This stage was conducted following the Soil and Groundwater Pollution Remediation Act (SGWPR Act) announced in 2000. The contaminated control or remedial sites were announced based on the criteria of pollutant levels listed in the SGWPR Act (Taiwan EPA, 2003).

According to the survey of rural soils with potential contamination conducted by Taiwan EPA in 2002, more than 300 ha of rural soils were contaminated by heavy metals. The regulations of heavy metals (mg/kg) in the SGWPR Act are as follows: Cd 5.0, Cr

250, Cu 200, Ni 200, Pb 500, and Zn 600, based on aqua regia and total digestion methods. The contaminated area by different metals which was higher than the regulation of pollutants in SGWPR Act of paddy soils were about 159 ha for Ni, 148 ha for Cu, 127 ha for Cr, 113 ha for Zn, 17 ha for Cd, 4 ha for Pb, and 0.3 ha for Hg, respectively. Most of them (184 ha) were located in Changhua prefecture, central Taiwan which were mainly contaminated by Cu, Zn, Ni, and Cr (Taiwan EPA, 2003). The other serious contaminated prefectures are Hsinchu (27.54 ha), Taoyuan (11.46 ha), Pingtung (6.9 ha), Taipei (1.62 ha), Miaoli (0.55 ha), Nantou (0.39 ha), and Taichung (0.3 ha), respectively. According to the AGWPR Act, the crops grown in the contaminated soils should be collected and destroyed by the governmental agency to avoid the human health risk through food chain. Although the heavy metal contents of the contaminated paddy soils were higher than those in the regulation, the effects of these total concentrations of the metals on the crop quality and human health were needed further examinations.

4.2. The suitability of total metal concentration of pollutants as regulation

4.2.1. Arsenic

The regulation of As total contents in soils were ranged from 20 mg/kg to 75 mg/kg in the world. The upper limit of background As contents of representative rural soil was 18 mg/kg in Taiwan (Table 5). If the total As in the soil was lower than 20 mg/kg, the As content of the brown rice (fresh weight) was 0.15 mg/kg (in average) and the As content of other crops was 0.01 mg/kg (in average). However, if the total As contents of the rural soils reached up 60 mg/kg, the rice production clearly decreased. Therefore, the regulation of As in soils of Taiwan is proposed to keep in the present level (60 mg As/kg).

4.2.2. Cadmium

The regulation levels of soil Cd total contents were ranged from 1 mg/kg to 5 mg/kg in the world. The relative studies in Taiwan and Japan have suggested that the Cd content in brown rice and in soil was not significantly correlated. The upper limit of back-

Table 5. The upper limit of background content, the EPA regulation, and the proposed regulation of soil heavy metals in Taiwan.

	As[*]	Cd	Cr	Hg	Cu	Ni	Pb	Zn
			Background content of soil heavy metal in Taiwan[§]					
Mean	7.8	0.23	1.51	0.26	17	7.7	11.6	23.4
Middle value	7.3	0.16	0.53	0.13	7.6	2.3	9.2	12.7
Proposed regulation	25	1	30	1	100	40	120	100
Upper limit of background content (total content)	18	3	100	35	0.5	60	120	120
			Taiwan EPA regulation (2000)					
Total content (rural soil)	60	5	250	5	200	200	500	600
Total content (general land)	60	20	250	20	400	200	2000	2000
			Proposed regulation					
Total content (rural soil)	60	4	250	5	600	200	1000	800
Total content (general land)	60	20	250	20	1000	200	2000	2000

*: As and Hg: total content; Cd, Cr, Cu, Ni, Pb, Zn : 0.1M HCl extraction (n = 9000).

ground Cd contents of representative rural soil was 3 mg/kg in Taiwan (Table 5). The most brown rice and the polished rice were regarded as Cd-contaminated rice when the total soil Cd content is > 5 mg/kg (Chen, 1991). Liu et al. (1998) suggested that the brown and polished rice were Cd-contaminated rice when the soil Cd concentration was higher than 2 mg/kg extracted by 0.1 M HCl in the potentially contaminated areas of Taiwan (Fig. 7). The estimated total content of Cd in the rural soils was about 5 mg/kg based on the above 0.1M HCl extractable Cd levels. The regulation of Cd in brown rice is 0.5 mg/kg in Taiwan. The database in Taiwan and Japan indicated that the Cd-contaminated rice could be found in areas with different soil properties and soil management, even though the total content of Cd in soil was less than 5 mg/kg. We recommend that the regulation of total contents of Cd in Taiwan rural soils should be reduced to 4 mg Cd/kg from 5 mg/kg.

4.2.3. Chromium

The regulation levels of soil Cr total contents were ranged from 100 mg/kg to 1,500 mg/kg in the world. The upper limit of background Cr contents of representative rural soil was 100 mg/kg in Taiwan (Table 5). The mean content of Cr is 0.14 mg/kg in brown rice, <0.01 mg Cr/kg in the shoot and root vegetables. The rice production will be reduced when the total Cr content of rural soil reached to 250 mg/kg, but the rice should be edible because the Cr level of polished rice was <4 mg/kg (Liu et al., 1998) (Fig. 8). The regulation of Cr in soil of Taiwan is proposed to keep in the present level (250 mg/kg).

4.2.4. Copper

The regulation levels of soil Cu total contents were ranged from 100 mg/kg to 1,500 mg/kg in the world. The upper limit of background Cu contents of representative rural soil was 35 mg/kg in Taiwan (Table 5). The soil total concentration of Cu ranged from 20 to 320 mg/kg. The Cu content of polished rice ranged from 4 to 8 mg/kg, and it is not increased with increasing soil Cu content (Liu et al., 1998) (Fig. 9). When the soil total Cu level reached to 320 mg/kg, the rice production will be significantly reduced by 30%. The rice production will reduce 50% when the total Cu content of rural soil reached 600 mg/kg, but the brown rice would be edible because the Cu content of polished rice was <17 mg/kg (Liu et al., 1998). We proposed the regulation of total contents of Cu in Taiwan rural soils should be revised as 600 mg/kg.

4.2.5. Mercury

The regulation levels of soil Hg total contents were ranged from 1 mg/kg to 10 mg/kg in the world. The upper limit of background Hg contents of representative rural soil was 0.5 mg/kg in Taiwan (Table 5). The mean concentration of Hg in brown rice of Taiwan was 0.0014 mg/kg, and that of leaf vegetables was 0.04 mg/kg (Liu et al., 1998). Because all the total Hg

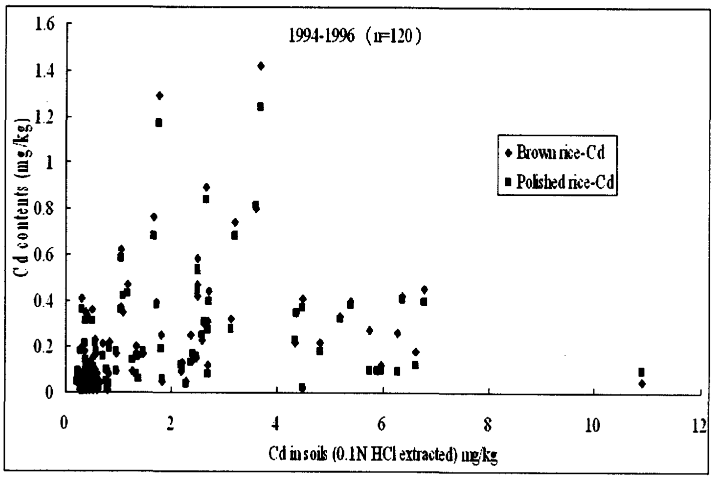

Fig. 7. The relations of Cd content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

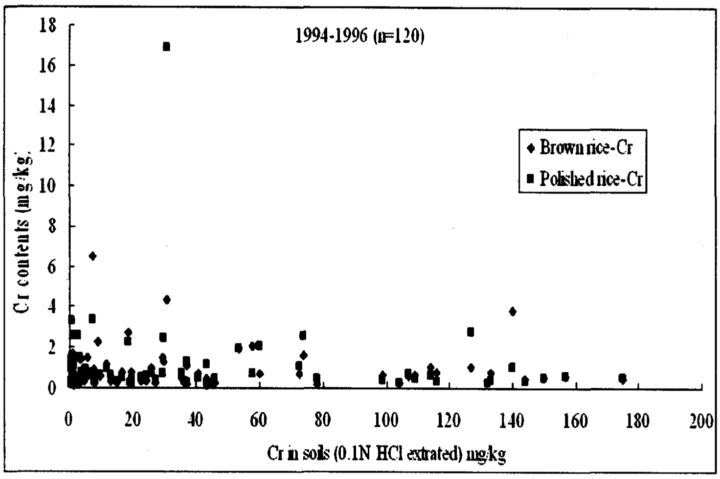

Fig. 8. The relations of Cr content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

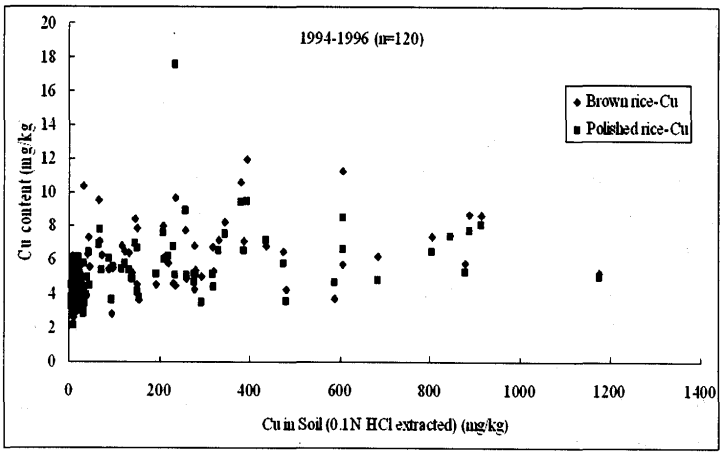

Fig. 9. The relations of Cu content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

contents of the rural soils were lower than 5 mg/kg, the regulation of Hg in soil of Taiwan is proposed not to be changed (5 mg Hg/kg).

4.2.6. Nickel

The regulation levels of soil Ni total contents were ranged from 20 mg/kg to 400 mg/kg in the world. The upper limit of background Ni contents of representative rural soil was 60 mg/kg in Taiwan (Table 5). The Ni content of the brown rice ranged from 4 to 30 mg/kg when the total Ni of rural soil ranged from 40 to 320 mg/kg in Taiwan. When the total Ni content of rural soils reached 600 mg/kg, the Ni content of polished rice was still <14 mg/kg (Liu et al., 1998) (Fig. 10). Because only a few data suggested that the total content of Ni was higher than 200 mg/kg in the rural soils, the regulation of Ni in soil of Taiwan is proposed not to be changed (200 mg Ni/kg).

4.2.7. Lead

The regulation levels of soil Pb total contents were ranged from 100 mg/kg to 1,000 mg/kg in the world. The upper limit of background Pb contents of representative rural soil was 120 mg/kg in Taiwan (Table 5). The Pb content of the brown rice and polished rice was almost <1 mg/kg when the total soil Pb ranged from 50 to 1350 mg/kg in Taiwan (Liu et al., 1998) (Fig. 11). We estimated that the rice production will be reduced by 20% if the total content of Pb reached 2,000 mg/kg. We recommend that the regulation of

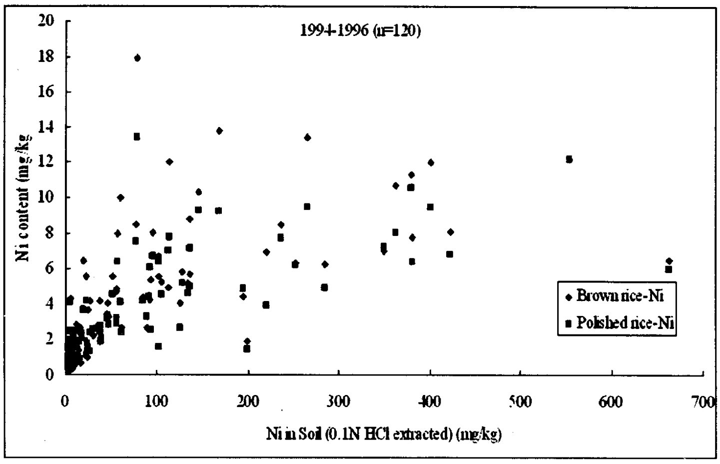

Fig. 10. The relations of Ni content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

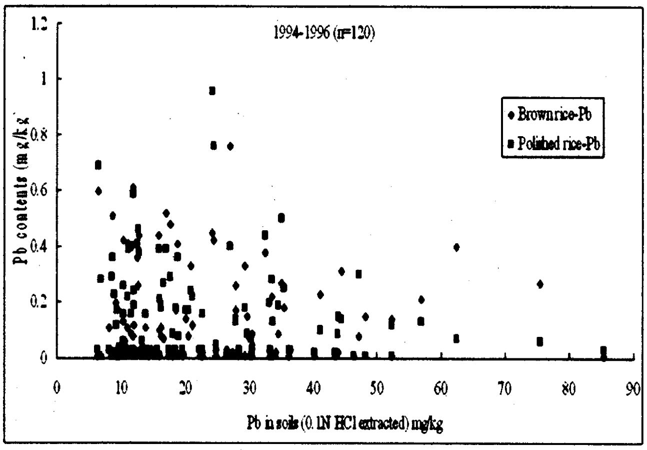

Fig. 11. The relations of Pb content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

total contents of Pb in Taiwan rural soils should be revised as 1,000 mg/kg.

4.2.8. Zinc

The regulation levels of soil Zn total contents were ranged from 200 mg/kg to 3,000 mg/kg in the world. The upper limit of background Zn contents of representative rural soil was 120 mg/kg in Taiwan (Table 5). The Zn content of the polished rice ranged from 20 to 80 mg/kg when the soil total Zn ranged from 60 to 960 mg/kg. If the total soil Zn content reached to 500 mg/kg, the rice production will be significantly reduced by 30% and the Zn level of polished rice ranged from 50 to 80 mg/kg (or the Zn level of brown rice ranged from 30 to 90 mg/kg). The rice production will be reduced by 50% when the total Zn content of soil reached to 800 mg/kg, but the rice should be edible because the polished rice Zn content was <30 mg/kg (Liu et al., 1998) (Fig. 12). The regulation of Zn in soil of Taiwan is proposed not to be changed (2,000 mg Zn/kg).

5. Remediation Techniques Used in Taiwan

5.1. Soil Turnover and Dilution Method

If the heavy metal concentration is lower in the subsurface soil than that in the surface soil, deep plow and consequently mixing the two layers can significantly decrease the metal levels to meet the regulation of pollutants in the SGWPR Act of Taiwan. The depth of subsoil should be enough to di-

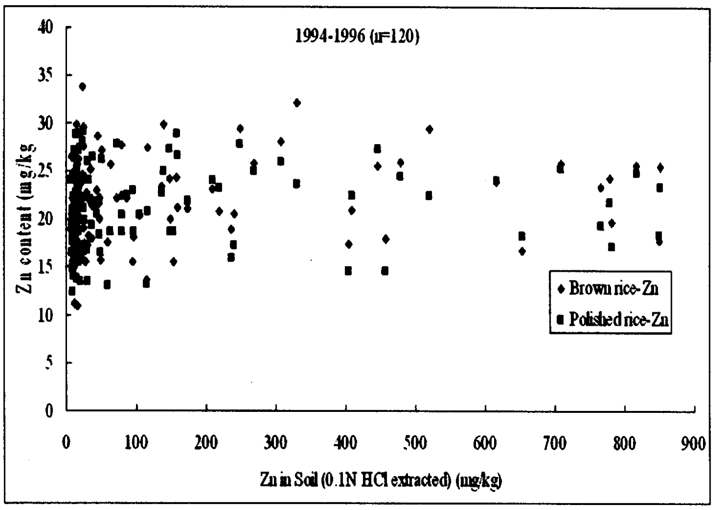

Fig. 12. The relations of Zn content in brown rice and in soil (0.1 N HCl extractable) for database of six cropping system of rice from 1994 to 1996 in central Taiwan Plotted from database of Liu et al (1998).

lute the total metal concentration of the surface soil (0-20 cm). This turnover and dilution method is thus suitable for contaminated paddy soil, especially for relatively low metal concentrations in Taiwan (Huang et al., 1995; Taoyuan Prefecture Government, 1999). The turnover and dilution method significantly improved in the decrease of the soil Cd concentration in Chungfu soil in northern Taiwan, which have 1-5 mg Cd kg^{-1} (extracted by 0.1M HCl) and are suitable for the contaminated soils more than 2 m soil depth. This method can decrease the concentration of metals in the surface soil (0-20cm) of the contaminated soil. However, the total amount of metals is still not reduced through the soil pedon.

For most of the metals-contaminated paddy soils in Taiwan since 2000, soil turnover and dilution method was the most popular remediation method because it has the advantages of low time economic costs compared with other soil remediation techniques such as acid washing and chelating agent extraction techniques. However, the subsoil has lower organic carbon content and the concentrations of metals are also lower compared with the surface soil. The soil turnover and dilution method produce the lower levels in organic carbon and nutrient after the above dilution. Fertilization by composts and chemical fertilizers should be added to the remediated soils to increase the soil fertility and to promote crop growth. For paddy soils in Taiwan, plowing layer was also disturbed by the diluting practices and their rebuilding is also requested if household farmers need to continue cultivation for lowland rice.

Chen and Lee (1997) used soil turnover and dilution method to decrease the Cd and Pb concentrations in the contaminated soils. The soils in the surface layer (0-20 cm) were mixed with the subsoil (20-40 cm) and then were planted by lettuce, water celery, and Chinese cabbage, respectively. These plants were harvested after planting in the treated soils for 4 weeks. Even the mixture of surface and subsurface soils decreased the soil Cd and Pb concentrations, but the mixed soils were still higher than 2.10 mg Cd/kg and 9.07 mg Pb/kg (0.1 M HCl) because the original metal concentrations were not significantly different in the upper 0-60 cm (data not shown). Soil turnover and dilution method can decrease the Cd and Pb concentrations of the crops (Table 6), but their concentrations were still too high and the treated soils were not suitable for rice planting (Chen, 1991).

5.2. Chemical Stabilization Techniques

This method is the application of chemical amendments to decrease the mobility and solubility of metals in the contaminated paddy soil and thus to decrease the metal uptake of plants. The reliable reclamation materials were successfully used in many contaminated cases of the world including lime materials, organic materials, compost, hydrous Fe oxides, hydrous Mn oxides, zeolites, etc. (Chen et al., 1992; Chen, 1994; Lin, 1998; Kuo and McNeal, 1984; Kuo et al., 1985; Chen, 1999a & b; 2000a & b; Yang et al., 2001; Basta et al., 2001; Hettiarachchi et al., 2001; Cheng and Hseu, 2002).

5.2.1. Case study 1

The studied soils for pot experiment were sampled from Chungfu village (Chungfu soil: CF-soil 1, CF-soil 2, CF-soil 3, and CF-soil 4) and Tatan village (Tatan soil: TT-soil 1, TT-soil 2, TT-soil 3, and TT-soil 4) Cd and Pb-contaminated sites, respectively. Table 7 shows the basic characteristics of the two studied soils (Chen et al., 2000 a and b). Those treatments used in this study include (1) control (CK), (2) Fe oxide (FO) (20 tons ha^{-1}) -Fe_2O_3, (3) Mn oxide (MO) (20 tons ha^{-1}) -(NaK) Mn_8O_{16}. X H_2O, (4) $CaCO_3$ (CA) (20 tons ha^{-1}), (5) Calcium phosphate (PP) (0.1 tons ha^{-1}) -10CaO. $3P_2O_5.H_2O$, (6) Compost (CO) (40 tons ha^{-1}), and (7) Zeolites (ZL) (20 tons ha^{-1}) (Na_3K_3) ($Al_6Si_{30}O_{72}$. 24 H_2O). The chemical treated soils (500 g, DW) were added in each pot and control the water content by weighing. Soil extractable Cd and Pb concentrations were analyzed at 1st and 2nd month after different chemical treatments by using 0.1M Ca $(NO_3)_2$, 0.05M EDTA (pH 7.0), 0.43M HOAc, and 0.1M HCl, respectively. Seeds of wheat (*Triticum vulgare*) were sowed in the different chemical amendments treated soils, harvested at 1st month after planting, and analyzed the Cd and Pb concentration by using $H_2SO_4/HClO_4$ method.

Except for PP treatment, other chemical amendments were significant to decrease the Ca $(NO_3)_2$ extractable Cd concentration of CF-soil 1 ($p < 0.1$). Application of treatments of CA, CO, and ZL were significant to decrease the EDTA extractable Cd concentration of TT-soil 1 and TT-soil 2 ($p < 0.1$) (data not shown). Different chemical amendments were significant to decrease the HOAc extractable Cd concentration of TT-soil 1 and TT-soil 2 ($p < 0.1$). For Chungfu clayey soils, the extractable Cd concentrations were only significantly decreased in some chemical amendments. The HCl extractable also significantly decreased in different chemical amendments except for TT-soil 2 ($p < 0.1$). Except for PP and CO treatments, different chemical amendments was significant to decease the Ca $(NO_3)_2$ extractable Pb concentration of CF-soil 1 and CF-soil 2 ($p < 0.1$). Different chemical amendments significantly decrease the EDTA extractable Pb concentration of TT-soil 1 and TT-soil 2 except for PP ($p < 0.1$). The treatments of MO, PP, CO, and ZL can significantly decrease the

Table 6. The accumulated Cd and Pb concentration of different crops after planting in the turnover and dilution method treated soil for 4 weeks

	Water celery		lettuce		Chinese cabbage	
Treatment	Cd	Pb	Cd	Pb	Cd	Pb
	-------------------------------- mg kg^{-1} --------------------------------					
Control	23.2	4.11	70.4	4.79	49	2.76
After dilution	18.4	2.77	39.6	3.44	34	6.94

Chen and Lee (1997)

Table 7. The basic soil characteristics of contaminated Chungfu and Tatan soils in Taiwan (Chen et al., 2000a and b).

Soils	pH			Extractable concentration¶	
	(H_2O)	O.C.#	CEC†	Cd	Pb
		g kg^{-1}	cmol$_{(+)}$ kg^{-1}	------mg kg^{-1}-----	
TT-soil 1 & 2	5.4-5.5	12.1-12.9	4.5	5.02-17.6	25.1-377
TT-soil 3 & 4	5.9-6.0	12.1-12.9	4.5	9.96-32.0	121-158
CF-soil 1 & 2	5.0-5.5	15.2-23.5	9.90-12.4	1.36-5.04	8.80-13.2
CF-soil 3 & 4	5.1-5.4	15.2-23.5	9.90-12.4	1.40-2.17	9.93-13.8

#: O. C.: organic carbon content
†: CEC: cation exchange capacity
¶: 0.1M HCl extractable concentration

HOAc extractable Pb concentration only in TT-soil 2 (p <0.1).

The treatments of MO, CA, CO, and ZL significantly decrease the total uptake of Cd by wheat grown in the TT-soil 1 and CF-soil 1 (p <0.1) (Table 8). In the Chungfu soils (CF-soil 1 and CF-soil 2), the applying of CA, PP, CO, and ZL also significantly decrease the total removal of Pb by wheat (p <0.1) (Table 8). The experimental result shows that the chemical treatments of CA and ZL were efficient to decrease the total uptake of Cd and Pb among those treatments.

5.2.2. Case study 2

The used soils for pot experiments were sampled from Tatan village (TT-soil 3 & soil 4) and Chungfu village (CF-soil 3 & soil 4), respectively. Those treatments include (1) control (CK), (2) compost (CO) (40 tons ha^{-1}), (3) $CaCO_3$ (CA) -to rise soil pH to 7.5, (4) Zn oxide (ZN) (50 kg ZnO ha^{-1}), (5) mixture of $CaCO_3$ and Zn oxide (CA+ZN), and (6) mixture of $CaCO_3$ and compost (40 tons ha^{-1}) (CA+CO) (Lee et al., 2004). The treated soils were incubated for 6 months and then planted the seeds of wheat (*Triticum vulgare*). Soil solution was sampled by using Rhizon Soil Moisture Sampler (RSMS) and the metal concentration in soil was extracted by 0.005M DTPA (pH 5.3) and 0.05M EDTA (pH 7.0), respectively. The metal concentration in wheat was digested by H_2SO_4/$HClO_4$ method and determined by ICP.

The treatments of CA, CA+ZO (or CA+CO) were significantly to decrease the EDTA extractable Cd concentration in TT-soil 3 and CF-soil 4 (p <0.01). The DTPA extractable Cd concentration in TT-soil 3 also decreased after applying these chemical amendments. Because of the formation of insoluble cadmium carbonate after applying $CaCO_3$ (Holm et al., 1996), the extractable Cd and Pb concentration and their solubility was thus decreased (Chlopecka et al., 1996; Krebs et al., 1998). Different chemical amendments were not significantly to affect the EDTA extractable Pb concentration. However, the treatments of CA, CA+ZN (or CA+CO) were significantly to decrease the DTPA extractable Pb concentration in TT-soil 3, TT-soil 4, and CF-soil 3, respectively

Table 8. Effect of applying different chemical amendments on total uptake of Cd and Pb by wheat (Chen et al., 2000a and b)

Treatment#	Total uptake of Cd and Pb by wheat			
	CF-soil 1	CF-soil 2	TT-soil 1	TT-soil 2
	-------------------------- mg 20 plants^{-1} pot^{-1} --------------------------			
			Cd	
CK	0.05 a	0.03 ab	0.09 a	0.13 a
FO	0.02 bcd	0.03 a	0.10 a	0.13 ab
MO	0.02 bcd	0.01 b	0.06 b	0.10 b
CA	0.01 d	ND b	0.03 c	0.10 ab
PP	0.04 ab	0.02 b	0.09 a	0.12 ab
CO	0.03 abc	0.01 b	0.06 b	0.12 ab
ZL	0.02 cd	0.01 b	0.02 c	0.06 ab
			Pb	
CK	0.14 a	0.10 a	0.08 a	0.31 a
FO	0.02 b	0.05 ab	0.05 ab	0.25 ab
MO	0.05 b	0.07 ab	0.02 b	0.21 b
CA	0.05 b	0.03 b	0.03 ab	0.15 ab
PP	0.02 b	0.03 b	0.07 ab	0.23 ab
CO	0.02 b	0.03 b	0.03 ab	0.18 ab
ZL	0.02 b	0.03 b	0.05 ab	0.14 ab

: CK-control; FO- Fe oxide (20 tons ha^{-1}); MO-Mn oxide (20 kg ha^{-1}); CA-$CaCO_3$(20 tons ha^{-1}); PP-Calcium phosphate (0.1 tons ha^{-1}); CO-compost (40 tons ha^{-1}); ZL-zeolite (20 tons ha^{-1})

The probability level of significant difference is at $p = 0.1$. Replicates (n) = 2

(p <0.01). There was no effect of different chemical amendments on the Pb concentration in soil solution because the initial Pb concentration is very low.

The yield of wheat grain significantly increased in the treatments of CA, CA+ZN (or CA+CO) in TT-soil 3, TT-soil 4, and CF-soil 4 (p <0.01) (Table 9). In Chungfu and Tatan soils, the Cd concentration in the grain, stem, and husk of wheat also significantly decreased after applying these treatments (p <0.01) (Table 14). However, there is no effect of different chemical amendments on Pb concentration in the grain, stem, and husk of wheat (data not shown). The application of $CaCO_3$ significantly decrease the Cd concentration in the grain, stem, and husk of wheat and some of them were less than the Cd standard of rice (0.5 mg kg^{-1}) (p <0.01). Except for TT-soil 3, the application of CA and CA+ZN (or CA+CO) significantly decreased the total uptake of Cd by wheat grown in the TT-soil 4, CF-soil 3, and CF-soil 4 (p <0.01) (data not shown). The experimental re-

Table 9. Effect of applying soil amendments on grain yield and Cd concentration in grain, stem, and husk of wheat (Lee et al., 2004).

		Cd concentration		
Treatmwnt[#]	Grain yield	Grain	Stem	Husk
	----g pot^{-1}----	--------------------mg kg^{-1}	----------------------	
		TT-soil 3		
CK	0.09 b	11.0 a	136 a	27.2 b
CO	0.59 b	7.14 ab	56.0 b	16.1 c
ZN	0.08 b	10.3 ab	125 a	37.6 a
CA	3.04 a	4.63 b	28.4 c	10.2 d
CA+ZN	3.15 a	4.43 b	27.2 c	11.3 d
CA+CO	3.64 a	5.58 ab	38.8 bc	12.0 d
		TT-soil 4		
CK	0.49 bc	10.1 a	62.0 a	19.5 a
CO	1.31 bc	6.79 b	34.8 bc	13.0 b
ZN	0.11 c	8.10 ab	49.4 ab	16.6 b
CA	2.57 a	4.32 c	18.1 c	8.13 c
CA+ZN	1.50 ab	3.74 c	16.0 c	7.46 c
CA+CO	2.64 a	3.53 c	20.4 c	7.19 c
		CF-soil 3		
CK	3.84 a	1.49 b	8.09 a	6.50 a
CO	2.06 a	1.75 a	9.62 a	6.98 a
ZN	3.55 a	1.53 b	7.47 a	6.78 a
CA	4.47 a	0.52 c	1.79 b	1.32 b
CA+ZN	4.57 a	0.36 c	1.25 b	1.00 b
CA+CO	4.05 a	0.47 c	1.73 b	1.40 b
		CF-soil 4		
CK	2.08 b	1.46 b	7.56 b	5.97 b
CO	1.58 b	1.87 a	9.82 a	8.64 a
ZN	2.15 b	1.76 a	8.04 b	7.07 b
CA	4.79 a	0.16 c	0.72 c	0.41 c
CA+ZN	4.52 a	0.13 c	0.71 c	0.32 c
CA+CO	3.20 ab	0.23 c	1.41 c	0.66 c

; CK-control; CO-compost (40 tons ha^{-1}); ZN-ZnO (50 kg ha^{-1}); CA-$CaCO_3$ (rise soil pH to 7.5); CA+ZN-$CaCO_3$+ZnO; CA+CO-$CaCO_3$+compost

The probability level of significant difference is at p = 0.01. Replicates (n) = 4 sult shows that the use of $CaCO_3$ to increase the soil pH value can decrease the bioavailability of Cd in contaminated soil and thus to decrease the uptake by wheat.

5.3. Soil Washing Techniques

The suitable extracting agents which can be applied to the different heavy metals-contaminated soils include water, synthetic chelating agents and acid. Water can be used in the contaminated soils when the most of the metals in the contaminated soils were in the water soluble fractions. The other potential agents for soil washing include diluted acids or synthetic chelating agents. Compared with other remediation methods, soil washing method using diluted acids is highly destructive. This method can decrease the soil pH value, nutrient content, and some exchangeable bases. The population of soil microorganism will disappear after soil acid washing processes. Lime materials, organic materials, and chemical fertilizers are needed to apply and restore the soil characteristics after soil washing.

An off-site study was conducted to assess the effect of applying soil washing method for metals-contaminated soils remediation (Chang et al., 1991). Their experimental results indicated that application of EDTA or citric acid on contaminated paddy soils is efficient to remove Pb and Cd, respectively. Water celery was grown in the initial and treated soils and was harvested at 45th day after first planting. The accumulated Cd and Pb concentration increased from 35-80 and 80-125 (before soil washing) to 68 and 71 mg kg^{-1} (after soil washing), respectively. The experimental results also showed that soil washing had risk potential in increasing the availability of metals in the contaminated soils which was not suitable for crops planting. Further treatments are needed to decrease the high availability of metals after the treatment with soil washing method.

Apollo Technology Co., Ltd. in Taiwan applied acid washing method to remediate a Cd-contaminated site (0.98 ha) of Hsinchu city in the northern Taiwan (Apollo Technology Co., 2000). A pilot study is necessary to obtain the optimum condition before using soil acid washing method to remediate metal-contaminated soils in Hsinchu city, including metal concentration distribution in different sized soil particles and ideal agent for soil acid washing, etc. In this study, the contaminated soils were all soaked in the treatment system by 0.2 M HCl and the maximum operation rate was about 1.8 m^3 soils/day. The used waste liquids (HCl) were drained into the wastewater treating system at the end of the day, recycled as the diluting water after treated and the sludge was packed and treated legally. Soil acid washing method can decrease the soil Cd concentration from 9.58 ± 1.39 to 5.02 ± 0.35 mg/kg and the treating efficiency is about 33-72%. The experimental result shown in the addition of lime materials into the acid washing-treated soils can increase the germination percentage of Chinese kitam. It is necessary for further experiment to assess the effects of applying different soil amendments on the soil fertility of acid washing-treated soils considered by the soil properties and crop metal concentrations.

5.4. Phytoremediation Techniques

Phytoremediation of heavy metals that are usually persistent in the environment is a low-cost and environmentally compatible alternative to the chemical methods and therefore has attracted growing interest since last decade (Blaylock et al. 1997; Baker et al. 1998; Lasat, 2002). Moreover, phytoremediation offers the great advantage of causing only minimal environmental disturbance, since it does not adversely alter the soil matrix. Thus after successful phytoremediation, the soil can be directly used for agricultural purposes. All plants have the potential to extract metals from soil, but some of them have shown the ability to extract, accumulate and tolerate high levels of heavy metals, which would be toxic to other organisms. Such plants are so called hyperaccumulators and also provide the vegetation to control soil erosion on contaminated sites (Brooks et al., 1977; Cunningham and Ow, 1996; Evangelou et al., 2004). For phytoremediation to be successful, plants with high metal uptake capacity and high biomass production are needed. Since most of the known hyperaccumulators have a low annual biomass, much research is being done to enhance the availability of heavy metals in soils and increase phytoextraction efficiency of the potential accumulators (Baker et al., 1998). Another drawback of hyperaccumulator in phytoextraction is not able to accumulate various metals in multi-metal contaminated soils (Lombi et al., 2001; do Nascimento et al., 2006).

Chen and Lee (1997) planted 42 species of garden flowers in the Cd- and Pb-contaminated sites to study the possibility of using these flowers for phytoextraction of metals-contaminated soils. These potential phytoremediation plants include Rainbow pink (*Dianthus chinensis*), Star cluster (*Pantas lanceolata*), Cock-comb (*Celosia cristata*), Impatiens (*Impatiens wallerana*), and French marigold (*Tagetes patula*). After growing in the metals-contaminated sites for 5 weeks, the shoot Cd concentration of rainbow pink increased from 1.56 to 115 mg kg^{-1} (Table 10). The accumulated Cd concentration in their shoot was beyond the threshold of a Cd hyperaccumulator (100 mg kg^{-1}) (Baker et al., 2000). Because of the low availability and mobility of some metals, available synthetic chelating agents were applied to the metals-contaminated soils to increase their uptake by plants and thus to decrease the remediation period (Huang et al., 1997).

The experimental result showed that the application of 5 or 10 mmol 2Na-EDTA kg^{-1} on the soils significantly increased the Cd, Zn, and Pb concentration in soil solution when rainbow pink (*Dianthus chinensis*) was planted in an artificially Cd-, Zn-, and Pb-contaminated soil of Taiwan ($p < 0.05$). The total removal of Pb by rainbow pink was significantly increased after applying these two concentrations of 2Na-EDTA ($p < 0.05$). High metal concentration in soil solution after applying different chelating agents has high risk of groundwater contamination especially in the sandy soil. Lai and Chen (2005) applied 2 or 5 mmol 2Na-EDTA kg^{-1} soil to the single or combined metals-contaminated soils to study the effect of EDTA-enhanced phytoextraction using rainbow pink. The experimental result showed that 5 mmol 2Na-EDTA kg^{-1} soil was significantly to increase the metal concentration in soil solution (Fig. 13) or extracted by deionized water and thus to increase their concentration in the shoots of plants. Results of this studies indicated that rainbow pink is a potential hyperaccumulator for phytoextraction of metals-contaminated

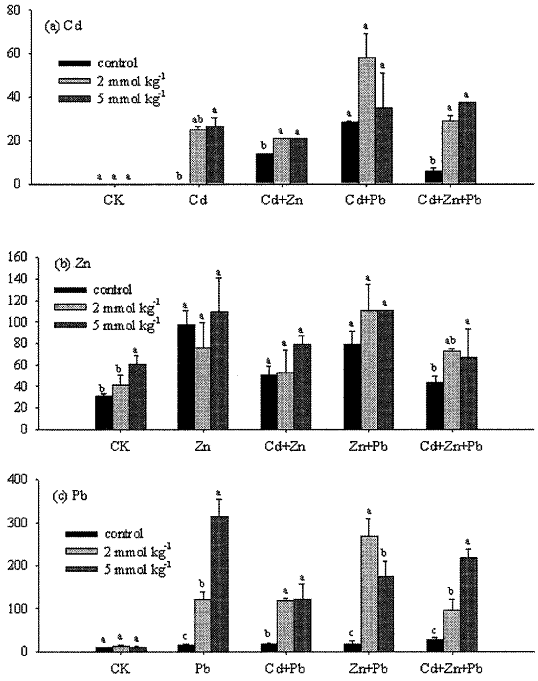

Fig. 13. The (a) Cd, (b) Zn, and (c) Pb concentrations (mg/kg) in rainbow pink shoots harvested at the 7th day after applying 2 and 5 mmol kg^{-1} EDTA solutions. Rainbow pink was grown for 21 days before applying the EDTA solutions. The probability level of significant difference is at $p = 0.05$. Replicates (n) = 3. (Lai and Chen, 2005)

Table 10. The concentration and total uptake of Cd in the leaves of plants after growing in the contaminated site for 5 weeks (Chen and Lee, 1997)

Plant	Site	Cd concentration in leaves* ------------mg kg^{-1}------------		Total uptake# g ha^{-1}yr^{-1}
		Before	5 weeks	
Star cluster	Tatan	1.44	43.6	50
Cock-comb	Tatan	2.3	86.7	56
Impatiens	Tatan	1.82	41.5	50
Rainbow pink	Tatan	1.56	115	90
	Chungfu	0.39	11.1	50
French marigold	Tatan	1.15	27.5	70
	Chung-Fu	1.26	11.1	50

*: Replicates (n) = 4; #: 70,000 plants ha^{-1} and 3 times y^{-1}

soils in Taiwan. The phytoextraction effect increased after applying 2Na-EDTA, but the risk of groundwater contamination also increased because of the high metal concentration in soil solution.

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