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Innovations techniques en agriculture urbaine pour la production de légumes non contaminés par les métaux à Lubumbashi, République Démocratique du Congo

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Innovations techniques en agriculture urbaine pour la production de légumes non contaminés par les métaux à Lubumbashi, République Démocratique du Congo

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Dissertation originale présentée en vue de l'obtention du grade de Docteur en Sciences Agronomiques et Ingénierie Biologique

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Année civile : 2024

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Citation : Mununga Katebe Félicien, 2024. Innovations techniques en agriculture urbaine pour la production de légumes non contaminés par les métaux à Lubumbashi, République Démocratique du Congo. Thèse de doctorat. Université de Liège - Gembloux Agro-Bio Tech, Belgique. 229p.

Abstract

In the 21st century, environmental contamination by trace metal elements has become a major issue due to their impact on soil quality, water, plants, and human health. The general objective of this thesis was to develop new methods for producing quality vegetables free from metallic contamination in an environment heavily impacted by mining activities in Lubumbashi, Democratic Republic of the Congo (DRC).

First, the typology of soil pollution in the urban and peri-urban market gardens of Lubumbashi was described using contamination indices, enrichment factors, and soil pollution indices. The results show that Lubumbashi and its surroundings host 40 market gardens and 33 urban markets. Copper and cobalt are the two main trace elements responsible for contaminating over 75% of the soils in these gardens. Additionally, more than 80% of the vegetables sold in the markets are also contaminated. The initial results established a link between the soils of the market gardens and the actual contamination levels for each garden, as well as for each trace metal element (copper, cobalt, cadmium, lead, zinc, and arsenic).

Second, this thesis aimed to evaluate the effects of organo-calcic amendments on reducing metal transfer from soil to plants on the one hand and to calculate the daily vegetable consumption index on the other. Three gardens were selected based on their levels of copper contamination: low, medium, and high. Organic amendments made from chicken manure and sawdust, in increasing doses, were used with or without agricultural lime. The results demonstrate that the organo-calcic amendments reduced metal transfer from soil to plants. For the garden with low copper contamination, the daily vegetable consumption index was determined and found to exceed the limits set by WHO/FAO, particularly for cobalt for an individual weighing 60 kg, unlike the two other gardens (Manoah and Chem-Chem) which did not produce sufficient biomass for analysis, and thus the daily consumption index could not be determined.

Third, this thesis aimed to develop bioponic nutrient solutions for application in hydroponic systems under the agro-environmental conditions of Lubumbashi. Two experiments were conducted to determine the quantities of organic matter to be used in the preparation of nutrient solutions, as well as the total ammonia nitrogen concentration needed for optimal plant growth. All nutrient solution preparation methods were repeated three times (0.35%, 3.5%, and 7% dry matter), resulting in nine tanks for the first trial and six repetitions of the single treatment (2.5% dry matter), totaling six tanks. The total ammonia nitrogen (TAN) concentration required for the first trial was 150 mg/L of TAN for each raft, according to the treatments, and 60, 90, and 120 mg/L of TAN for the second trial. The results showed significant differences between the reference chemical treatment and the bioponic treatments in terms of lettuce crop yield (*Lactuca sativa*).

In addition to the reference chemical treatment, which produced very high yields, the bioponic treatments with low dry matter percentages and low ammoniacal nitrogen concentrations showed no significant difference compared to those with higher dry matter quantities and TAN concentrations. Furthermore, the crops produced from both biological and chemical hydroponics did not contain heavy metals in their aerial biomass.

This thesis established a mapping framework to determine the contamination, enrichment, and pollution levels of Lubumbashi's market gardens. It demonstrated that applying organo-calcic amendments does not reduce the vegetable contamination risk below the toxicity threshold. Bioponics proves to be an effective soilless cultivation technique for producing vegetables free of metal contamination. We recommend that local high-value crops continue to be tested with organic hydroponics under the agro-environmental conditions of Lubumbashi and that the technique's dissemination be supported by the political and administrative authorities.

Résumé

Au XXIe siècle, la contamination de l'environnement par les éléments traces métalliques est devenue un problème majeur car ils ont un impact sur la qualité des sols, des eaux, des plantes et de la santé humaine. L'objectif général de cette thèse était de développer des nouvelles méthodes de production de légumes de qualité exemptent de toute contamination métallique dans un environnement fortement impacté par l'exploitation minière à Lubumbashi, République Démocratique du Congo (RDC).

Primo, la typologie de la pollution des sols des jardins maraîchers urbains et périurbains de Lubumbashi a été décrite en utilisant les indices de contamination, le facteur d'enrichissement et l'indice de pollution des sols. Les résultats obtenus montrent que la ville de Lubumbashi et ses environs comptent 40 jardins maraîchers et 33 marchés urbains. Le cuivre et le cobalt sont les deux principaux éléments traces responsables de la contamination de plus de 75 % des sols de ces jardins maraîchers. Par ailleurs, plus de 80 % des légumes vendus sur les marchés sont également contaminés. Les premiers résultats ont permis d'établir un lien entre les sols des jardins maraîchers et les niveaux réels de contamination de chacun d'eux, ainsi que pour chaque élément trace métallique (cuivre, cobalt, cadmium, plomb, zinc et arsenic).

Secundo, cette thèse avait pour objectif d'évaluer les effets d'amendements organocalcaires sur la réduction du transfert des métaux du sol vers les plantes d'une part et de calculer l'indice de consommation journalière des légumes d'autre part. Nous avons choisi trois jardins dont le degré contamination en cuivre est faible, moyen et élevé. Des amendements organiques à base de fientes de poules et de sciure de bois, à des doses croissantes, ont été utilisés avec ou sans chaux agricole. Les résultats démontrent que les amendements organocalcaires ont diminué le transfert des métaux du sol aux plantes. Pour le jardin faiblement contaminé en Cu, l'indice de consommation journalière des légumes a été déterminé et l'indice dépasse les limites fixées par l'OMS/FAO, notamment pour le cobalt pour un individu de 60 kg de poids corporel, contrairement aux deux jardins (Manoah et Chem-Chem) qui n'ont pas produit suffisamment de biomasse pour l'analyse, et donc l'indice de consommation journalière n'a pas pu être déterminé.

Tertio, l'objectif de cette thèse était de développer des solutions nutritives bioponiques pour l'application en cultures hydroponiques dans les conditions agro-environnementales de Lubumbashi. Deux essais ont été réalisés afin de déterminer les quantités de matières organiques à utiliser dans la fabrication des solutions nutritives d'une part, mais aussi la concentration en azote ammoniacal total à apporter aux plantes afin d'assurer leur meilleure croissance d'autre part. Toutes les méthodes de fabrication des solutions nutritives ont été répétées trois fois (0,35 % ; 3,5 % et 7 % M.S), soit neuf bidons pour l'essai 1 et six répétitions de l'unique modalité (2,5 % M.S) soit six bidons) ont été produites.

La concentration en azote ammoniacal total (TAN) requise pour le premier essai était de 150 mg/l de TAN pour chaque raft, selon les modalités, et de 60, 90 et 120 mg/l de TAN pour le second essai. Les résultats obtenus montrent qu’il existe des différences significatives entre la modalité chimique de référence et les modalités bioponiques pour ce qui est du rendement des cultures de laitue (*Lactuca sativa*). En plus de la modalité chimique de référence qui a donné des rendements très élevés, les modalités bioponiques ayant reçu des pourcentages faibles en matières sèches et des concentrations faibles d'azote ammoniacal total ne présentent aucune différence significative avec les modalités ayant reçu des grandes quantités en matières sèches et des fortes concentrations en TAN. Par ailleurs, les cultures issues de l'hydroponie biologique et chimique ne contiennent pas des métaux lourds dans leurs biomasses aériennes.

Cette thèse a mis en place une cartographie et un canevas pour déterminer le niveau de contamination, d’enrichissement et de pollution des jardins maraîchers de Lubumbashi. Elle a démontré que l’application des amendements organocalcaires ne réduit pas le risque de contamination de légumes en dessous du seuil de toxicité. La bioponie s’avère être une technique de production hors-sol des légumes non contaminés par les métaux. Nous proposons que les cultures locales à valeur ajoutée plus élevée continuent d’être testées avec l’hydroponie organique dans les conditions agro-environnementales de Lubumbashi et que la vulgarisation de la technique soit accompagnée par les autorités politico-administratives.

Remerciements

Tout d'abord, je tiens à remercier sincèrement mon promoteur de thèse, le Professeur Haïssam Jijakli, pour le soutien et l'encadrement dévoué dont vous avez fait preuve tout au long de ce parcours doctoral. Votre rigueur en recherche scientifique nous a permis d'atteindre l'excellence et de mener à bien notre formation doctorale dans un domaine aussi innovant, qui me passionne et que je souhaite continuer à explorer. Merci de m'avoir accueilli chaleureusement au sein du laboratoire de Phytopathologie Urbaine et Intégrée et d'avoir permis une collaboration amicale avec mes collègues de l'Axe Agriculture Urbaine, auquel j'appartiens depuis 2019. Je vous serai toujours reconnaissant de m'avoir soutenu tant sur le plan scientifique que personnel, en facilitant l'obtention de bourses complémentaires et en m'associant aux différents colloques internationaux. Encore une fois, merci, car sans vous, je n'aurais pas pu arriver à bon port.

Par la suite, je voudrais remercier le co-promoteur de cette thèse de doctorat, le professeur Michel Mpundu Mubemba pour les échanges, ses conseils et encouragements sur terrain que nous avons eu pour la mise en place des essais durant cette thèse de doctorat.

Je remercie sincèrement les membres du jury, les professeurs Jan Bogaert (Président), Haïssam Jijakli M. (Promoteur), Michel Mpundu (Co-promoteur), Grégory Mahy, Gilles Colinet, Thomas Dogot, et Guy Kateta, tous membres, qui ont accepté d'évaluer ce travail. Vos orientations, votre disponibilité et vos remarques pertinentes nous ont permis d'améliorer cette thèse de doctorat.

Merci à l'Académie de Recherche et d'Enseignement Supérieur (ARES), d'avoir financé cette étude durant ces cinq années mais également à l'Université de Liège qui m'a accueilli depuis 2019 à travers le laboratoire Phytopathologie Urbaine et Intégrée de la faculté de Gembloux Agro-Bio Tech et qui a financé les six derniers mois de ma thèse.

Je dis également merci au centre pour le partenariat et la coopération au développement (PACODEL), particulièrement les dames Lindsay Lebeau, Voyeux Valérie et Manon Van de Weghe.

Je remercie également les gestionnaires du projet Zorglub, les professeurs Gilles Colinet (Uliège) et Mylor Ngoy Shutcha (UNILU), pour la gestion, l'encadrement et le suivi réalisé durant les cinq années du projet, qui nous ont permis de réaliser cette thèse de doctorat dans de bonnes conditions.

Par cette occasion, je tiens à remercier nos partenaires Nord et Sud, la Wallonie-Bruxelles International (WBI), le Réseau des Femmes pour le Développement (REFED) à travers sa Coordonnatrice Madame Bernadette Kapend, le Bureau Diocésain pour le Développement (BDD) à travers son Coordonnateur Monsieur Placide Mukebo, pour leur accompagnement sur terrain, formation des maraîchers urbains et la mise en place des dispositifs pilotes de production hydroponique dans les ménages des producteurs Lushois qu'ils nous ont apporté.

Je tiens plus particulièrement à remercier Pierre Raulier, Iris Szekely et Clément Burgeon pour leur accompagnement dans la correction des articles, les échanges sur la mise en place des essais, la concrétisation de la bioponie, ainsi que pour la vulgarisation de nos résultats auprès des maraîchers à Lubumbashi, réalisée pendant deux jours avec Iris, une expérience riche en émotions et en apprentissage.

Je remercie également toute l'équipe de Phytopathologie Urbaine et Intégrée pour leur accueil chaleureux, leur bienveillance et le climat amical qu'ils ont su créer à mon égard. Je remercie également le professeur Sébastien Massart ainsi que mes collègues de bureau, anciens et nouveaux, Gilles Stouvenakers, Mathilde Eck, Madame Françoise Bafort, Roxane Huart, Nicolas Ancion, Pascale Papolaus, Olivier Parisis, Arthur Libault, Fanny Leleux , Waël Benhmouda, Madame Coralie Martin, Bérénice Foncoux, Lamine Yazidi, Eline Junique et Emilie Thys.

Merci à Madame Gladys Rufflard pour les services qu'elle nous a rendus dès notre arrivée au laboratoire de Phytopathologie, pour l'achat des appareils et réactifs, ainsi que pour la gestion du projet d'hydroponie maraîchère. Vous avez été une pièce maîtresse sur le plan administratif, contribuant à la réussite de cette thèse.Je remercie toute l'équipe des techniciens, Jimmy, Mr. Angelo, Cyril, Julien, Frédéric, Damien, Vanessa, Igor, Sam et Adrien, pour leurs échanges, leur coup de main, leur disponibilité, ainsi que leur aide dans la mise en place des essais à Gembloux, afin d'atteindre les objectifs fixés dans cette thèse de doctorat.

Je remercie sincèrement Leurs Excellences, Messieurs le Gouverneur Jacques Kyabula Katwe et les Vice-Gouverneurs de la province du Haut-Katanga, Jean-Claude Kanfwa et Martin Kazembe Shula ; le Ministre provincial de la Santé du Haut-Katanga, le Professeur Joseph Nsambi Bulanda ; le Recteur de l'Université de Lubumbashi, le Professeur ordinaire Gilbert Kishiba Fitula ; le Recteur honoraire de l'Université de Lubumbashi, le Professeur ordinaire Ildephonse Cabu Mumba ; le Recteur de l'Université de Likasi, le Professeur ordinaire Louis Mpala Mbabula ; le Secrétaire Général Académique de l'Université de Lubumbashi, le Professeur ordinaire Jean-Marie Dikanga Kazadi ; l'Archevêque Paulin Mwewa Kunda ; ainsi que Monsieur Oscar Manikunda Musata pour le soutien moral, scientifique, spirituel et financier que vous nous avez apporté.

Je remercie également les autorités décanales pour le soutien scientifique et financier qu'elles m'ont apporté durant ce parcours doctoral, notamment les professeurs Mylor Ngoy Shutcha, Doyen de la faculté ; Sylvestre Cabala Kaleba, Vice-Doyen chargé de l'Enseignement ; Jonas Lwalaba wa Lwalaba, Vice-Doyen chargé de la Recherche ; Wilfried Kalenga Masengo, Vice-Doyen chargé du tutorat ; ainsi que le chef de travaux Xavier Mwilambwe Kapoma, Secrétaire Académique, tous de l'Université de Lubumbashi.

Merci également aux Professeurs Jean-Marc Kaumbu Kyalamakasa et Sylvestre Cabala Kaleba pour leurs conseils, leurs encouragements et les échanges scientifiques que vous m'avez offerts depuis mes premiers jours à l'université, durant le cycle d'Ingénieur, le Master, et le doctorat.

J’exprime ma gratitude infinie à notre cher père défunt, Télesphore Katebe Mukeya, qui nous a quittés trop tôt et qui aurait tant voulu voir son fils mener à bien ce long parcours académique. Paix à ton âme. Merci également à notre chère mère, Godelieve Chanshi Mwewa, qui s’est sacrifiée matin, midi et soir pour que ses enfants puissent étudier, malgré les moments difficiles. Grâce à elle, nous sommes arrivés à bon port.

Je remercie mes cousins, Gilbert Kapya Lundeba et Victoire Kyota, ainsi que ma grande sœur Micheline Mpundu Lundeba, qui ont souhaité et accepté de me voir un jour devenir ingénieur. Me voici aujourd’hui pour vous rendre hommage, chers grand-frère et grande sœur.

J’en profite pour remercier ma famille, grand parent, oncles, tantes, frères, sœurs, cousins (e), Natengu Katebe et Joachim Ntengu, Jean-bosco Katebe Mukeya, Augustin Kazembe Katebe, Mukeya Katebe, Nicodème Kisanga Mwewa, Gisèle Kasanda, Emmanuel Mwape Kalobolobo, Benoni Kibwe Mwewa, Martine Kitila et Kanswe, Hortense Muteba, Raphaël Ntengu, Mireille Muyambo et Jean-Pierre Kibombwe, Augustin Chola Kazembe, Amos Mwashi et Christine, Fabien Katontoka, Jean-Claude Mwape Kazembe, François Mukeya Muyembe, Célestine Kapya Mwatshikamb, Pierre Chola Mambwe, Ignace Lundeba et Olga, Jean-Pierre Ngoie Kombe, Jeremy Cabu Kapakwe, Angel Mwape Kasonta, Désanges Kasonta Eric Kalela Nfunda et Mathias Wansambo, pour l’amour et l’accompagnement me témoigné.

Je dis merci à ma chérie, Marianna Kikonde Cizungu pour son amour, sa patience durant le parcours de cette thèse de doctorat, Bisous.

Également merci à mes beaux-parents Papa Dominique Kikonde et Maman Esther, pour la patience et la confiance donnée à ma personne d’etre votre nouvel enfant aîné dans votre famille.

Merci aussi à nos parrains, Papa Marc Tshiyaz et Maman Zaina Kadiongo pour l’encadrement spirituel, social et l’accompagnement de notre couple.

De votre vivant, j’aurais aimé vous remercier pour les conseils que vous nous avez prodigués, très cher professeur ordinaire Auguste Chocha Manda, mais hélas, vous êtes parti trop tôt. Paix à votre âme.

Merci également aux collègues doctorants du projet Zorglub, Maurice Kesonga Nsele, Serge Langunu et Grace Mashagiro, avec qui nous avons cheminé tout au long de notre parcours doctoral.

A mes amis, collègues et connaissances, les professeurs Georges Mulumbeni, Yannick Useni, Audry Tshibangu, Robert-Prince Mukobo, Emmanuel Abwe, Many Madika, Christian Kunda, Patrick Tshilunga, Magnifique Chiumika, Bibiche Kirika, Arsène Mushagalusa, Hugues Ilunga et Salomon Waselin, aux chefs de travaux Méli Kimpinde, Dieudonné N’tambwe, Serge Kashimbo, Franco Mwamba, Emmanuel Muyambo, Gyrhaiss Kasembele, Didier Kasongo et Linda Basheke. Aux Assistants et amis, Michael Lwanga, François Kapoma, Pacifique Kiwele, Alphonse Kalambulwa, Urbain Mumba, Colin Ndoba, Myriam Tshiswaka, Carmel Kalombo, Christian Mukweze, Clément Kalombo, Christian Kamwanya, Éric Kilomba, Trésor Kisimba, Ir Laurin Lebeau, Janvier Zigashane, Maria Amisa, Christelle Katuta, Marcelin Cituma, Stéphane Mwemena, Isaac Kalume, Augustin Mbuyu et Nathalie Katund, Joseph Kambiré, Marcelin Cokola, Patient Gakuru, Rodrigues Lugendo, Marcelin Aganze, François Nimbeshaho, Roselande Jesuka, Mireille Twite,Crispin, Pacifique Bulambo, Françoise Madamo, Virgnie Korangi et Christian Kanunda, pour vos conseils, services et moments formidables passez ensemble.

Je remercie tous les étudiant (e,s) qui m'ont accompagné durant cette thèse, Peter Mutabazi, Ildephonse Mubanda, Odia Ntumba, François Duse, Abraham Musans, Yannick Kabamba, Laurenne Kapinga, Ines Kay, Stanis Muganza, David Mwaku, Emmanuel Mutentu, Exaucée Mpweto, Rose Kalenga, Gloire Sango, Abner Mwenze et Fabien Edope, Isaac Mukonga et Angelani Banza, pour votre coût de mains et disponibilité nous apporté ainsi que les questions pertinentes nous posées avant la mise en place de vos essais.

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RDC : République Démocratique du Congo

FAO : Organisation des Nations Unies pour l'Alimentation et l'Agriculture

WHO : World Health Organization

OMS : Organisation Mondiale de la Santé

pH : Potentiel d'Hydrogène

DWC : Deep Water Culture

NFT : Nutrient Film Technique

PO : Pression Osmotique

EC : Conductivité électrique

AFNOR : Association Française de Noramlisation

TMEs : trace metal elements

GCS : Geographic Coordinate System

OCC : Office Congolais de Contrôle

HUP : Horticulture Urbaine et Péri urbaine

ICP : Indicateur Clé de Performance

CFI : Contamination Factor

EF: Enrichment Factor

EC: Electroconductivité

PLI: Soil Pollution Load Index

USA: United States of America

GECAMINES : Générales des Carrières et des Mines

TAN : Azote Total Ammoniacal

BIODEV : unité de recherche Biofortification, Défense et Valorisation des cultures

TMN : Total Mineral Nitrogen

C/N : Rapport Carbone Azote

REGIDESO : Régies de Distribution d'eau

REFED : Réseau des Femmes pour le Développement

BDD : Bureau Diocésain pour le Développement

UNILU : Université de Lubumbashi

M.S : Matières sèches

Chapitre 1

Introduction

1.1. Mise en contexte de l’étude

Entre 2005 et 2010, le projet REMEDLU, qui visait à remédier à la contamination métallique des sols, a abouti à plusieurs conclusions : les zones urbaines et périurbaines s'étendaient de manière anarchique et les jardins maraîchers urbains de Lubumbashi étaient contaminés par des éléments traces métalliques, entraînant des risques de contamination de la chaîne alimentaire (Mpundu et al., 2014). L'application d’amendements organiques et calcaires aux sols contaminés par les métaux a réduit la mobilité et la biodisponibilité des métaux dans les sols, ce qui a permis l'installation de la végétation sur les sols nus de Penga-Penga fortement contaminés en cuivre avec l'espèce *Microchloa altera* (Shutcha et al., 2010). Les amendements organo-calcaires appliqués aux sols des jardins maraîchers urbains contaminés par les métaux ont permis de réduire la mobilité des métaux dans les sols agricoles ainsi que leur transfert vers les légumes (*Amaranthus vulgaris et Beta vulgaris*). Cependant, les teneurs retrouvées dans les légumes dépassaient les seuils de toxicité recommandés par l'OMS pour la consommation humaine de ces légumes. En parallèle à ce projet, un autre projet financé par la Belgique et mis en place par la FAO entre 2000 et 2010 proposait d’autres techniques agricoles, cette fois-ci uniquement dans le but d'améliorer la productivité agricole.

C'est dans ce contexte qu'a été développé le Projet de Recherche et Développement (PRD ZORGLUB), visant à soutenir d'une part les populations locales qui bénéficient des services écosystémiques urbains par le renforcement de leurs capacités, et d'autre part les acteurs de la production agricole urbaine en améliorant leurs conditions de vie et de travail. L'Académie de Recherche et d'Enseignement Supérieur (ARES) a financé ce Projet de Recherche et de Développement (PRD), en partenariat avec l'Université de Liège (Gembloux Agro-Bio Tech) et l’Université de Lubumbashi (Faculté des Sciences Agronomiques), pour une durée de cinq ans (2018-2023). Pour atteindre les résultats escomptés, le projet Zorglub a formulé quatre questions scientifiques correspondant à quatre thématiques doctorales : (1) Est-il possible d'évaluer les services et disservices offerts par les écosystèmes urbains dans la ville de Lubumbashi et d'améliorer ces services par le développement d'infrastructures vertes innovantes dans une ville comme Lubumbashi ? (2) Quelles techniques innovantes peuvent être employées pour améliorer les services de production dans les espaces dégradés ? (3) Comment les populations acceptent-elles les innovations et les changements de pratiques ? et (4) Comment les sols pollués par les métaux lourds peuvent-ils favoriser une production maraîchère saine dans la ville de Lubumbashi et sous quelles conditions peuvent-ils offrir d'autres services écosystémiques dans les espaces verts dégradés ? Ma thèse s’inscrit donc dans la deuxième thématique du projet Zorglub, qui vise à développer des méthodes innovantes pour améliorer la qualité et la productivité des aliments dans l'agriculture urbaine de Lubumbashi.

1.2. Croissance démographique et autosuffisance alimentaire en Afrique

La population mondiale devrait atteindre 9,8 milliards d'individus d'ici 2050, entraînant une forte hausse de la demande alimentaire en raison de l'augmentation du nombre de personnes à nourrir (Eigenbrod & Gruda, 2015; Hall et al., 2017; P. Smith, 2013). Cependant, cette croissance démographique sera particulièrement concentrée dans les zones urbaines, où plus de 70 % de la population résidera, contrairement aux zones rurales qui subiront un exode important. En Afrique, la population atteindra 2,4 milliards d'ici 2050, avec des rendements agricoles constants, ce qui entraînera une augmentation significative des surfaces cultivées et des productions agricoles pour répondre aux fortes demandes alimentaires (Ciceri & Allanore, 2019; Misselhorn et al., 2012). La nécessité d'accroître les superficies agricoles, combinée à la diminution de celles-ci en raison de l'urbanisation croissante qui menace les villes africaines, constituera une situation contradictoire (Azizan & Hussin, 2015; Mwegoha & Kihampa, 2010). Des situations similaires ont été observées à Java, où la conversion des terres agricoles en zones résidentielles et industrielles a eu des répercussions sur la productivité des cultures, comme l'ont montré plusieurs études (Jayne et al., 2014; L. Jiang et al., 2013).

Les pays en développement doivent déployer de nombreux efforts pour garantir leur autosuffisance alimentaire. L'autosuffisance alimentaire est la capacité d'un pays ou d'une région à produire en quantité et en qualité suffisantes les aliments nécessaires à sa population, sans dépendre des importations pour assurer la sécurité alimentaire de tous ses habitants (Clapp, 2017; Grewal & Grewal, 2012; Pradhan et al., 2014; Soltani et al., 2020). Au cours du dernier siècle, le monde a été confronté à de nombreux problèmes, tels que les conflits entre nations ayant causé des pertes humaines et des déplacements, les enjeux environnementaux ou climatiques, ainsi qu'une insécurité alimentaire aiguë. Près de 810 millions de personnes souffrent de malnutrition et d'insécurité alimentaire dans le monde, principalement en Afrique et en Asie. Certaines études révèlent qu'environ 210 millions de personnes en Afrique souffrent de malnutrition, un chiffre qui devrait augmenter dans les années à venir. Par ailleurs, près de 520 millions de personnes en Asie sont également touchées par ce même problème d'insécurité alimentaire (Brown & Brown, 2016; FAO/WHO, 2016; Zhang et al., 2023).

La sécurité alimentaire peut être envisagée à trois niveaux : local, national et international (Baer-Nawrocka & Sadowski, 2019; Srinivasan, 2000). La ville de Lubumbashi ne fait pas exception à ce problème d'insécurité, car sa population n'a cessé de croître de façon significative depuis deux décennies (Gambe et al., 2023; Mulumbati, 2022; Useni et al., 2022), ce qui complique l'alimentation d'une population en augmentation rapide, souvent sans emploi ni revenu. La sécurité alimentaire à Lubumbashi repose donc en grande partie sur les importations en provenance des pays voisins, bien que cette sécurité reste principalement précaire (Tshomba et al., 2020). La seule production locale importante est celle du maraîchage, pratiquée par des personnes sans emploi pour subvenir à leurs besoins (Badibanga & Ulimwengu, 2020; Ilunga & Shengo, 2020; Tshomba et al., 2015).

1.3. Exploitation minière et son impact sur l'environnement

1.3.1. Brève historique de l'exploitation minière dans le Haut-Katanga

Le Haut-Katanga est une province du sud-est de la République Démocratique du Congo (RDC) qui possède d'importantes ressources minérales (Kalenga, 2019; Katz-Lavigne, 2019; Megaw et al., 2017). Ces ressources sont exploitées industriellement depuis le début du XXe siècle, durant la période coloniale, dite du Congo Belge (Birchard, 1940; Larmer & Taylor, 2021). Le secteur minier y a connu une croissance spectaculaire, en particulier dans le Haut-Katanga et en RDC de manière générale (Deberdt, 2021; Elbel et al., 2023; Malaisse et al., 1999). Les industries minières de l'ancienne province du Katanga sont nombreuses en raison de ses gisements abondants, notamment la célèbre mine cuprocobaltifère de Tenke Fungurume et celle de Kamoto, l'une des carrières les plus riches en ressources minérales au monde. Cette industrie minière a apporté de nombreux bénéfices aux populations et à l'État, notamment une contribution significative au budget national ainsi qu'un rôle majeur dans le développement du pays, avec la construction de routes de desserte agricole, d'infrastructures hospitalières, et la réduction du chômage pour les habitants des zones minières (Elbel et al., 2023; Rubbers, 2023; Waldburger, 2023; Katz-Lavigne, 2020).

Malgré ces bénéfices, l'industrie minière est à l'origine de la pollution de l'environnement, notamment la pollution des sols dans les zones habitées, ainsi que celle de l'eau, de l'air et des organismes vivants (Mununga al., 2023; Butsic et al., 2015; Ericsson & Löf, 2019; Galli et al., 2022; Otchia, 2015; Sovacool, 2019). Ces perturbations sont causées par les pratiques d'exploitation minière à grande échelle. L'hydrométallurgie, qui consiste à extraire les minéraux, est responsable de nombreux dégâts environnementaux dans le Haut-Katanga et dans tout le pays (Butsic et al., 2015; de Oliveira-Ferreira et al., 2022; Dey et al., 2023; Ilunga & Shengo, 2020; Michée et al., 2023; Mukendi et al., 2018; Mununga et al., 2023; Tepanosyan et al., 2020).

Néanmoins, la RDC a mis en place plusieurs actions de bonne gouvernance et de gestion de la pollution des sols, de l'eau, de l'air et des êtres vivants, en renforçant ses capacités en matière de réglementation environnementale pour améliorer les pratiques minières et réduire l'empreinte écologique de ces activités. Cependant, l'application de ces mesures demeure un enjeu majeur pour la RDC en général et pour le Haut-Katanga en particulier. Les préoccupations environnementales sont aujourd'hui au premier plan à l'échelle mondiale et nécessitent une modification de nos comportements pour préserver la planète. Ainsi, la transition écologique est devenue une obligation pour tous les pays. En raison de ses importantes réserves minérales stratégiques, la RD Congo occupe une position clé pour contribuer à cette transition écologique. Il est donc crucial pour la RD Congo, dans le contexte des défis mondiaux actuels, de gérer ses ressources minérales de manière responsable afin de participer activement à la transition énergétique et de faire bénéficier le plus grand nombre de ses habitants, ainsi que les générations futures, des avantages de l'exploitation minière (Kabemba, 2016; Zongwe, 2008).

1.3.2. Contamination de l’eau de surface et souterraine par les métaux

Les nappes phréatiques constituent les principales sources d'eau douce dans le monde pour des usages domestiques, agricoles et industriels. Cependant, les pratiques agricoles, l'urbanisation et les activités industrielles en constante expansion entraînent une dégradation de la qualité de ces eaux souterraines (Li et al., 2021). Les métaux lourds, également appelés oligoéléments, sont essentiels aux processus métaboliques humains, car ils participent à diverses réactions biochimiques, notamment le cuivre (Cu), le cobalt (Co), le plomb (Pb), le zinc (Zn), l'arsenic (As), le nickel (Ni), etc. La présence de maladies telles que le choléra, la dysenterie, la typhoïde et l'hépatite A peut avoir des répercussions sur l'environnement et la santé humaine, entraînant un dysfonctionnement de l'organisme (Lin et al., 2022; Bansal, 2016; Payment et al., 1997). Le plomb et le cadmium, en particulier, sont des métaux pouvant provoquer des troubles neurologiques, rénaux, reproductifs, voire des cancers chez l'homme. En Chine, des cas similaires ont montré que la consommation d'eaux contaminées par l'arsenic était la principale cause de maladies telles que la perte de réflexes, une fatigue intense, la gastrite, l'anorexie et la chute des cheveux chez une grande partie de la population (Bissen et al., 2003; H. Guo et al., 2014; Tong et al., 2021). L'augmentation des maladies rénales et cancéreuses à Lubumbashi depuis plus de deux décennies pourrait être attribuée à la contamination croissante des eaux des rivières et des forages. Les espèces halieutiques des rivières Kafubu et Kapolowe ont été décimées par la contamination des eaux par les métaux dans la région de Lubumbashi, en raison des concentrations élevées de métaux dans l'eau et de leur accumulation dans les muscles des poissons (Bansal, 2016; Katemo et al., 2010; Lin et al., 2022).

1.3.3. Contamination métallique des sols agricoles et résidentiels

Les métaux lourds présents dans la croûte terrestre sont parmi les principaux polluants environnementaux et peuvent devenir extrêmement toxiques car ils ne sont pas biodégradables (Del Val et al., 1999). La contamination des sols par l'introduction de métaux dans l'environnement a été aggravée par la révolution industrielle, ce qui a provoqué un problème environnemental grave, avec des répercussions sur la biodiversité, la perte de fertilité des sols, la sécurité alimentaire et la santé humaine (Loureiro et al., 2005, 2006; Tangahu et al., 2011). Les métaux les plus dangereux pour l'environnement incluent le cadmium, le plomb, le mercure, le nickel, le chrome, l'arsenic, le cuivre et le zinc (Gupta et al., 2016; Nagajyoti et al., 2010). Des concentrations excessives de métaux lourds dans les sols ont un impact négatif sur leur productivité et leur fertilité.

Des observations similaires ont été rapportées par (Mpundu et al., 2014; Mununga et al., 2023), selon lesquelles les plantes d'*Amaranthus vulgaris* ont été contaminées par les métaux lourds. Plusieurs cancers et pertes de cheveux ont été diagnostiqués chez les consommateurs de ces plantes, en raison de l'ingestion de produits contenant des métaux lourds (Manzoor, 2020). La majorité des sols des jardins maraîchers étaient contaminés par des métaux lourds (Cu, Co, As, Cd, Pb et Zn), ce qui a entraîné des malformations chez les populations consommant les produits issus de ces cultures (Banza et al., 2009; Mpundu et al., 2014; Mununga et al., 2023; Shutcha et al., 2015).

1.3.4. Contamination métallique des plantes

Les sols et les eaux peuvent être contaminés de diverses manières, transmettant ainsi les polluants aux plantes qui y poussent, ce qui altère leur métabolisme. Ces contaminations peuvent entraîner des pertes en quantité et en qualité des productions agricoles. Les légumes peuvent contenir des substances nocives dépassant les normes acceptables pour la consommation humaine (Cheng et al., 2015; Langunu et al., 2023; Marti & Puertas, 2020; Mununga et al., 2023b). Ainsi, dans la plupart des villes du monde, la contamination des aliments par différents éléments traces métalliques constitue une problématique majeure. Cette contamination peut survenir lors de la production (Davis et al., 2021; Yeleliere et al., 2017), au moment de la vente par exposition à des poussières contenant des particules métalliques (Biswas et al., 2019; Djahed et al., 2018; Romero-Estévez et al., 2023), ou encore par l'irrigation des cultures avec de l'eau de mauvaise qualité sanitaire (Biswas et al., 2019; Hosseini-Zare et al., 2014; Slamini et al., 2022). La détérioration de la sécurité alimentaire est étroitement liée à ce phénomène, car celle-ci repose sur la disponibilité d'aliments de qualité accessibles aux populations locales (Awuchi, 2023; Kamboj et al., 2020; Qin et al., 2021). De nombreuses normes ont été établies pour évaluer la qualité sanitaire des produits agricoles, notamment par des organismes canadiens, français, américains, chinois et l'OMS (Awuchi, 2023; Kamboj et al., 2020; Qin et al., 2021; Tóth et al., 2016). Par ailleurs, des normes sous-régionales sont également mises en place pour la détection des zones contaminées (Bogaert et al., 2018; Ercilla-Montserrat et al., 2018). Une surveillance régulière et des tests permettent de vérifier si les produits agricoles sont aptes à la consommation humaine ou à d'autres usages, y compris pour la nutrition animale, afin de protéger la santé des consommateurs contre l'ingestion de produits contaminés par des métaux traces (Fei et al., 2022; Rossatto et al., 2023; Q. Yang et al., 2018).

1.3.5. Contamination métallique de l’air et/ou de l’atmosphère

De nombreuses recherches ont été menées ces dernières décennies, car la santé humaine est étroitement liée à l'environnement, et l'exposition aux polluants atmosphériques est une source de préoccupation majeure (Almetwally et al., 2020). La propagation des métaux lourds dans l'atmosphère est principalement due aux activités de l'industrie métallurgique, minière et chimique, aux centrales électriques au charbon, à l'incinération des déchets, aux transports, à l'agriculture, ainsi qu'à des phénomènes naturels tels que les éruptions volcaniques et les incendies de forêts. Les métaux lourds présents dans l'atmosphère, tels que le plomb, le cuivre, le cadmium, l'arsenic, le chrome, le zinc et le nickel, proviennent en grande partie des activités humaines.

Les dépôts atmosphériques et la bioaccumulation de ces métaux peuvent avoir des conséquences néfastes sur l'environnement et sur la santé humaine, notamment par l'inhalation de poussières, l'ingestion d'aliments contaminés, ou l'absorption cutanée de ces substances. Bien que certains métaux lourds soient nécessaires au bon fonctionnement de l'organisme, leur surconcentration entraîne de nombreuses maladies chez l'homme, telles que des cancers, des maladies gastro-intestinales, respiratoires, cardiovasculaires, etc…(Hui Chen et al., 2022; Nieuwenhuijsen et al., 2014; Santana et al., 2020; Van Tran et al., 2020). La pollution atmosphérique a causé d'importants dommages dans le monde entier, entraînant plus de 800 000 décès par an liés à cette pollution (Anderson et al., 2012). À Lubumbashi, il a été constaté que l'émission de SO2 dans l'atmosphère par la cheminée de la GECAMINES, lors de l'extraction et de la transformation des minerais, avait conduit à la formation de pluies acides, acidifiant ainsi les sols résidentiels et agricoles (Longo-Mbenza et al., 1998). Par ailleurs, la forte circulation routière constitue une autre source de métaux lourds dans l'air ambiant. Les concentrations de métaux lourds (Cd, Ni, Cu, Fe, Zn et Pb) mesurées dans les poussières le long de la route Kassapa dépassaient les normes de l'OMS (Paul-Didi et al., 2021).

1.3.6. Effets de la contamination métallique sur la santé humaine

Les organismes vivants sont menacés par les métaux lourds lorsque leur accumulation dépasse leur capacité d'élimination. Chez l'être humain, ces métaux peuvent pénétrer dans le corps par plusieurs voies, notamment l'ingestion, l'absorption cutanée et l'inhalation (Kamran et al., 2013). La pollution métallique des êtres vivants provient de diverses sources : émissions industrielles, combustibles fossiles, incinération des déchets, batteries (Ni-Cd), engrais phosphatés, pesticides, eaux usées, etc. Les organismes vivants sont contaminés par des métaux lourds tels que le plomb (Pb), le mercure (Hg), le cadmium (Cd), l'arsenic (As), le nickel (Ni), le zinc (Zn), le cuivre (Cu) et le chrome (Cr). Des études similaires menées par (Maurya et al., 2019; Vu et al., 2017) ont confirmé que la pollution métallique des rivières était responsable de la contamination de sept espèces de poissons (*Cirrhinus mrigala, Cirrhinus reba, Catla catla, Labeo rohita, Crossocheilus latius, Clupisoma garua*, et *Mystus tengara*), où des concentrations élevées de zinc, plomb, cuivre, cadmium et chrome ont été retrouvées dans les branchies de ces poissons. Des observations similaires ont été faites dans l'ancienne province du Katanga, dans les rivières Lufira et Tshangalele, où les concentrations de métaux lourds (Pb, U, V, Cu, Co et Cd) dans les muscles et les branchies de Tilapia niloticus, Tilapia rendalli et Clarias gariepinus étaient bien au-dessus des normes de l'OMS pour la consommation humaine de poissons (Katemo et al., 2010; Vu et al., 2017). L'ingestion d'aliments contaminés ou l'inhalation de particules fines de métaux lourds constitue la principale voie de bioaccumulation dans l’organisme, malgré les différentes sources de contamination.

Les recherches menées dans l'ex-province du Katanga montrent que la consommation d'aliments contaminés (poissons, maïs et légumes) par des métaux lourds constitue la principale source d'exposition au cobalt chez les enfants (Nemery & Banza, 2018). Les populations vivant à moins de 3 km des sources de pollution, ainsi que les travailleurs artisanaux de l'extraction du cobalt, du cuivre et de l'or, présentent des concentrations urinaires très élevées, dépassant largement les seuils de toxicité pour la plupart des métaux, notamment l'uranium, le manganèse, le mercure et le plomb (Banza et al., 2009; Nemery & Banza, 2018). Les conséquences de l'exposition à la contamination par les métaux, principalement l'arsenic et le cadmium, entraînent une dégradation de la mobilité des spermatozoïdes chez les personnes vivant à proximité des activités minières, contrairement à celles qui vivent plus loin, où la mobilité des spermatozoïdes reste relativement stable. Cela entraîne une baisse significative de la fertilité masculine chez les personnes exposées (Mukendi et al., 2018). Les métaux lourds agissent généralement comme des cofacteurs dans les voies enzymatiques et métaboliques. Ils peuvent causer des décès chez toutes les formes de vie, y compris les plantes, les microorganismes, les animaux et les humains (Nies, 1999; Atlas and Bartha, 2016). Une concentration excessive de métaux lourds dans le corps humain peut avoir des effets graves tels que le cancer, les maladies neuromusculaires et les troubles psychiques, entre autres (Chandra et al., 2011).

1.4. Rôles des amendements organocalcaires sur la croissance des plantes et la bioaccumulation des métaux.

Plusieurs facteurs influencent la capacité d'un sol à favoriser la croissance des plantes, notamment la quantité et la qualité des éléments nutritifs, la texture et la structure du sol, le pH, la matière organique, la capacité de rétention d'eau et l'activité biologique. Pour maintenir une productivité élevée, les agriculteurs ont recours à des engrais chimiques synthétiques. Cependant, le coût de ces engrais n'a cessé d'augmenter au cours des dernières années dans les pays en développement, les rendant inaccessibles pour la majorité des agriculteurs (Tshomba et al., 2020). Les sols agricoles se sont détériorés en raison de l'augmentation des surfaces emblavées et de la production agricole. Les amendements représentent une solution alternative intéressante pour accroître la productivité des exploitations agricoles (Babla et al., 2022).

Il est possible d'améliorer la structure et la texture du sol en appliquant des amendements organocalcaires aux sols contaminés par les métaux, ce qui permet de réduire leur mobilité et leur biodisponibilité, limitant ainsi leur absorption par les plantes et les microorganismes (Guo et al., 2020; Jalali & Latifi, 2018; Mpundu et al., 2014; Raiesi & Dayani, 2021; Shahkolaie et al., 2020; Shutcha et al., 2015). Les composés organiques, tels que les acides humiques et fulviques présents dans les composts, les résidus agricoles et les fumiers, peuvent former des chélates avec les éléments traces métalliques du sol (Bahemmat et al., 2016; Fakour & Lin, 2014; Isrun et al., 2021; Rashid et al., 2018; Yupeng Wang et al., 2020). Ces chélates ont la capacité de réduire la mobilité des métaux dans le sol, limitant ainsi leur absorption par les plantes et favorisant leur lixiviation vers la nappe phréatique (Caporale & Violante, 2016; Shuailong Cheng et al., 2020; Wang et al., 2020). Toutefois, la faune microbienne diminue lorsque les concentrations en métaux sont très élevées, et l'application d'amendements organiques à ce type de sols crée un environnement propice à leur développement. Ces microorganismes secrètent en effet des substances capables de rendre certains métaux moins toxiques et moins solubles (Ma et al., 2022; Sarwar et al., 2017).

1.5. Mécanismes d’absorption des métaux par les plantes

1.5.1. Absorption foliaire

Les formes physico-chimiques des métaux, ainsi que le type de métal, d'une part, et la cuticule végétale ainsi que la texture de la surface foliaire, d'autre part, sont des facteurs qui influencent l'absorption des métaux lourds à travers les feuilles (Beckett et al., 2012). Le temps d'exposition et les conditions environnementales constituent également des facteurs supplémentaires. Les métaux lourds présents dans l'atmosphère proviennent de plusieurs sources, telles que le transport routier et l'industrie (Chaloulakou & Mavroidis, 2002; Sawidis et al., 2012). Les plantes absorbent les métaux lourds par voie foliaire à travers les stomates, les ectodermes, les lenticelles, les pores aqueux et les fissures cuticulaires (Shahid et al., 2017). Les canaux non plasmiques (ectodermes) situés entre la paroi cellulaire épidermique et les cellules subsidiaires retiennent les métaux lourds sur les surfaces foliaires (Uzu et al., 2014). Les métaux sont retenus sur les feuilles par les trichomes et les cires cuticulaires avant de pénétrer à l'intérieur des feuilles des plantes. Ainsi, les stomates peuvent introduire le Cu et le Ni dans les feuilles (Bondada et al., 2004; Shahid et al., 2017). D'autres recherches menées en Russie montrent une absorption des métaux lourds qui dépend de la dose, c'est-à-dire que les concentrations de métaux dans les feuilles sont linéaires par rapport à celles des métaux dans les sols (Bondada et al., 2004).

1.5.2. Absorption racinaire

Les métaux lourds et/ou métalloïdes sont des éléments chimiques dont la masse atomique est supérieure à 5 g/cm³. Des concentrations élevées de métaux lourds dans les sols entraînent des signes de toxicité qui entravent le développement des plantes et altèrent, d'autre part, les processus biochimiques et physiologiques. La plupart des espèces végétales utilisent divers mécanismes intra et extracellulaires pour tolérer et/ou détoxifier les métaux afin de minimiser les impacts négatifs sur leur croissance. Cependant, les plantes disposent de deux mécanismes importants pour tolérer les fortes concentrations de métaux dans les sols : l'évitement et la tolérance aux métaux (Dalvi & Bhalerao, 2013).

- L'évitement : c'est un système qui empêche les plantes d'absorber les métaux du sol dans les cellules racinaires. La première barrière extracellulaire est constituée par les symbioses mycorhiziennes, la complexation des exsudats racinaires, l'exsudation des acides organiques et la modification du pH du sol (Dalvi & Bhalerao, 2013).

a) L'association symbiotique mycorhizienne : La symbiose entre les racines végétales et les champignons permet de bloquer l'absorption des métaux dans les sols contaminés par chélation ou adsorption, constituant ainsi une barrière d'exclusion des métaux grâce aux ectomycorhizes et aux endomycorhizes (Janoušková et al., 2006; Jentschke & Godbold, 2000; S. Shah et al., 2019).

b) Les exudats racinaires : Plusieurs substances sont présentes dans les racines des plantes, telles que les diffusats (acides aminés et organiques), les excrétions (dioxyde de carbone, bicarbonates et protons) et les sécrétions (sidérophores, composés allélopathiques et mucilages). Ces substances permettent aux plantes de survivre dans des conditions de forte contamination métallique des sols. Ainsi, des métalligands se forment autour des racines des plantes, rendant les métaux lourds indisponibles et augmentant par conséquent le pH du sol (Agarwal et al., 2024; B. Wu et al., 2024; Yonghui Xing et al., 2022).

- La tolérance : Ce second mécanisme de défense des plantes contre la contamination métallique élevée des sols permet d'immobiliser, d'accumuler et de stocker les métaux lourds par l'intermédiaire des acides aminés, des protéines et des peptides. Il s'agit d'un mécanisme intracellulaire qui réduit la toxicité des métaux lourds, pouvant se réaliser par deux phénomènes : l'exposition des plantes aux métaux lourds et la pénétration d'ions métalliques dans la plante.

a) Fixation des métaux par la paroi cellulaire : Les hydrates de carbone extracellulaires et les sites pectiques présents dans la paroi cellulaire immobilisent les métaux et entravent leur absorption dans le cytosol. La liaison entre les acides polygalacturoniques et les métaux lourds empêche également leur absorption par les plantes (Meychik et al., 2014; Wei et al., 2021).

b) Pompage actif d'efflux à la membrane plasmique : Ce mécanisme consiste à diminuer la teneur intracellulaire en métal à des niveaux subtoxiques. Il est utilisé par les plantes pour atténuer la toxicité métallique et est le plus fréquemment observé chez les bactéries et les cellules animales (Kaplan et al., 2019; Thakur et al., 2016).

c) Les acides organiques : Lorsque des acides organiques sont présents dans les cellules, ils réduisent la toxicité des métaux par complexation, ce qui diminue leur disponibilité pour les plantes. De plus, ils interviennent comme intermédiaires métaboliques dans la production d'ATP à partir des hydrates de carbone pour maintenir l'équilibre ionique. Cependant, de grandes quantités d'acides organiques utilisées dans des sols très riches en métaux parviennent à détoxifier ces sols, tandis que de faibles quantités, dominées par une forte concentration de métaux, entraînent un stress des plantes lié à la toxicité métallique (Osmolovskaya et al., 2018; Wuana et al., 2010).

d) L'inactivation des métaux toxiques : Les phytochélatines et les métallothionéines présentes dans le cytoplasme jouent un rôle important dans la tolérance à la toxicité des métaux. Elles sont transférées dans le cytosol par le tonoplaste vers la vacuole, où elles ne présentent pas de toxicité métallique (Cobbett, 2000; Monferrán & Wunderlin, 2013; Rao, 2014).

De ce fait, en fonction de l'évitement et de la tolérance à la toxicité métallique, on peut identifier quatre catégories de plantes : les plantes indicatrices, exclueuses, accumulatrices et hyperaccumulatrices (Dahmani-Muller et al., 2000; Dalvi & Bhalerao, 2013).

- ✓ Les plantes indicatrices : Ce sont des plantes qui absorbent presque tous les métaux présents dans les sols et, par conséquent, présentent des signes de toxicité métallique. Plus les concentrations de métaux augmentent, moins la biomasse aérienne devient importante.

- ✓ Les plantes exclueuses : Ce sont des plantes qui empêchent les métaux toxiques d'être absorbés dans les parties aériennes. De ce fait, les plantes exclueuses présentent des concentrations élevées de métaux dans les parties racinaires par rapport aux parties aériennes et sont généralement utilisées pour stabiliser les sols fortement contaminés par les métaux.

- ✓ Les plantes accumulatrices : Ces plantes absorbent des concentrations élevées de métaux et les transfèrent vers leurs parties aériennes, reflétant ainsi les teneurs présentes dans les sols, sans montrer de symptômes de toxicité métallique.

- ✓ Les plantes hyperaccumulatrices : Ces plantes ont la capacité d'absorber des métaux à des niveaux jusqu'à 100 fois supérieurs à ceux des plantes non contaminées. La classification des plantes hyperaccumulatrices doit respecter quatre critères : le facteur de transfert (biomasse aérienne/racine) est supérieur à 1 ; le coefficient d'extraction (quantité de métaux dans les biomasses aériennes par rapport à la concentration totale de métaux lourds dans les sols) est supérieur à 1 ; la concentration de métaux lourds est supérieure de 10 à 500 fois aux concentrations retrouvées dans les plantes non contaminées ;

enfin, l’absorption des métaux dans les parties aériennes dépasse le seuil de toxicité métallique de 1 % du poids sec de la biomasse aérienne des plantes.

1.6. Techniques de production actuelles en agriculture urbaine dans les pays du Sud

L'agriculture urbaine peut être définie comme toute activité agricole réalisée au sein de la ville. Elle comprend notamment des espaces tels que les toits, les balcons, les cours, les terrains vacants et les jardins communautaires. Cette forme d'agriculture vise à fournir des produits frais aux habitants des villes, réduisant ainsi les coûts de transport des aliments et améliorant la sécurité alimentaire locale (Brock & Foeken, 2006; Shackleton et al., 2009).

L'agriculture périurbaine désigne toute forme d'agriculture qui se déroule dans les zones périphériques des villes, où l'espace cultivé est généralement plus vaste que dans les zones urbaines. Cette agriculture tend à se développer davantage que l'agriculture urbaine et inclut des fermes, des jardins maraîchers, des élevages et d'autres formes d'exploitation agricole (Shackleton et al., 2009).

1.6.1. Pratiques de production agricole courantes

Plus de 30 % de la population citadine mondiale pratique cette forme d'agriculture en milieu urbain. L'agriculture urbaine représente une opportunité intéressante pour ces citadins dans les pays en développement, où le taux de pauvreté est en augmentation, car elle accroît la capacité d'approvisionnement alimentaire, contribue à l'économie locale et facilite l'intégration sociale entre les populations (Orsini et al., 2013). La culture des légumes à Lubumbashi est principalement dominée par le chou de Chine et l'amarante (*Brassica chinensis* et *Amaranthus vulgaris*), cultivés entre avril et août (Mutshail, 2014; Nsele et al., 2022).

Les systèmes de production en agriculture urbaine sont diversifiés et peuvent être classés en quatre catégories, notamment :

- ✓ Les jardins communautaires ou familiaux : ceux-ci sont généralement installés en milieu urbain, sur des terrains temporairement inoccupés ou destinés à des activités agricoles. Les jardins familiaux sont utilisés pour cultiver divers légumes, allant des légumes-feuilles aux légumes-tubercules, tels que les choux, les haricots, les oignons et les solanacées, dans les cours des maisons ou le long des routes (Orsini et al., 2013). Les semences locales, souvent achetées sur les marchés, sont les plus fréquemment utilisées dans ces jardins, et il est courant d'utiliser de la matière organique pour fertiliser les cultures. En milieu tropical, l'irrigation est effectuée manuellement entre deux et trois fois par jour, ce qui représente une tâche importante dans la production de légumes. De grandes quantités d'eau sont nécessaires pour la culture des légumes, avec un besoin de 400 à 800 L/m² pour la production de tomates et de 150 à 300 L/m² pour la production de légumes-feuilles, dont le cycle de culture est compris entre 30 et 40 jours (Tixier et de Bon 2006).

- ✓ Monocultures extensives pour la consommation domestique et le marché : ces jardins sont généralement situés à la périphérie des villes, et les cultures ne sont pas arrosées. Les engrais organiques et inorganiques sont rarement utilisés par les producteurs, mais les cultures cultivées sont des espèces locales adaptées aux milieux. L'exploitation se fait généralement sur de vastes surfaces Lemeilleur et al. (2003).
- ✓ Systèmes de culture itinérante : ce système, également connu sous le nom de culture sur brûlis, est souvent appliqué dans plusieurs zones tropicales occupées ou louées par le responsable des terres. Avec les mouvements migratoires des paysans vers les villes, ce système se déplace vers les alentours de celles-ci, entraînant ainsi l'agrandissement urbain. Les plantes cultivées cohabitent avec d'autres espèces, allant du maïs au manioc, en passant par les haricots, le riz, le gombo, les piments, etc. La fertilisation des sols est essentielle, utilisant des cendres issues de la combustion de la végétation comme engrais, car aucun apport externe d'engrais n'est adopté. Dans ce mode de production, les rendements sont très élevés au début, mais diminuent avec l'augmentation des temps de rotation des cultures (Gómez-Meda et al., 2017).
- ✓ Système de culture horticole intensive : ce système est généralement pratiqué sur de grandes surfaces, prenant de réelles formes d’exploitations agricoles, et se situe en milieu périurbain. Les productions sont orientées vers les marchés urbains. Cette forme d’agriculture utilise des semences améliorées, des amendements organiques et fertilise les sols pour maximiser la production de cultures diversifiées, allant des fruits aux légumes, etc. Les techniques agricoles utilisées dans ce système sont mécanisées, recourant ainsi à une irrigation adaptée et motorisée, ainsi qu’à l’utilisation de pesticides, qui peuvent présenter des risques élevés pour les consommateurs (Amoa at al. 2006 ; Midmore and Jansen 2003 ; Moustier et al. 2006).

1.6.2. Limites des pratiques agricoles et politiques publiques de l’agriculture urbaine dans les pays du Sud

Les réformes financières menées dans les pays en développement ne favorisent pas le développement des marchés financiers urbains et ruraux pour répondre aux divers problèmes des exploitations agricoles (Dumont et al., 2010). La coopération entre les acteurs agricoles pour mettre en place des stratégies visant à améliorer l'agriculture urbaine en termes de qualité et de quantité de production est limitée par de nombreux facteurs institutionnels et structurels (Guo et al., 2022). La contamination des sols par les métaux lourds, due à la proximité des zones minières et industrielles avec les jardins maraîchers, constitue une contrainte majeure pour l'agriculture urbaine à Lubumbashi. Cette contamination impacte directement la qualité des légumes produits dans ces jardins, diminue la productivité des cultures et représente donc un risque pour la santé des consommateurs. Avec près de 70 % de sa population vivant dans la pauvreté, la République démocratique du Congo est confrontée à de nombreux problèmes socio-économiques. Les agriculteurs urbains sont également désavantagés par l'absence de moyens pour obtenir des intrants agricoles de qualité, tels que des semences améliorées, des engrais minéraux et des pesticides, ce qui limite la production et l'amélioration de la qualité de leurs cultures. Par conséquent, ils se tournent vers des méthodes traditionnelles, moins efficaces et productives, entraînant des rendements faibles (Malone et al., 2023; Sasidharan & Dhillon, 2022).

En plus de la pollution des sols et des légumes cultivés dans les jardins maraîchers de Lubumbashi, l'utilisation d'eaux usées non traitées pour l'irrigation des cultures est devenue une pratique répandue en milieu urbain, faute d'eau propre pour l'agriculture (Balasha & Peša, 2023; Nsele et al., 2022). Toutefois, cette pratique constitue une menace pour la santé, car elle peut contaminer les légumes par les métaux présents dans ces eaux usées d'une part, et par des microorganismes pathogènes d'autre part. L'agriculture urbaine à Lubumbashi repose en grande partie sur une main-d'œuvre manuelle, avec un recours de moins en moins important à la mécanisation, ce qui entraîne de faibles rendements qui entravent le développement de cette agriculture. Les terres ne peuvent pas exprimer pleinement leur potentiel, limitant ainsi l'utilisation des petites superficies. Le problème majeur à Lubumbashi est la forte urbanisation anarchique, car les terres utilisées pour l'agriculture urbaine ne sont souvent pas sécurisées et présentent un risque élevé de réaffectation pour des projets immobiliers ou industriels. Ces luttes foncières découragent les investissements à long terme dans l'agriculture urbaine et entraînent l'exclusion des agriculteurs urbains. Ainsi, l'agriculture urbaine est privée de financement par les institutions financières, et les producteurs urbains doivent recourir à des financements informels pour leurs activités agricoles (Kesonga Nsele et al., 2023).

La gestion de l'agriculture urbaine en RD Congo, en particulier à Lubumbashi, est assurée par le service National d'Horticulture Urbaine et Périurbaine (SENAHUP), qui est représenté par les services locaux, y compris la ville et les communes (B. Kitiakak, 2014). Malgré l'existence de ces structures censées réguler l'agriculture urbaine, elles ne fonctionnent pas dans la ville de Lubumbashi auprès des agriculteurs urbains, faute de financement par le gouvernement central et provincial. Les agriculteurs urbains ne disposent pas d'un cadre clair pour régir l'utilisation des terres, la gestion des ressources en eau ou la sécurité alimentaire, limitant ainsi leur capacité à se développer et à innover. Par conséquent, il y a un déficit d'actions visant à octroyer des subventions, des formations ou un soutien technique aux agriculteurs urbains. Ces pratiques conduisent à un faible développement de nouvelles techniques agricoles, qui entravent l'accès aux marchés, et maintiennent les agriculteurs dans une économie de subsistance. On remarque un manque de coordination entre les différents acteurs impliqués dans l'agriculture urbaine, y compris les autorités locales, les ONG et les agriculteurs urbains, dans toutes ces structures (Mutshail, 2014). Les agriculteurs développent d'autres techniques pour pallier les faiblesses organisationnelles et structurelles, telles que l'entraide, une forme d'association informelle des producteurs qui rassemblent leurs forces pour répondre aux besoins de la communauté (Ajates, 2020; Kesonga et al., 2023). Cependant, l'agriculture urbaine de Lubumbashi présente des difficultés comme le manque d'accès à la terre, l'insécurité foncière, la pollution des sols et le manque de soutien institutionnel, ce qui limite la capacité des agriculteurs à optimiser l'impact socio-économique de leurs activités (Useni Sikuzani, et al., 2017).

1.6.3. Impact socio-économique de l'agriculture urbaine de Lubumbashi

L'agriculture urbaine de Lubumbashi (RD Congo) joue un rôle crucial dans la vie des citadins, même si elle est négligée. Ces fonctions prennent différentes formes, concernant les dimensions économiques, sociales et environnementales. Elle contribue aussi à la sécurité alimentaire dans la ville de Lubumbashi. De nombreuses familles peuvent produire des légumes frais (légumes feuilles et tubercules), ce qui réduit leur dépendance envers les pays voisins où les prix sont de plus en plus instables. Les ménages urbains peuvent bénéficier d'une alimentation plus stable et plus nutritive, en particulier pour les populations à faible revenu qui pourraient être exposées à la malnutrition en raison d'un manque d'aliments en quantité et en qualité. L'agriculture urbaine au monde crée des emplois supplémentaires entre 100 et 200 millions d'agriculteurs urbains (Orsini et al., 2013). A Lubumbashi, elle constitue également une source importante de revenus pour les habitants de Lubumbashi sans emploi et à faible revenu. Elle génère des emplois dans la production, la transformation, ainsi que dans la commercialisation des produits agricoles (Nsele, 2024; Tshomba et al., 2015). En plus de créer des emplois directs, l'agriculture urbaine apporte un soutien aux entreprises locales de vente d'intrants agricoles, de transport et de vente au détail, ce qui stimule l'économie locale. L'agriculture urbaine contribue à réduire la pauvreté des agriculteurs urbains en permettant aux ménages à faible revenu de produire leur propre nourriture et de vendre les excédents de récolte. Dans un contexte où les possibilités d'emploi formel peuvent être limitées, elle offre une alternative économique. En fournissant un filet de sécurité économique et en diversifiant les sources de revenus pour les familles urbaines (F. Adams et al., 2024; Tambwe, 2015).

Elle contribue aussi à l'intégration sociale en engageant des populations défavorisées dans des activités agricoles productives. L'autonomisation des femmes par l'agriculture urbaine renforce leur position dans les ménages et les communautés, améliorant ainsi l'équité de genre et le bien-être familial (Shengo Lutandula & Mpanga, 2022; Tambwe, 2015). L'agriculture urbaine contribue à protéger les collectivités urbaines contre les chocs économiques, les crises alimentaires et les effets du changement climatique. La production locale d'aliments permet aux agriculteurs urbains de diminuer leur dépendance vis-à-vis de longues et fragiles chaînes d'approvisionnement (Langemeyer et al., 2021; Yan et al., 2022). L'approvisionnement alimentaire local et diversifié permet donc à la ville de Lubumbashi de mieux faire face aux crises économiques et environnementales.

1.6.4. Les techniques récentes en agriculture urbaine

En ce 21è siècle, la majorité de la population mondiale vit dans les villes, ce qui a entrainé une expansion de celles-ci dans le monde remplaçant les terres agricoles, le couvert végétal par les bâtis (Useni et al., 2022). Cette migration de la population des milieux ruraux vers les centres urbains a conduit à l'augmentation des productions agricoles tant des produits vivriers ou maraîchers. La population de Lubumbashi étant estimée à environ 6 millions d'habitants, ce qui ramène une forte pression sur les ressources tant animales, végétales, qu'environnementales (Mpinda et al., 2016). Suite au niveau de vie de la population de Lubumbashi qui est précaire vivant avec moins de 1,25 USD/jour, cette dernière s'adonne de plus en plus aux activités champêtres pouvant couvrir certains besoins de première nécessité dans leurs ménages ; ainsi la majorité trouve refuge dans le maraichage (Nsele et al., 2022).

L'agriculture urbaine de Lubumbashi présente des avantages tels que la création d'emplois et la réduction de la dépendance à l'égard des produits alimentaires en provenance des pays voisins (De Nys-Ketels, 2022). Cependant, cette forme d'agriculture est confrontée à divers problèmes, notamment la limitation de l'espace, la contamination des sols et des sources d'approvisionnement en eau, ainsi que le manque de soutien financier (Hardman & Larkham, 2014; Lwasa et al., 2014; Ngoran, 2015). Après l'arrivée du projet HUP, 2000, vingt types de légumes sont cultivés dans les jardins maraîchers de Lubumbashi notamment, le *Brassica chinensis, Brassica carinata*, etc…(Mutshail, 2014). A ce jour, le chou de chine et l'amarante, constituent les deux légumes

les plus cultivés dans les jardins maraîchers de Lubumbashi. Suite à cette limitation en espace cette agriculture se pratique principalement sur sol sur une superficie moyenne de 3,7 ares par producteur (Kesonga et al., 2023). L'agriculture urbaine de Lubumbashi, satisfait principalement les besoins locaux en produits frais notamment les légumes qui constituent les produits de première nécessité de moins en moins importés des pays voisins.

Face aux divers problèmes que connait l'agriculture urbaine dans toutes ses formes, les études de la FAO démontrent que d'autres formes d'agriculture peuvent être développées dans les milieux où l'accès à l'espace, à l'eau pose problème. Ainsi, les micro-jardins peuvent être développés dans les villes afin de pallier aux problèmes énumérer ci-dessus, afin de garantir un approvisionnement de légumes de qualité, une réduction de la pauvreté des personnes défavorisées. Ce modèle des micro-jardins a été testé pour la première fois en Afrique, principalement au Sénégal, mélangeant les techniques de productions hors sol, sur substrat inertes. Il est atypique pour les personnes à revenus faibles la mise en place des micro-jardins, qui est moins couteuses et fait recours aux matériaux locaux dans sa construction (https://www.fao.org/fileadmin/templates/agphome/documents/microgardens/manuals/Manuel_micro-jardins.pdf).

Les micro-jardins présentent d’énormes avantages dans l’agriculture urbaine, cependant aucun modèle de ce type n’existe jusqu’à ce jour dans la ville de Lubumbashi, d’où la mise en place de ce modèle parviendrait à autonomiser les populations à faibles revenus vivant en dessous du seuil de pauvreté.

L'agriculture urbaine est une pratique ancienne qui a été largement répandue en Asie pour répondre aux besoins alimentaires des citadins (Drechsel, P., Quansah, C., and Penning De Vries, 1999; Smit et al., 1996). Elle est considérée comme un élément du développement durable en milieu urbain, contribuant à la gestion de l'environnement en traitant les eaux usées et les déchets urbains, tout en favorisant la cohésion au sein des communautés urbaines. L'agriculture urbaine englobe toutes les formes d'agriculture visant à cultiver des produits alimentaires, qu'ils soient d'origine végétale ou animale, à l'intérieur ou aux alentours des zones urbaines (Lwasa et al., 2014; Puppim de Oliveira & Ahmed, 2021; Zezza & Tasciotti, 2010).

Parmi les différentes formes d'agriculture urbaine dans le monde, on peut citer les jardins communautaires, qui consistent en des espaces agricoles partagés où les habitants cultivent collectivement des denrées alimentaires en raison de la limitation de l'espace disponible (Egli et al., 2016; Krikser et al., 2016; X. Mai et al., 2023; Malone et al., 2023; Zheng et al., 2023) (Figure 1-1).

Figure 1-1. Illustrations des jardins communautaires (Lucke et al., 2019)

Les jardins situés en hauteur, communément appelés jardins sur les toits, désignent des espaces de culture aménagés sur les toits de maisons, de gratte-ciels ou d'établissements hôteliers. Leur vocation est de produire une variété de denrées alimentaires, notamment des légumes, des fruits, ainsi que des arbres et des arbustes

(Appolloni et al., 2021; Keynoush & Daneshyar, 2022; WINNICKA-JASŁOWSKA & TKACZUK, 2022) (Figure 1-2).

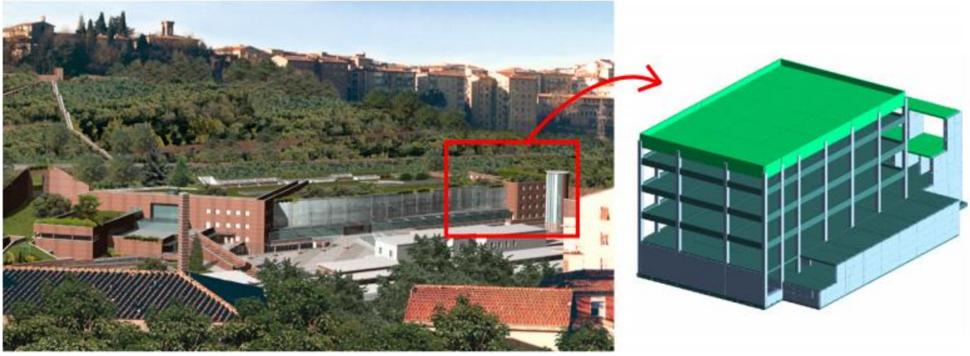


Figure 1-2. Agriculture urbaine sur toits des maisons (Matta & De Stefano, 2009).

L'agriculture verticale peut-être définie comme étant une modalité de l'agriculture urbaine qui implique la culture de végétaux dans des environnements contrôlés, avec une fertilisation précise adaptée aux besoins de chaque plante. Dans ce type de culture, les plantes peuvent être cultivées sur plusieurs niveaux ou étages (Benke & Tomkins, 2017; Butturini & Marcelis, 2019; de Carbonnel et al., 2022; Jeff, 2016; Van et al., 2022) (Figure 1-3).

Figure 1-3. Fermes verticales urbaines (Benke & Tomkins, 2017; M. H. M. Saad et al., 2021).

L'aquaponie et l'hydroponie, techniques de culture qui intègrent l'élevage de poissons, sont considérées comme des méthodes de production hors-sol en raison de leur complexité, de leurs rendements élevés et de la qualité des produits alimentaires procurés (Baganz et al., 2022; Goddek et al., 2019; Mchunu et al., 2017; Palm et al., 2018). Dans les pays en développement, les jardins communautaires sont de plus en plus répandus en tant que formes d'agriculture urbaine prédominantes (Figure 1-4).

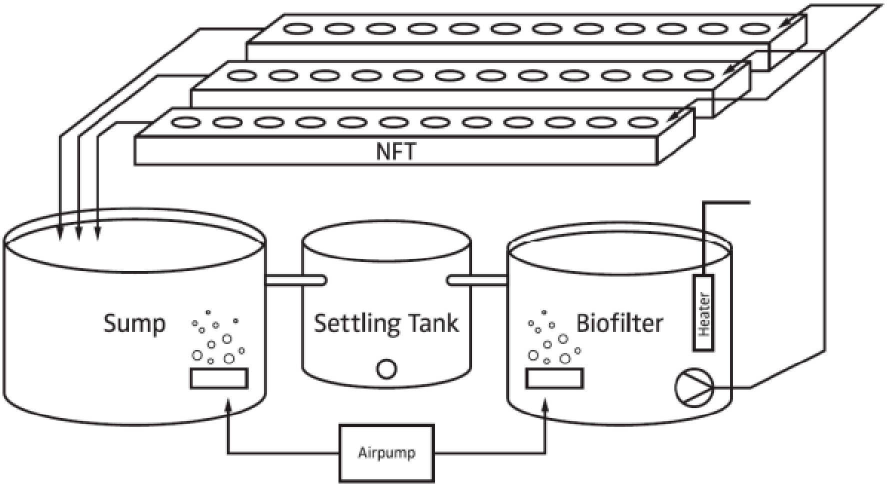


Figure 1-4. Fermes verticales urbaines (Goddek et al., 2016).

1.7. Techniques innovantes en agriculture urbaine

Les cultures hors-sols regroupent des méthodes de production végétale qui ne dépendent pas du sol, notamment l'hydroponie, l'aquaponie et l'aéroponie. Le terme "hydroponie" provient des mots grecs "hydro" (eau) et "ponos" (travail). En résumé, l'hydroponie désigne les techniques de culture des plantes dans un environnement aquatique enrichi en solutions nutritives inorganiques, utilisant un substrat inerte tel que la laine de roche, la tourbe, la perlite, ou d'autres matériaux non liés au sol. Cette méthode est particulièrement utile pour résoudre divers problèmes environnementaux, tels que le manque de terres cultivables, la pollution des sols et les conditions climatiques défavorables.

1.7.1. Historique des cultures hydroponiques

Souvent perçues comme une technique novatrice en agriculture, les cultures hors-sols remontent à plus de 4000 ans, à l'époque des Égyptiens, qui cultivaient des plantes dans des conteneurs (Ceasar et al., 2022; Gericke, 1938; Lea-Cox et al., 1999; Naville, 1894). Cette pratique était née du besoin de cultiver des plantes avant de les transférer depuis leur environnement naturel vers les palais royaux, où elles étaient maintenues en culture dans ces récipients. La curiosité scientifique a poussé les chercheurs à étudier les besoins nutritionnels des plantes, un domaine qui a été initié par des chercheurs français et allemands au 19e siècle, puis approfondi par des chercheurs américains au milieu du 20e siècle (Gericke, 1938; Naville, 1894).

Vers 1946, des chercheurs britanniques ont confirmé la possibilité de cultiver des plantes sur des substrats siliceux en leur fournissant des solutions nutritives pour répondre à leurs besoins en éléments nutritifs essentiels à leur croissance et développement (Hershey, 1994). Dans les années 1970, les chercheurs ont réussi à élaborer des solutions nutritives complètes afin d'optimiser la croissance des plantes, en garantissant ainsi des rendements élevés (Cooper, 1975; Verwer1978). Par ailleurs, les chercheurs ont également cherché à comprendre le phénomène de réduction des maladies observé dans les cultures hors-sol par rapport aux cultures en pleine terre. C'est ainsi que Gericke, en 1937, a inventé le terme "hydroponie" pour décrire une technique de culture des plantes dans un milieu aquatique, sans l'utilisation de substrats solides comme le sol. Après la Seconde Guerre mondiale, l'hydroponie moderne a commencé à se perfectionner en tant que technique de culture hors-sol durable, offrant des rendements accrus, une réduction des risques de maladies et une main-d'œuvre moins coûteuse (Gericke, 1938).

1.7.2. Types des systèmes de production hors-sol

Plusieurs systèmes de production hors-sol ont été répertoriés et catégorisés en deux groupes notamment les systèmes à circuit ouvert et les systèmes à circuit fermé. Parmi les systèmes à circuit ouvert, on distingue l'aéroponie, dans laquelle les solutions nutritives ne sont pas réutilisées dans les systèmes (jetées dans l'environnement) ; mais parmi les systèmes à circuit fermé, dans lequel les solutions nutritives sont réutilisées on peut citer l'hydroponie (technique de flottaison profonde (DFT), technique du film nutritif (NFT), nouvelle technique de système de culture (NGST) et l'aquaponie, qui utilisent les solutions nutritives différemment pour la croissance des plantes (Birlanga et al., 2022; Hussain et al., 2014; Martinez-Mate et al., 2018) (Figure 1-5).

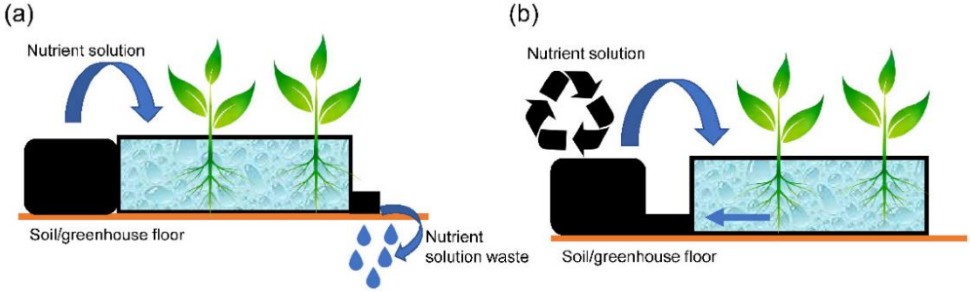


Figure 1-5. Système de culture en circuit ouvert (a) et système de culture en circuit fermé (b) des cultures hors-sol (Birlanga et al., 2022).

De toutes les techniques, la DFT (Technique de flottaison profonde) ou bien système de radeaux flottant de culture en eau profonde (DWC), offre plusieurs avantages dont, l’utilisation efficiente d’éléments nutritifs et de l’eau, la réduction des parasites et des maladies, le contrôle précis des paramètres physico-chimiques des solutions nutritives, l’amélioration de la qualité des cultures enfin une augmentation des rendements des cultures (Gruda, 2012; Resh, 2013). Cette technique permet une réutilisation des eaux par un système de’ recyclage, et réduit les pertes par évaporation et drainages des solutions nutritives. Elle permet aussi aux plantes d’avoir accès en permanence aux nutriments afin d’assurer leur meilleure croissance (Gruda, 2012; Resh, 2013) (Figure 1-6).

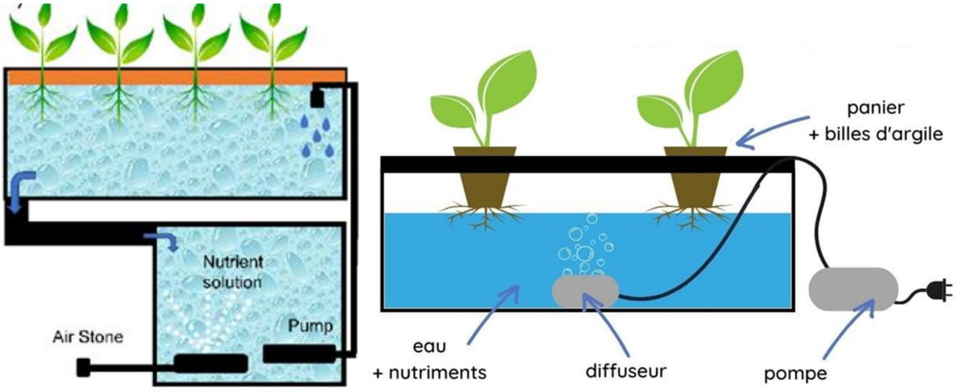


Figure 1-6. Illustration du système de culture DWC (Birlanga et al., 2022).

1.7.3. Les variantes de l’hydroponie

La "bioponie" est une méthode qui utilise des engrais organiques liquides dérivés de déchets animaux ou de résidus végétaux, en remplacement des engrais chimiques de synthèse. Elle englobe donc l’aquaponie qui est un cas particulier où l’animal vivant fait partie du système de production. Cette approche organique représente une alternative à l'hydroponie moderne, car elle permet non seulement la production de légumes en utilisant des matières organiques, mais aussi la décontamination de l'environnement en valorisant ces déchets organiques qui, autrement, constitueraient une source de pollution (Gartmann et al., 2023; Szekely et al., 2023; Szekely & Jijakli, 2022; Wongkiew et al., 2021).

D'autre part, l'aquaponie est une technique qui combine la culture de plantes avec l'élevage de poissons dans un système en circuit fermé. L'un des avantages majeurs de cette technique est la réduction des intrants, car elle exploite les déjections des poissons comme source d’éléments nutritifs pour la croissance des plantes (Baganz et al., 2022; Goddek et al., 2018; Palm et al., 2018; Wongkiew et al., 2021).

L'aéroponie, dérivée des termes grecs "Aéro" signifiant air et "Ponos" veut-dire travail, est une technique de culture des plantes qui les suspend dans l'air ou dans un brouillard nutritif, sans utiliser de sol ou de milieu de culture combiné. Cette technique repose sur le principe que les plantes en suspension ne sont pas en contact avec le sol, mais sont exposées à un courant d'air enrichi en solutions nutritives (Buckseth et al., 2016; Gopinath et al., 2017; Lakhiar et al., 2018).

1.7.4. Techniques de fabrication des solutions nutritives

La solution nutritive, quant à elle, est un liquide composé d'eau et de sels minéraux essentiels à la croissance des végétaux. Elle est utilisée dans le but d'optimiser d’une part la quantité et d’autre part la qualité des cultures produites (Z. F. R. Ahmed et al., 2021; Sapkota et al., 2019; Tessema et al., 2017; Van Delden et al., 2020).

Les cultures hydroponiques connaissent une demande croissante en termes d'expansion de leurs superficies de production afin de satisfaire les besoins alimentaires des populations. Cette technique présente de nombreux avantages en termes de production alimentaire, tant en quantité et qualité, mais aussi pour la gestion de l'espace agricole disponible (Hemathilake, D.M.K.S; Gunathilake, 2021; Rufí-Salís et al., 2020; Stegelmeier et al., 2022; Treftz & Omaye, 2016; Velazquez-Gonzalez et al., 2022). Les engrais chimiques utilisés en agriculture conventionnelle existent depuis le début du XX^{ème} siècle (Basit et al., 2022; Russel & Williams, 1977; Souri, 2016). Les premiers engrais chimiques de synthèse sont apparus grâce aux travaux de deux chercheurs, Fritz Haber et Carl Bosch, qui ont mis en place une méthode d'extraction de l'azote atmosphérique et de l'hydrogène. Cette méthode a permis la production d'ammoniac nitrate et d'urée, des composés utilisés pour fertiliser les sols et soutenir les divers processus physiologiques des plantes (Davis et al., 2021; Russel & Williams, 1977; Sheridan, 2018). En plus des engrais azotés, des engrais phosphatés et potassiques sont également apparus, contribuant à augmenter les rendements des cultures et à améliorer la fertilité des sols appauvris en nutriments. Cependant, ces innovations ont également engendré d'importants problèmes environnementaux (Vonk et al., 2022).

Aujourd'hui, les éléments nutritifs se répartissent en deux catégories : les éléments majeurs et les oligo-éléments, également appelés éléments mineurs. Les éléments majeurs jouent un rôle crucial dans les processus physiologiques des plantes, et leur déficience peut perturber le cycle de vie des plantes (Dissanayake & Chandrajith, 2009; Lian et al., 2018; Nadarajan & Sukumaran, 2021; Seleiman et al., 2021). Tous les éléments essentiels proviennent du milieu de croissance des plantes, à l'exception du carbone et de l'oxygène, qui sont obtenus à partir de l'atmosphère. La qualité de la solution nutritive dépend de plusieurs facteurs, notamment la conductivité électrique, la pression osmotique et le pH de la solution. Le pH mesure l'acidité et/ou l'alcalinité d'un milieu donné, et peut impacter directement la disponibilité d’éléments nutritifs dans les milieux affectant la santé des plantes, comme le montre le diagramme de Troug (Hartemink & Barrow, 2023; Neina, 2019; Oshunsanya, 2019; Penn & Camberato, 2019). Modifier le pH d'une solution nutritive peut influencer la biodisponibilité, la composition et la spéciation des éléments nutritifs, créant différentes formes chimiques et physiques, telles que des complexes solubles, des chélates, des paires d'ions solides et gazeux, des ions libres et différents états d'oxydation (Z. L. He et al., 1999; Roem & Berendse, 2000; L. Yang et al., 2021; Zhalnina et al., 2015; J. Zhao et al., 2011).

Pour les cultures hydroponiques, la croissance des plantes est étroitement liée à la qualité de la solution nutritive, qui doit contenir des ions sous des formes assimilables par les plantes (He et al., 1999; Zhalnina et al., 2015). De plus, le pH de la solution nutritive influe sur la forme de l'azote, par exemple, le NH3 forme des complexes uniquement en présence d'ions H+, tandis que le NH4+ prédomine lorsque le pH de la solution nutritive se situe entre 2 et 7. Au-delà de 7, la concentration de NH4+ diminue dans la solution nutritive (Soti et al., 2015). En outre, des études menées par (St Martin, 2014) ont révélé que le taux de nitrification de la solution nutritive dans un biofiltre était influencé par les variations du pH de la solution nutritive, et que l'absorption des microéléments par les plantes devenait difficile lorsque le pH dépassait 8,5.

1.7.4.1. Phosphore

La croissance des plantes nécessite également du phosphore dans leurs tissus. Cependant, le phosphore peut se présenter sous différentes formes, notamment le PO_4^{3-}, le HPO_4^{2-}, et le H_2PO_4-. Parmi ces formes, seules les deux dernières, le HPO_4^{2-} et le H_2PO_{4-}, sont assimilables par les plantes. L'absorption du phosphore par les plantes est étroitement liée au pH de la solution nutritive. Le phosphore est le plus disponible pour les plantes lorsque le pH de la solution nutritive se situe autour de 5. Cependant, lorsque le pH devient très acide ou alcalin, la disponibilité du phosphore diminue (Dyśko et al., 2008). De manière similaire à l'azote, la forme sous laquelle le phosphore se présente dépend du pH de la solution nutritive.

1.7.4.2. Potassium

Le potassium présente une plage de tolérance très étendue en ce qui concerne le pH de la solution nutritive, allant de 2 à 9. Cependant, il peut former des liaisons avec des ions tels que SO_4 et Cl- à de faibles concentrations de K+ (Wei Li et al., 2018 ; L. Drummond, 1994). La disponibilité du potassium peut être entravée par la présence d'autres ions dans la solution nutritive, formant ainsi des composés moins solubles. Un exemple clair de ce phénomène concerne l'anion HCO3 présent dans l'eau, qui peut se transformer en CO3 lorsque le pH de la solution nutritive atteint 8,3. En revanche, l'ion H_2CO_3 peut être en équilibre lorsque le pH de la solution est inférieur à 3,5.

1.7.4.3. Oligoéléments

Certains éléments tels que le cuivre, le bore, le zinc, le manganèse et le fer sont des éléments nutritifs dont les plantes ont besoin en de petites quantités pour répondre à leurs besoins physiologiques. Cependant, leur présence dans une solution nutritive en quantités excessives peut devenir toxique pour les plantes. La disponibilité de ces oligo- éléments est également dépendante du pH de la solution nutritive, et ces microéléments deviennent indisponibles lorsque le pH atteint 6,5 (Anugoolprasert et al., 2012; Resh, 2013; Schwartz et al., 2019).

1.7.4.4. Eléctroconductivité

La croissance, le développement et la production des plantes sont étroitement liés à la concentration en sels minéraux présents dans la solution nutritive (Shrestha et al., 2020). Cette concentration totale en sels minéraux dans la solution nutritive est dite pression osmotique (PO), qui dépend de la quantité de sels dissoutes dans la solution nutritive. La pression osmotique peut être mesurée grâce à l'électroconductivité (EC) de la solution nutritive du milieu. En effet, l'EC est un indicateur fiable de la présence des ions dans une solution nutritive (Ende et al., 1975; Nemali & Van Iersel, 2004).

La variation de la conductivité électrique est étroitement liée à l'introduction d'ions tels que le Mg2+, le Na+, le OH-, le K+, le H+, le NO_3-, le S_2O4-, le Ca_2+ et le Cl- dans la solution nutritive. Cependant, l'ajout de microéléments tels que le Cuivre (Cu), le Manganèse (Mn), le Zinc (Zn), le Fer (Fe), le Molybdène (Mo), le Nickel (Ni) et le Bore (B) à la solution nutritive n'a généralement pas d'impact significatif sur la modification de la conductivité électrique de la solution nutritive (Dorais et al., 2001; Maggio et al., 2007; Sambo et al., 2019; Tavakkoli et al., 2011). Pour garantir la meilleure absorption des nutriments et une bonne croissance des plantes, l'électroconductivité optimale pour la production des plantes de laitue varie entre 1200 et 2000 µS/cm (microsiemens par centimètre). Cette gamme d'électroconductivité permet d'atteindre une absorption optimale d'éléments nutritifs tout en minimisant le risque de carence ou toxicité des minéraux vis-à-vis des plantes (Gruda, 2012; Jensen, 2019; Resh, 2013) (Figure 1-7).

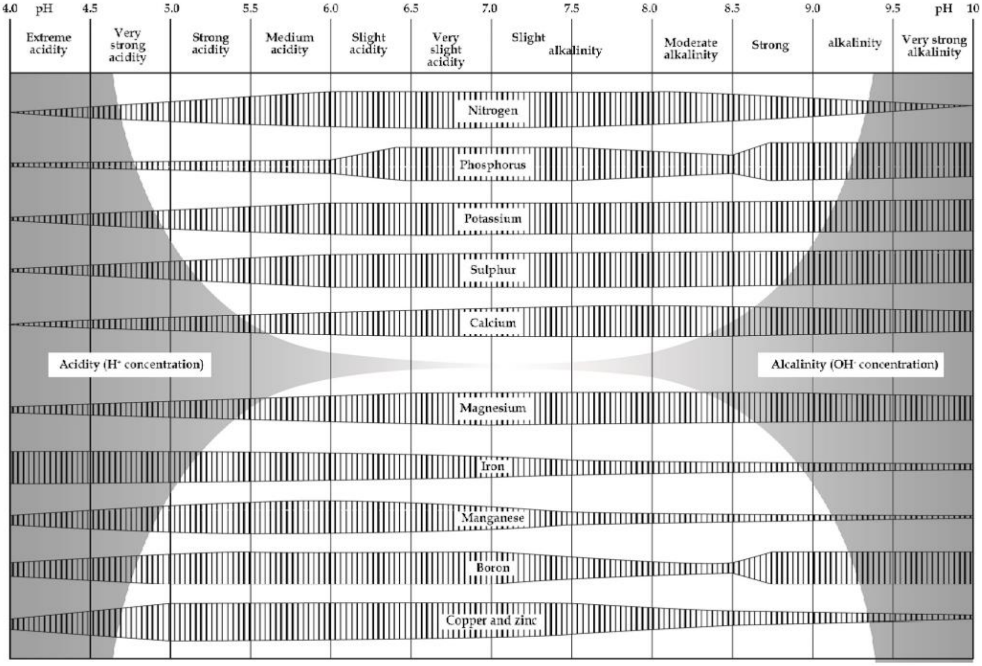


Figure 1-7. Absorption d'éléments nutritifs par les plantes selon le diagramme de Troug, en fonction du pH du milieu (Asao, 2012).

1.8. Principes de production des solutions nutritives organiques : Bioponie

Dans les pays en développement, les engrais minéraux deviennent de plus en plus chers et souvent inaccessibles pour les producteurs agricoles (Chianu et al., 2012). C'est pourquoi, il est impérieux que les chercheurs proposent des solutions durables et moins coûteuses pour répondre aux problèmes auxquels le monde est confronté, notamment l'épuisement et la cherté des engrais minéraux de synthèse. Le recours aux matières organiques d'origine animale et végétale pour la fabrication des engrais organiques pourrait constituer une alternative pour la production des engrais organiques dans l'agriculture durable. Toutefois, la composition des solutions nutritives peut varier d'une matière à l'autre, selon la provenance et les types des matières organiques de base. Cependant, les plantes n'ont pas les mêmes besoins nutritifs, les plantes à feuilles exigent plus des nutriments riches en azote contrairement aux plantes fruitières qui demandent des solutions nutritives plus riches en potassium, phosphore et calcium (Resh, 2013). Dans la fabrication des solutions nutritives, le rapport C/N constitue un indicateur pour déterminer la performance et le temps de la matière organique à minéraliser pour l'azote et le phosphore. Ainsi, les matières organiques d’origine animale sont plus riches en N, P et K que les matières organiques d’origine végétale (Green, 2015; Shaji et al., 2021).

Parmi, les fumiers d’origine animale, ceux provenant d’animaux herbivores tel que les bovins, la chèvre, le mouton et le cheval, présentent des concentrations en NPK faibles plus que les fumiers d’animaux nourrit avec les aliments très concentrés en protéines, vitamines etc…, donnent des fumiers très enrichis en NPK (Eghball et al., 2002) et par conséquent leur rapport C/N est plus faible et ces matières organiques ont tendance à vite minéraliser que les fumiers issues d’animaux herbivores. Dans la production des solutions nutritives organiques, plusieurs méthodes existent notamment le Thé compost, décomposition microbienne aérobique, décomposition microbienne anaérobique et la décomposition anaérobie-aérobie des matières organiques (Figure 1-8).

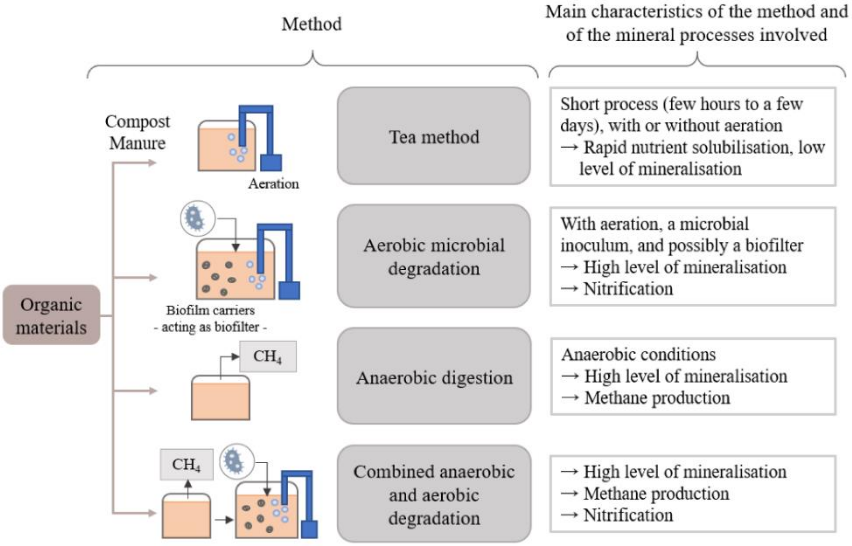


Figure 1-8. Illustration des différentes techniques de fabrication des solutions nutritives organiques (Szekely & Jijakli, 2022).

La technique de décomposition anaérobique-aérobique consiste à décomposer des matières organiques par les microorganismes en l’absence d’oxygène. Ce processus produit du biogaz (un mélange de méthane et de dioxyde de carbone) et un digestat (un résidu semi-solide ou liquide riche en éléments nutritifs), puis s’ensuit la minéralisation aérobique où les microorganismes en présence de l’oxygène transforment les matières organiques en composés sous forme minérale simples tel que le dioxyde de carbone, l'eau et les sels minéraux, rendant les nutriments disponibles pour la croissance des plantes. Les fumures de volailles contiennent des teneurs très élevées d’azote organique et la digestion anaérobique permet de transformer l’ammoniac en nitrate. La minéralisation aérobique par contre permet de diminuer le rapport N-NH4^{+}/N-NO3^{-}, de l’ordre de 75%, diminue les teneurs en métaux lourds qui restent fixés dans les digestats solides pendant la minéralisation des matières organiques et rend les solutions nutritives inodores (Parravicini et al., 2008; Mingchuan et al., 2011).

En culture bioponique des légumes, il a été démontré que la minéralisation des digestats anaérobiques pendant 14 jours en conditions aérobiques avaient produits des rendements élevés de culture de *Brassica rapa* avec un pH de la solution nutritive maintenu entre 5,5-6,0 (Bergstrand et al., 2020). La nitrification des matières organiques n'étant pas totalement complète, les digestats nitrifiés contiennent d'importantes quantités deNH4+ et NO_2^-. Toutefois, le NO_2^-, est réputé d'être toxique pour les plantes quelques soient sa quantité (OKE, 1969). Cependant les digestats peuvent être tamisés pour les séparer des grosses particules ceci permettrait d'accélérer une minéralisation des digestats qui produirait des nutriments proches des solutions nutritives chimiques de référence (Pelayo Lind et al., 2021). Pendant le processus de minéralisation, on assiste à une acidification des solutions nutritives, ainsi une forte accumulation de $NO2^-$ peut entrainer une diminution d'oxygène dissout dans les solutions nutritives et une augmentation de $NH4^+$/NH3 conduisant ainsi une diminution des bactéries oxydant les nitrites par rapport aux bactéries oxydant l'ammonium (Prinčič et al., 1998; Mingchuan Zhang et al., 2011).

Chapitre 2

Objectifs de la thèse

2.1. Défaillances à corriger dans la détermination de la contamination métallique des légumes et des sols

Les émissions de polluants, provenant principalement de l'industrie et de l'utilisation des éléments chimiques, constituent l'un des phénomènes majeurs du XXIe siècle qui entraînent la pollution de l'environnement (Kristiansson et al., 2021). De nombreuses études montrent que ces polluants endommagent de plus en plus les écosystèmes, causant des mortalités chez certains organismes et présentant des risques élevés pour la santé humaine (Banza et al., 2009). Les recherches contemporaines des experts portent donc sur les méthodes de dépollution de l'environnement, incluant les caractéristiques physico-chimiques, la mobilité, la biodisponibilité, la toxicité et les effets des polluants sur les organismes vivants (Mununga et al., 2023; Shutcha et al., 2015; Silbergeld et al., 2015). Plus de 130 000 publications scientifiques ont associé l'industrie aux différentes formes de contamination métallique présentes dans l'environnement, mettant en lumière l'amélioration des méthodes d'évaluation de cette contamination pour réduire les risques (Kristiansson et al., 2021).

De nombreuses études ont évalué la pollution de l'environnement en fonction de ses différentes composantes, y compris le sol, l'eau et les plantes (Mpundu et al., 2014; Kilela et al., 2022; Kilela et al., 2022; Shutcha et al., 2015). Bien que peu d'études mettent en relation cette contamination et ses composantes environnementales, cela permet d'optimiser les techniques d'évaluation pour réduire les risques sanitaires qu'elle engendre. L'analyse séparant les différentes composantes de l'environnement et l'absence d'application des divers indices de pollution constituent un obstacle à la compréhension de ce phénomène (Mununga et al., 2023 ; F. Cabrera et al., 1999 ; Q.W. Yang et al., 2006).

Les effets de l'exploitation minière sur l'environnement sont évidents, mais les méthodes de détermination de la contamination et/ou de la pollution, basées sur les teneurs totales en métaux comparées aux seuils de toxicité canadiens ou français, sont moins efficaces. Ces études montrent que l'évaluation de la pollution en fonction des concentrations totales ne permet pas de véritablement expliquer la dangerosité de cette pollution sur l'environnement, bien que ces recherches soient précurseurs. Des études similaires menées à Lubumbashi révèlent que les méthodes de décontamination par amendements sont moins adaptées aux producteurs de légumes, car des quantités importantes d'amendements organocalcaires sont nécessaires pour immobiliser les métaux dans les sols (Mpundu et al., 2014; Shutcha et al., 2015).

Cette étude se concentre sur le principe de la production de légumes non contaminés par les métaux lourds dans un environnement caractérisé par des activités minières intenses. Les recherches sur les métaux lourds se multiplient, mettant en péril la qualité de la chaîne alimentaire en raison de leur toxicité pour l'environnement. En premier lieu, l'identification et la cartographie des jardins maraîchers de Lubumbashi posent des problèmes. Par conséquent, le niveau réel de pollution/contamination n'est pas connu pour la majorité de ces jardins maraîchers urbains. Concernant les sols des jardins contaminés, la revue bibliographique indique que les sols affectés par les métaux lourds peuvent être dépollués grâce à l'application d'amendements organocalcaires, qui permettent d'immobiliser les métaux et, par conséquent, de réduire leur biodisponibilité pour les plantes (Franco-Uría et al., 2009; Muimba-Kankolongo et al., 2021a).

C'est pourquoi, pour parvenir à produire des légumes non contaminés par les métaux dans un environnement fortement impacté par les activités minières, plusieurs concepts doivent être étudiés séparément et de manière séquentielle pour pallier ce problème.

2.2. Cadre conceptuel et stratégique de la thèse

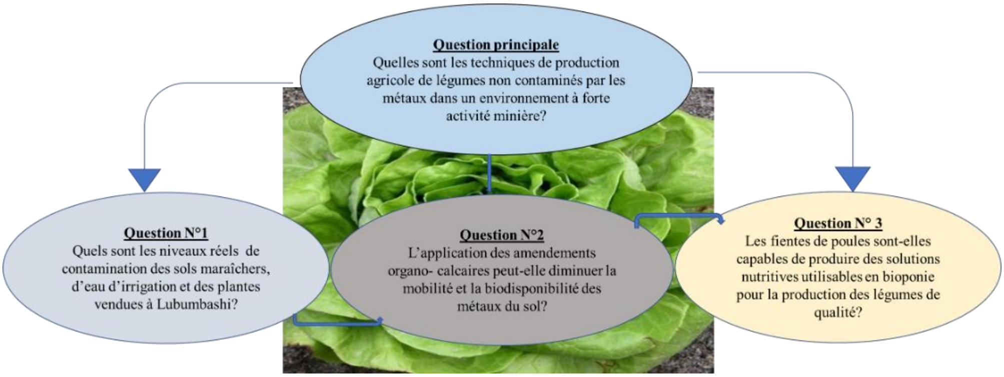


Figure 2-1. Cadre conceptuel de la thèse

Pour traiter cette thématique, trois orientations ont été choisies : l'évaluation, la dépollution et la bioponie (Figure 2-1).

Dans un premier temps, une cartographie de tous les jardins maraîchers ayant au moins cinq producteurs de légumes et des marchés comptant au moins cinq vendeurs de légumes a été réalisée, dans le but d'établir une cartographie qui n'existait pas dans la ville de Lubumbashi. Jusqu'en 2019, peu d'informations étaient disponibles sur la localisation des lieux de production et de vente des légumes dans toute la ville, bien que quelques jardins aient fait l'objet de plusieurs études. Par la suite, des prélèvements de sols et d'eaux ont été effectués dans les jardins maraîchers identifiés afin de déterminer la qualité de ces sols agricoles et de l'eau d'irrigation des cultures. Enfin, nous avons choisi quatre légumes parmi les plus consommés dans la ville de Lubumbashi pour évaluer leur qualité sanitaire en vue de la consommation humaine. Ainsi, dresser un état des lieux sur la contamination des jardins maraîchers et des légumes constitue une démarche susceptible de nous aider à résoudre les problèmes tant décriés par les populations riveraines. La première question phare que nous nous sommes posés est complétée par les sous-questions suivantes :

Question phare 1 :

Quels sont les niveaux réels de contamination des sols des jardins maraîchers, des eaux d'irrigation et des légumes vendus dans la ville de Lubumbashi ?

Sous-questions :

- ✓ La ville de Lubumbashi possède-t-elle une cartographie des jardins maraîchers et des marchés où les légumes sont produits et vendus ?
- ✓ Quels sont les jardins maraîchers urbains dont les sols, les eaux d'irrigation et les plantes ne sont pas contaminés par les métaux lourds de manière précise ?

Nous avons produit trois types de cartographie : une carte des 40 jardins maraîchers urbains et périurbains, une autre carte identifiant tous les marchés où les légumes sont vendus, et enfin une carte des sources d'eau d'irrigation des cultures. Par la suite, cette question s'est concentrée sur les analyses chimiques des sols, des eaux et des légumes, avec lesquelles divers indices ont été utilisés pour déterminer le niveau de contamination, d'enrichissement et de pollution des sols en les comparant aux différents seuils de toxicité (Chapitre 3).

La seconde question et ses sous-questions sont détaillées ci-dessous :

Question phare 2 : L'application d'amendements organo-calcaires peut-elle diminuer la mobilité et la biodisponibilité des métaux dans le sol ?

Sous-questions :

- ✓ Quelle quantité d'amendements organiques et calcaires est capable de réduire la mobilité et la biodisponibilité des métaux dans le sol ?
- ✓ Existe-t-il des matières organiques plus efficaces pour immobiliser les métaux dans les sols et diminuer leur transfert vers les plantes ?
- ✓ Quelles cultures peuvent tolérer de fortes concentrations de métaux lourds ?

Pour réduire la mobilité et la biodisponibilité des métaux lourds dans les sols, de fortes quantités d'amendements organiques sont proposées (225 t/ha de matières organiques et 10 t/ha de chaux agricole), ce qui pose un problème de faisabilité pour cette technique. En ce qui concerne les types de matières organiques, les auteurs soulignent que les fientes de volailles sont celles qui libèrent rapidement les composés organiques capables d'immobiliser les métaux dans les sols, contrairement aux autres types de matières qui mettent plus de temps à se décomposer et, par conséquent, libèrent lentement les acides organiques. Pour ce qui est des cultures, la littérature indique que les espèces de la famille des Brassicacées sont réputées pour leur capacité d'accumulation. Cependant, nous avons choisi quatre légumes les plus cultivés et consommés dans la ville de Lubumbashi afin de déterminer la qualité sanitaire de ces légumes (Chapitre 4).

Question phare 3 : Les fientes de poules sont-elles capables de produire des solutions nutritives utilisables en bioponie pour la production des légumes de qualité ?

Sous-questions :

- ✓ Quelle quantité de fientes de poules permet de produire des légumes en quantité et en qualité ?
- ✓ Quelle concentration d'azote total favorise l'augmentation des rendements des cultures ?

Deux essais ont été mis en place, au cours desquels nous avons déterminé différentes concentrations en matières sèches de fientes de poules afin de comparer les rendements des cultures. D'autre part, les teneurs en TAN (azote ammoniacal total) ont été testées pour la culture des légumes afin de déterminer la concentration idéale susceptible d'augmenter les rendements. Dans les deux essais, les paramètres tels que l'azote, le phosphore, le potassium, l'électroconductivité, le pH et les éléments traces métalliques ont été déterminés et comparés entre les différents traitements appliqués (Chapitre 5).

Le chapitre 6 présente une discussion générale, mettant en exergue les forces et les faiblesses des méthodes utilisées pour atteindre les objectifs fixés dans ce travail. Enfin, le chapitre 7 synthétise les résultats obtenus dans cette thèse et propose quelques pistes pour la poursuite de ces recherches futures.

Chapitre 3 :

Assessment of Heavy Metal Pollution of Agricultural Soil, Irrigation Water, and Vegetables in and Nearby the Cupriferous City of Lubumbashi, (Democratic Republic of the Congo).

Les techniques d'évaluation de la contamination présentées dans ce chapitre sont adaptées de : Mununga K.F.; Raulier P.; Colinet G.; Ngoy S.M.; Mpundu M.M.; Jijakli M.H., 2023. Assessment of Heavy Metal Pollution of Agricultural Soil, Irrigation Water, and Vegetables in and Nearby the Cupriferous City of Lubumbashi, (Democratic Republic of the Congo). *Agronomy **2023**, 13(2), 357;* **https://doi.org/10.3390/agronomy13020357**.

Abstract: Lubumbashi (DR Congo)—the capital of copper mining has been considered as one of the richest mining regions of the world for more than a decade. These riches have brought along multiple mining companies responsible for soil, river water and vegetable pollution, as in many African cities. The aim of the present study was to quantify and evaluate the pollution levels and the potential sources of soil, irrigation water and vegetable contamination by the metals As, Cd, Cr, Cu, Pb, Co and Zn in the urban gardens of Lubumbashi (DR Congo). The contamination, pollution and enrichment levels of the gardens were determined based on different indices in order to rank the soils. The results show that soils, waters and vegetables present contamination levels that represent a serious concern for human health. All soils presented contamination indices ranging from low (72% of the soils) to very high (3.4% of the soils) metal (copper, lead, zinc) contamination. The Cu and Cd contents varied between 1355 mg/kg et 236 mg/kg, much higher than the World Health Organisation (WHO) thresholds (100 mg/kg for Cu and 2 mg/kg for Cd). Moreover, the water used for crop and garden irrigation presented high Pb (57% of the waters), Fe (52%), Cu (19%) and Cd (10%) contamination levels, above the Association Française de Normalisation (AFNOR U4441) toxicity thresholds (2 mg/kg for Cu; 0.1 mg/kg for Fe and 0.01 mg/kg for Pb) for crop irrigation. Finally, the vegetables produced in these gardens and sold in the local markets had very high metal content (47% contained Cu; 100% contained copper and cobalt) above the WHO standard (10 mg/kg for Cu, 2 mg/kg for Cd and 1 mg/kg for Co) for human consumption. In the face of these issues, it would be preferable to consider cheaper, more sustainable techniques that reduce soil-to-plant metal transfer.

Keywords: spatial variability; pollution indices; market gardens; Lubumbashi

3.1. Introduction

Lubumbashi, the “capital of copper “located in the southeast of the Democratic Republic of the Congo, has been considered as one of the richest mining regions of the world for more than a decade. In recent years, the Haut-Katanga province and more particularly the city of Lubumbashi have witnessed the expansion of the mining industry and the subsequent construction of numerous ore extraction plants. Today, numerous studies show a link between human activities (e.g., mining activities, landfills) and environmental contamination, especially soil, water and plant contamination (Dheri et al., 2007; Fahmy et al., 2018; Kaninga et al., 2020; Y. C. Lin et al., 2018). In Lubumbashi, these companies are the source of the contamination of agricultural and household soils, market garden products and river waters (Mpundu et al., 2017; Mpundu et al., 2014). The extraction processes of these mining activities especially metalworking and pyrometallurgy have contributed to soil and water contamination from atmospheric emissions and mining effluents, in contrast to the sites located a distance aways from the pollution cone (S. Khalid et al., 2018; Mlangeni et al., 2022; Vongdala et al., 2019). These phenomena are the source of diverse health and environmental issues (Atibu et al., 2016; S. Khalid et al., 2018; Mlangeni et al., 2022). In Pakistan, for example, similar situations to those noted in Lubumbashi have been observed (Michel Mpundu Mubemba et al., 2014; Osaili et al., 2016). The authors showed that applying mining effluents as organic amendments was the main cause of soil contamination in market gardens. Furthermore, the studies by (M.M. Mubemba et al., 2013; Osaili et al., 2016; Sultana et al., 2019) showed that the vegetables produced in the market gardens and sold in Lubumbashi markets presented high levels of trace metal elements (TMEs) above the WHO toxicity threshold. Southeast of Casablanca (Morocco), crop irrigation with industrial effluents containing high loads of heavy metals was found to contaminate five vegetable crops with As, Cd, Cr and Cu (A. S. Abuzaid et al., 2022; Matech et al., 2014; N. Ullah et al., 2022). Similar situations have been observed in Lubumbashi, where market gardeners use water with high loads of metals to water their crops. This represents a notable hazard for vegetable consumption and human health, as very high metal contents have been detected in water and vegetables alike (Massadeh & Al-Massaedh, 2018; Muimba-Kankolongo et al., 2021b; Vongdala et al., 2019). Another issue under strong criticism in the city of de Lubumbashi is the growing number of poorly managed \landfills, which are potential sources of soil and urban market garden contamination. Very high heavy metal concentrations have been found in the soils of former landfills (Ciumasu et al., 2012; Gola et al., 2016; Mpinda et al., 2016).

Similar situations to Lubumbashi have been observed in the agricultural region of Sri Lanka where heavy metal-rich effluents (Cd, Fe, Pb) discharged into watercourses have caused chronic renal disease in around 5000 people aged 5 to 50. This disease was due to the consumption of rice irrigated with water containing a strong load of cadmium. Heavy metal contamination levels ten times as high as the toxicity threshold were found in the inhabitants' urine (Bandara et al., 2008; Ilechukwu et al., 2021; Scheen & Giet, 2012; Q. Song & Li, 2015). In the same vein, the studies by (Kayembe-Kitenge et al., 2019; Q. Song & Li, 2015) carried out in Lubumbashi showed that contamination of pregnant women by uranium and manganese led to the birth of three babies presenting malformations known as holoprosencephaly. Very high levels of uranium and manganese were found in their mothers' urine and blood. Therefore, the people currently living in and nearby Lubumbashi are going through a health crisis.

In Lubumbashi, (Mutshail, 2014) showed that vegetables mainly come from 23 market gardens and are sold in four main markets. This study stands out from other research in that the authors succeeded in analysing the different components (soils, water, plants) of market gardens separately. However, a study encompassing all three environmental components within the global setting of Lubumbashi urban market gardens has never been undertaken. In this context, the aim of the present study was to quantify and evaluate the pollution levels and the potential sources of soil, irrigation water and vegetable contamination by the metals As, Cd, Cr, Cu, Pb, Co and Zn in the urban gardens of Lubumbashi (DR Congo). The first step consisted of identifying market gardens and markets. Then, the concentrations in MTEs Al, As, Cd, Co, Cu, Fe, Pb and Zn in the vegetables were analysed to determine the safety of urban market products in Lubumbashi.

3.2. Materials and Methods

3.2.1. Identification of the Market Gardens and Urban Markets of Lubumbashi

Based on FAO mapping carried out in 2008 and on a separate survey led within the framework of this study, 40 market gardens and 33 Lubumbashi markets meeting our selection criteria were identified (Appendix A.1). The survey carried out within the framework of the present study led to the identification of 17 new market gardens and 29 new markets in addition to those listed by the FAO (Mutshail, 2014). Among the market gardens, 29 were selected following the criteria of the present study, as detailed below. These market gardens are the main local vegetable suppliers of the city of Lubumbashi (Appendix A.2). The criteria for including market gardens in our list were that they should be farmed by at least five market gardeners and that at least three of the most commonly cultivated vegetables in Lubumbashi be grown, among *Brassica chinensis, Amaranthus vulgaris, Brassica oleracea var. capitata, Lycopersicum esculentum Mill, Allium porrum, Lactuca sativa, Allium cepa., Brassica carinata, Abelmoschus esculentus, Daucus carota, Beta vulgaris, Petroselinum crispum, Solanum melongena* L., *Apium graveolens var. dulce, Beta vulgaris subsp. vulgaris, Brassica oleracea var. botrytis, Solanum tuberosum, Raphanus sativus, Hibiscus sabdariffa* L, and *Cucumis sativus* L. Moreover, the markets had to be (i) located in Lubumbashi, (ii) run by at least five vegetables sellers, and (iii) selling local vegetables within the market gardens of Lubumbashi (Matech et al., 2014).

For further analysis of the market gardens on the list, the geographic coordinates were recorded using a global positioning system (GPS; Garmin Montana 680t) and treated with the mapping software program ArcGIS 10.5 registered in the geographic coordinate system (GCS-WGS 84). The same procedures were applied to map the Lubumbashi markets where these vegetables are sold.

3.2.2. Sampling Methods

3.2.2.1. Soils

Soil samples were collected from five different points of each urban and peri-urban market garden, at 0–20 cm depth, and each batch of five samples was pooled to form a composite sample kept and analysed in the laboratory. Each composite sample was open-air-dried for 25 days, and then ground in a porcelain mortar and sieved to 2 mm.

3.2.2.2. Water samples

Only 21 out of the 40 identified market gardens had an easily accessible water collection point for determining the safety of the waters used to irrigate the crops. Five 100-mL water samples were collected and pooled to form a composite sample. The samples were collected between March and May 2019, a favourable period for market gardening in Lubumbashi. They were kept in a refrigerator at 4 °C for seven days and then sent to the laboratory of the Office de Contrôle du Congo (OCC/DR Congo).

3.2.2.3. Vegetables

The study was focused on four vegetables *Brassica chinensis*, *Brassica carinata*, *Amaranthus vulgaris* and *Spinacia oleacera* for the following reasons: The vegetables had to be identified among the 20 species grown in the city of Lubumbashi within the framework of the different projects run in its market gardening sector (HUP, 2000). They had to be grown intensively in Lubumbashi (Michel Mpundu Mubemba et al., 2014). Previous studies had to show that they presented a risk of MTE contamination (M. M. M. Mubemba et al., 2017; Michel Mpundu Mubemba et al., 2014). To collect the vegetable samples, we first questioned the sellers to determine where the vegetables had been produced, and only those from Lubumbashi market gardens were purchased. Then, composite samples were formed, the vegetables were washed under city tap water to remove dust particles, and oven-dried at 105 °C for 24 h. The dried samples were ground in a porcelain mortar, and 100 g of powder were kept for analysis.

3.2.2.4. Metal quantification in the soils, waters and vegetables was conducted.

The chemical analyses aimed at determining the total heavy metal (Al, As, Cd, Co, Cu, Fe, Pb and Zn) concentrations in the soils of Lubumbashi market gardens were carried out using a portable X-ray fluorescence spectrophotometer (XRF, Olympus Delta Classic Plus, model DCC-4000) calibrated with stainless steel alloy 316 (Muimba-Kankolongo et al., 2021b). The soil exchangeable Cu, Co and Pb concentrations were determined by $CaCl_2$ 0.01 M extraction, and the heavy metal concentrations were determined by ICP OES atomic absorption spectrometry (AAS, VARIAN 220, Agilent Technologies, Santa Clara, CA, USA) (Houba, Lexmond, et al., 1996).

The heavy metal (Al, As, Cd, Co, Cu, Fe, Pb and Zn) contents of the water samples were determined by inductively coupled plasma mass spectrometry (ICP-MS) (Hoet et al., 2013; Mpinda et al., 2016). The heavy metal (Cu, Co, Cd and Pb) contents of the vegetables were determined by acid mineralisation with HNO_3+$HClO_3$, and measurements were made by flame atomic absorption spectroscopy (AAS, VARIAN 220, Agilent Technologies, Santa Clara, CA, USA) (S. F. Adams & Miller, 1998).

3.2.3. Indices of Agricultural Soil Contamination and Pollution

3.2.3.1. Contamination Factor

The contamination factor can be calculated as the ratio of the measured concentration of a given metal in the soil to the background value of that metal expressed as a percentage (Al, As, Cd, Co, Cu, Fe, Pb and Zn) (Cabrera et al., 1999; Q. W. Yang et al., 2006) (Appendix A.3):

$$\boldsymbol{CFi} = \frac{\text{Cmetal(sample)}}{\text{Cmetal(background)}}$$

Consequently, CF_i designates the contamination factor of metal I, and four classes can be established: CF < 1 = low contamination, 1 ≤ CF < 3 = moderate contamination, 3 ≤ CF < 6 = high contamination, and CF ≥ 6 = very high contamination. The soil geochemical background values used in the present study are those of the soils of the city of Lubumbashi (Bogaert et al., 2018).

3.2.3.2. Soil Pollution Load Index

The pollution load index (PLI) is used to determine the level of the pollution load of all MTEs (Al, As, Cd, Co, Cu, Fe, Pb and Zn) on the sampled sites. It is the geometric mean of the contamination factors, according to the following formula (Tomlinson et al., 1980):

$$\boldsymbol{PLI} = \sqrt[n]{CFix\ CFjx\ \ldots\ldots CFn}$$

where n is the number of MTEs in the present study. A $PLI \leq 1$ highlights MTE pollution loads close to the background geological concentration, a $PLI = 1$ highlights a low pollution level, while a $PLI > 1$ highlights significant soil pollution (Appendix A.5).

3.2.3.3. Enrichment Factor

The enrichment factor is the ratio of the concentration of a given metal (Cx) to the concentration of the reference element (CFe) in a given sample divided by the ratio of the elemental concentration of a given element to the concentration of the reference element in the Earth’s crust (Chester & Stoner, 1974). However, for this study, the EF was evaluated to determine the level of contamination and the influence of anthropogenic activities in the urban vegetable garden soils of Lubumbashi. Thus, the geochemical normalization of the data for heavy metals has a conservative Al (Sinex and Wendy), Al (P.W.Balls et al., 1997; Rubio et al., 2000)], Fe (Abu-rukah & Rosen, 2011; Karim et al., 2015; Mucha et al., 2003). To determine the enrichment factor of vegetable soils, Fe was used as a conservative tracer to distinguish natural from anthropogenic components:

$$\boldsymbol{EF} = \frac{\mathrm{Cx/CFe(Sample)}}{\mathrm{Cx/CFe(Control)}}$$

Thus, seven classes were distinguished depending on the enrichment factor, namely EF < 1, 1 ≤ EF < 3, 3 ≤ EF < 5, 5 ≤ EF < 10, 10 ≤ EF < 25, 25 ≤ EF < 50, and EF > 50, meaning that MTE enrichment can be null, low, moderate, moderately high, high, very high and exceptionally high, respectively (Marrugo-Negrete et al., 2016) (Appendix A.4).

3.2.4. Habit Description

The market gardens of Lubumbashi are diverse in their particular characteristics. However, we have classified them according to their likely sources of heavy metal contamination. Thus, the market gardens with a water supply source were put into one group (Table 3-1).

Table 3-1. Description of the ecosystem at study locations near pollution sources.

Market Gardens	Habitat Description	Sources of Pollution in Gardens
Bongonga	Mining Effluents/Dump sites	Kafubu River Middle
Chem-chem	Mining effluents/MET-rich subsoil	Kafubu River Downstream
Daipen/Kashamata	Mining Effluents/Dumpsites	Kafubu River Upstream
Kabetsha	Mining Effluents/Dumpsites	Tshamilemba River
Kafubu	Mining effluents/MET-rich subsoil	Kafubu River Middle
Kalebuka	Mining Effluents/Dumpsites	Kafubu River Middle
Kalubwe	Mining Effluents/Dumpsites	Middle Lubumbashi River
Kalulako	Mining effluents/MET-rich subsoil	Kafubu River Downstream
Kamakanga	Metal-rich subsoil	Kafubu River Middle
Kamatete	TME-rich subsoil/Mining effluents	Lubumbashi River Upstream
Kamilombe	Mining effluents/MET-rich subsoil	Kafubu River Downstream
Kamisepe	Mining Effluents	Lubumbashi River Upstream
Kantumbwi	Mining Effluents/Dumpsites	Middle Lubumbashi River
Kasungami	Mining Effluents/Dumpsites	Kafubu River Upstream
Katemo	Effluents miniers/Metal-rich subsoil	Kafubu River Downstream
Kawama	MTE-rich subsoil	Kafubu River Downstream
Kikula/Sambwa	Metal-rich subsoil	Kafubu River Downstream
Kilobelobe	Mining Effluents/Dumpsites	Kafubu River Middle
Kinsense	Mining Effluents/Dumpsites	Tshamilemba River
Kinsevere (Manoah)	Effluents miniers/Metal-rich subsoil	Kiswishi River
Kitanda	TME-rich subsoil/Mining effluents	Kafubu River Downstream
Luano	MTE-rich subsoil	Luano River
Maendeleo	Dumpsites	Well

Mashimikila	Effluents/Metal-rich subsoil	Kafubu River Downstream
Mwenda	Metal-rich subsoil	Kafubu River Downstream
Penga-penga	Mining effluents/MET-rich subsoil	Régideso
Tingi-Tingi	Mining Effluents/Dumpsites	Tingitingi River
Tshamalale	Mining Effluents/Dumpsites	Lubumbashi River Upstream
Tshamilemba	Mining Effluents/Dumpsites	Tshamilemba River

3.2.5. Data Analyses

The data were analysed using Minitab 21.3.1.0 statistical software. The one-level analysis of variance was used to determine the significance levels of the different sources of soil contamination in the market gardens as well as the vegetables sold in the urban markets of Lubumbashi. The Tukey test at the 5% level was used to compare two means.

3.3. Results

3.3.1. Identification of the Market Gardens and Urban Markets of Lubumbashi

A total of 40 market gardens and 33 markets initially met our criteria. The survey carried out within the framework of the present study allowed us to identify 17 new market gardens and 29 new markets in addition to those selected by the FAO (Mpinda et al., 2022; Mutshail, 2014). The 29 markets with at least five local vegetable sellers selected within the framework of the present study were used to evaluate the safety of the vegetables sold and consumed by Lubumbashi people (Figure 3-1).

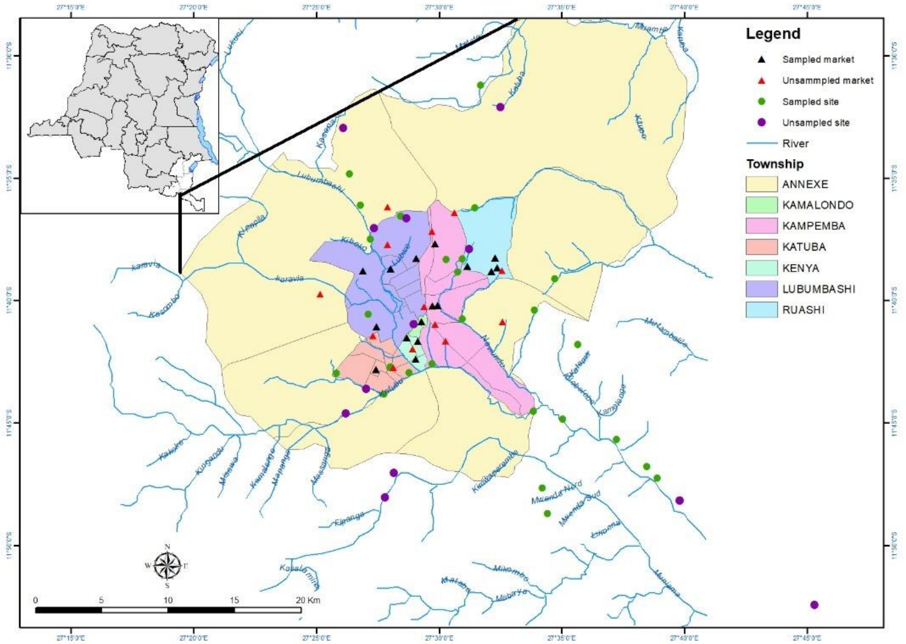


Figure 3-1. Map of the market gardens and urban markets of Lubumbashi (Mununga, K.F, 2022).

3.3.2. Characterisation of MTE-like Pollutants in Market Garden Soils, Waters and Vegetables

The one-way analyses of variance revealed that there was no significant difference between the different potential sources of contamination ($p>0.05$) and the levels of heavy metals in the soils. Laboratory analyses showed that around 80%, 21%, 17%, and 7% of the soils from the 29 selected market gardens were contaminated with copper, zinc, cadmium, and lead, respectively. The cobalt concentration was not measured due to a technical problem (Table 3-2).

Table 3-2. XRF determination of metals in 29 urban and peri-urban market gardens of Lubumbashi (mg/kg).

Contamination Source Categories	Fe	Cd	Cu	Pb	Cr	Zn
Kafubu River Middle	2.762 ± 0.94 ^{a}	47.2 ± 94.40 ^{a}	170.6 ± 104.66 ^{a}	9.6 ± 19.20 ^{a}	35.8 ± 31.68 ^{a}	118.4 ± 98.96 ^{a}
Kafubu River Downstream	3.092 ± 1.27 ^{a}	13.33 ± 20.88 ^{a}	293.82 ± 297.82 ^{a}	44.22 ± 67.18 ^{a}	31.44 ± 29.26 ^{a}	234.61 ± 254.27 ^{a}
Kafubu River Upstream	2.24 ± 0.33 ^{a}	0.00 ± 0.00 ^{a}	266.33 ± 165.59 ^{a}	68.00 ± 82.43 ^{a}	49.66 ± 5.24 ^{a}	169.00 ± 169.94 ^{a}
Tshamilemba River	2.78 ± 0.66 ^{a}	0.00 ± 0.00 ^{a}	144.66 ± 92.17 ^{a}	11.33 ± 16.03 ^{a}	32.00 ± 22.76 ^{a}	70.33 ± 46.58 ^{a}
Middle Lubumbashi River	3.69 ± 1.36 ^{a}	13.33 ± 18.86 ^{a}	359.33 ± 351.5 ^{a}	0.00 ± 0.00 ^{a}	51.00 ± 5.10 ^{a}	126.33 ± 123.83 ^{a}
Lubumbashi River Upstream	2.71 ± 0.69 ^{a}	0.00 ± 0.00 ^{a}	154.66 ± 74.02 ^{a}	8.66 ± 12.26 ^{a}	21.00 ± 29.70 ^{a}	81.66 ± 42.90 ^{a}
Effects of sources of contamination (*p*-value)	0.74	0.738	0.74	0.455	0.598	0.995

Contamination factors, enrichment factors and pollution indices of the soils based on the calculated soil contamination factors of Lubumbashi market gardens, we determined four MTE contamination classes, namely low contamination with iron, copper, lead and zinc (96.55%, 72.41%, 93.10% and 62.07% of the soils, respectively); moderate contamination with copper, lead and zinc (27.59%, 6.9% and 27.59% of the soils, respectively); high contamination with iron and zinc (3.45% and 6.9% of the soils, respectively); and very high contamination with zinc (3.45% of the soils). The enrichment factor revealed five enrichment classes, i.e., no enrichment (41.38%, 79.31% and 34.48% of the soils for copper, lead and zinc, respectively); low enrichment (48.28%, 13.79% and 37.93% of the soils for the same metals); moderate enrichment (3.45%, 3.45% and 13.79% of the soils); medium-high enrichment (6.9%, 3.45% and 10.34% of the soils); and high enrichment (3.45% of the soils, for zinc only).

Finally, the soil pollution index was calculated to determine the pollution levels of the soils of the market crops of the city of Lubumbashi. Two classes were established, namely unpolluted gardens (79.31%) and severely polluted gardens (20.69%), whatever the MTE. We considered soil contamination as any increase of components inducing a detectable negative effect on soil functioning (Table 3-3; Figures 3-2–3-4), while we considered soil pollution as an increase of components within a given environment that gradually becomes severe and deleterious and perturbs the functioning of soils up to their degradation (De Haan & Keuning, 1996).

Table 3-3. Contamination, enrichment, and pollution levels of the soils of 29 urban market gardens of Lubumbashi.

Market Gardens	Contamination Factor				Enrichment Factor			Soil Pollution Index (PLI)
	Fe	Cu	Pb	Zn	Cu	Pb	Zn	
Bongonga	0.45	0.13	0	0.17	0.29	0	0.37	0.21
Chem-Chem	0.55	2.97	2.69	8.17	5.4	4.87	14.82	2.45
Daipen/Kashamata	0.29	0.45	0.24	0.33	1.56	0.84	1.16	0.32
Kafubu	0.32	0.32	0	1.01	1.01	0	3.18	0.47
Kabetsha	0.3	0.25	0	0.23	0.84	0	0.79	0.26
Kalebuka	0.15	0.5	0	0.29	3.28	0	1.95	0.28
Kalubwe	0.67	1.87	0	1.67	2.78	0	2.49	1.28
Kalulako	0.25	0.52	0	0.47	2.11	0	1.9	0.4
Kamakanga	0.45	0.17	0	0.24	0.38	0	0.54	0.27
Kamatete	0.37	0.11	0	0.19	2.52	0	6.96	1.49
Kamilombe	0.57	1.44	0	3.98	1.81	0	1.61	0.36
Kamisepe	0.25	0.46	0	0.41	0.4	0	0.64	0.16
Kantumbwi	0.24	0.1	0	0.16	0.87	0	0.82	0.23
Kasungami	0.26	0.22	0	0.21	0.28	0	0.45	0.22
Katemo	0.44	0.12	0	0.19	2.32	0.84	2.58	0.85
Kawama	0.56	1.31	0.47	1.46	2.08	1.03	2.31	0.32
Kikula/Sambwa	0.21	0.44	0.22	0.49	1.51	1.16	3.15	0.77
Kilobelobe	0.5	0.76	0.58	1.58	1.19	0.83	1.51	0.55
Kinsense	0.5	0.59	0.41	0.76	0.26	0.22	0.48	1.84
Kinsevere (Manoah)	4.52	1.17	0.98	2.19	2.71	0.85	5.41	1.26
Kitanda	0.67	1.81	0.57	3.62	1.39	1.78	3.05	0.91
Luano	0.55	0.76	0.97	1.67	2.97	6.13	6.23	1.19
Maendeleo	0.36	1.08	2.24	2.27	6.89	2.67	3.85	0.96

Mashimikila	0.33	2.29	0.89	1.28	0.84	0	1.35	0.18
Mwenda	0.17	0.14	0	0.23	0.69	0	0.48	0.4
Pengapenga	0.58	0.4	0	0.28	1.01	0	1.06	0.36
Tingi-Tingi	0.35	0.35	0	0.37	0.3	0	0.51	0.2
Tshamalale	0.48	0.45	0.32	0.77	0.94	0.66	1.6	0.48
Tshamilemba	0.33	0.11	0	0.18	0.34	0	0.55	0.19

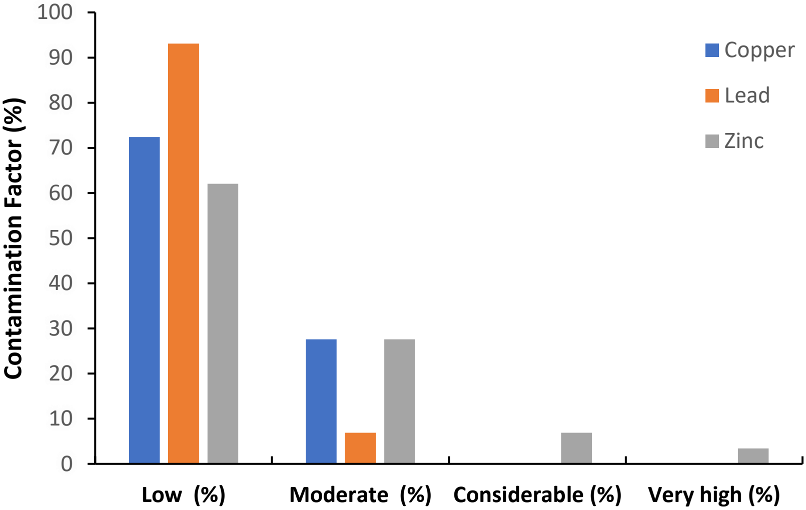


Figure 3-2. Distribution of the market gardens of Lubumbashi according to the contamination factors.

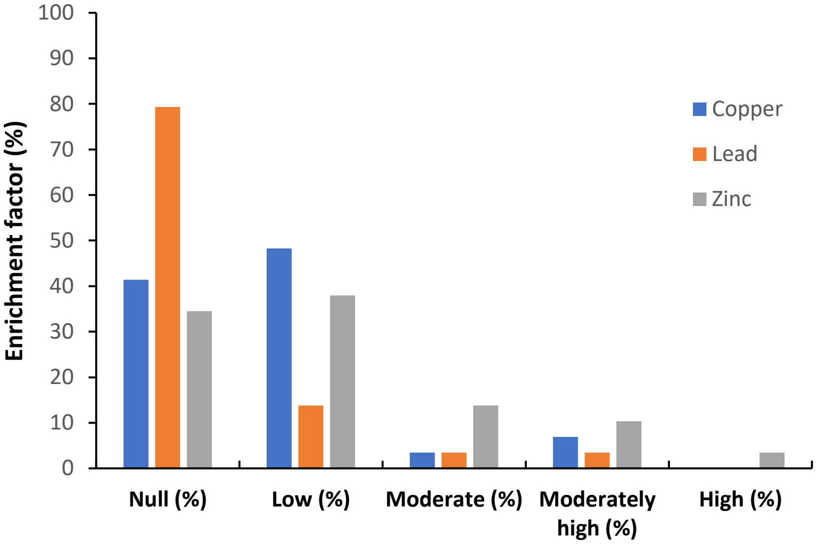


Figure 3-3. Distribution of the market gardens of Lubumbashi according to the enrichment factors.

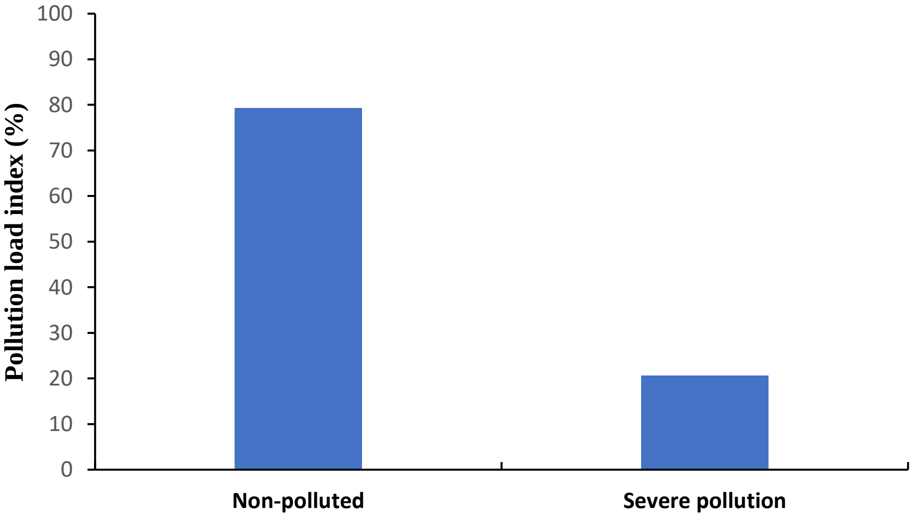


Figure 3-4. Distribution of the market gardens of Lubumbashi according to their pollution load index.

The maps show that among all the market gardens of Lubumbashi, those located along the northeast axis of the city present a medium-high contamination level, higher than those located along the southeast axis. MTE concentrations tend to decrease at a distance from the epicentres. Nevertheless, the presence of several mining facilities is linked to pollution hotspots. No clear trend was identified to describe the distribution of the other metals. However, these spatial representations highlight that nearly all the soils of Lubumbashi market gardens present some degree of MTE pollution, enrichment and contamination (Figures 3-5).

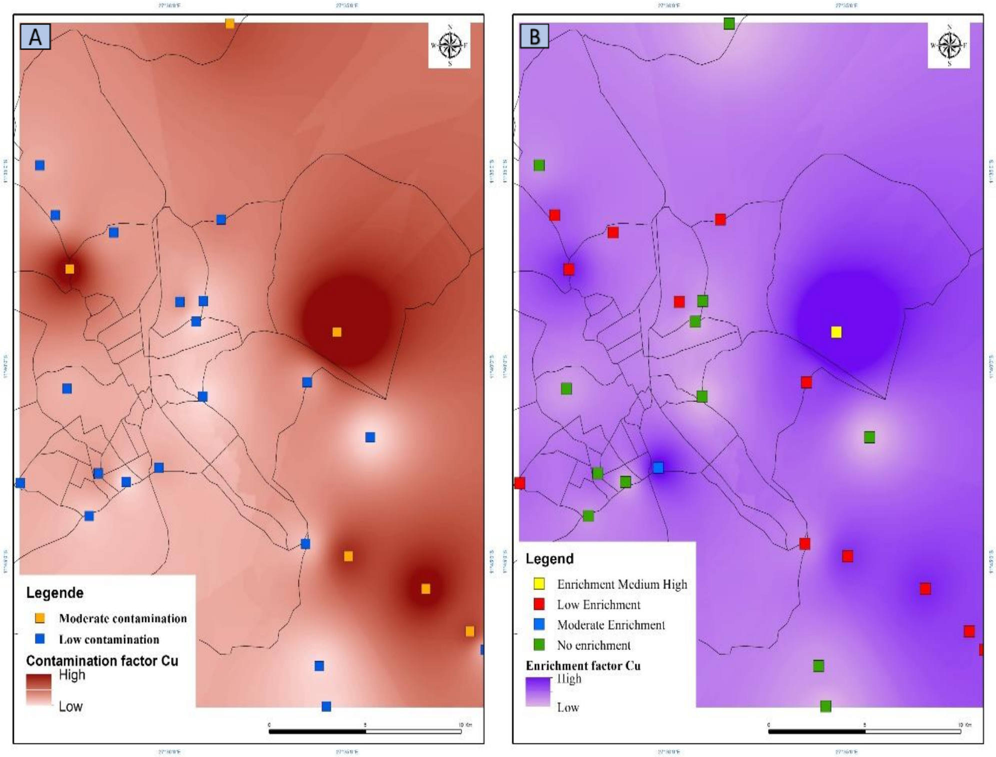


Figure 3-5. Map of the market gardens and urban markets of Lubumbashi (Mununga, K.F, 2022).

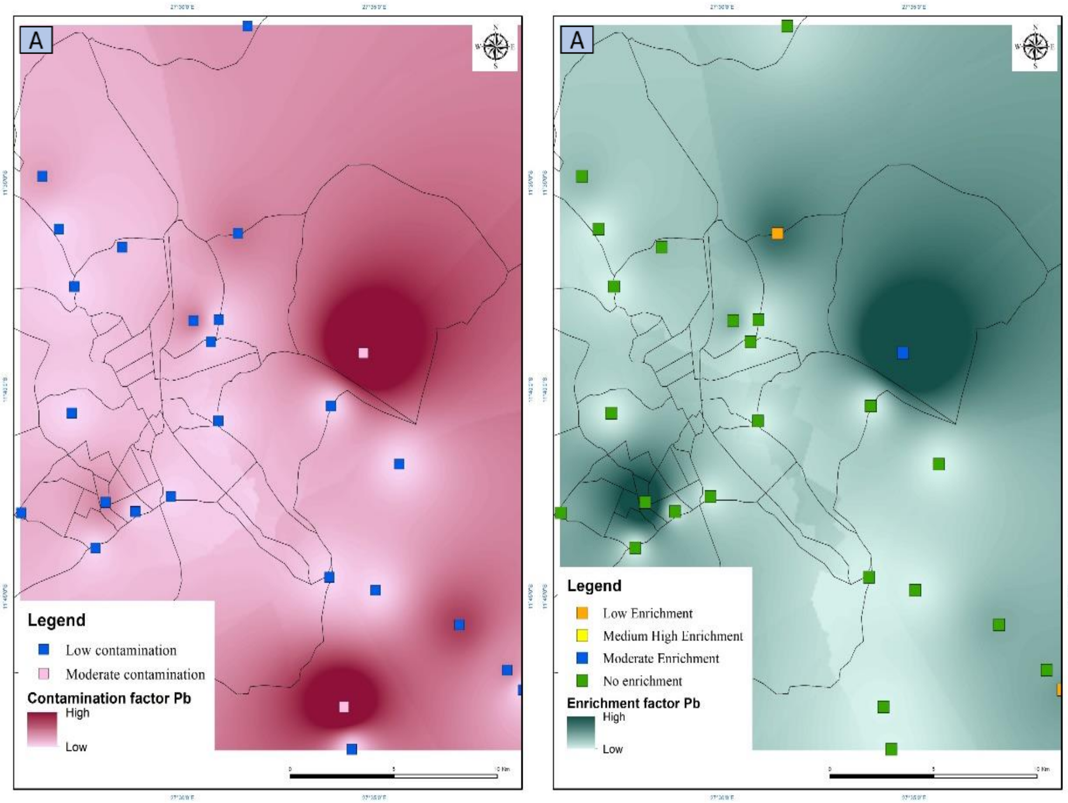


Figure 3-6. Spatial distribution of metals (Pb) in the market garden soils according to their contamination factor (A) and enrichment factor (B).

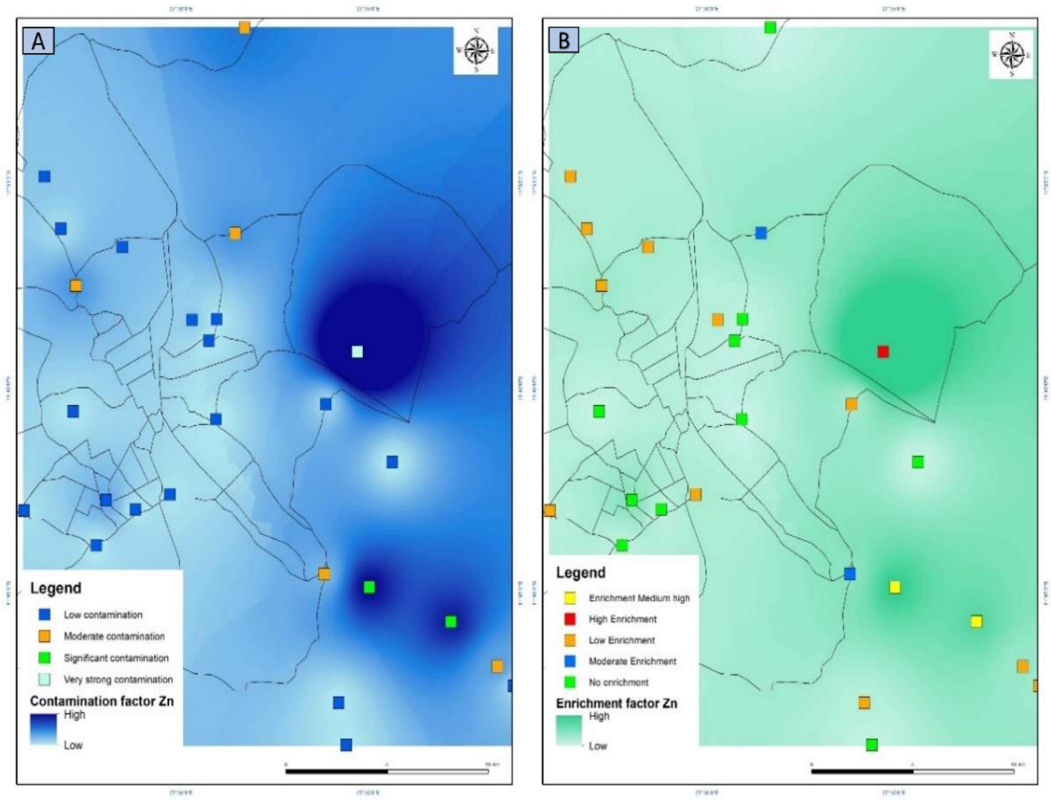


Figure 3-7. Spatial distribution of metals (Zn) in the market garden soils according to their contamination factor (A) and enrichment factor (B).

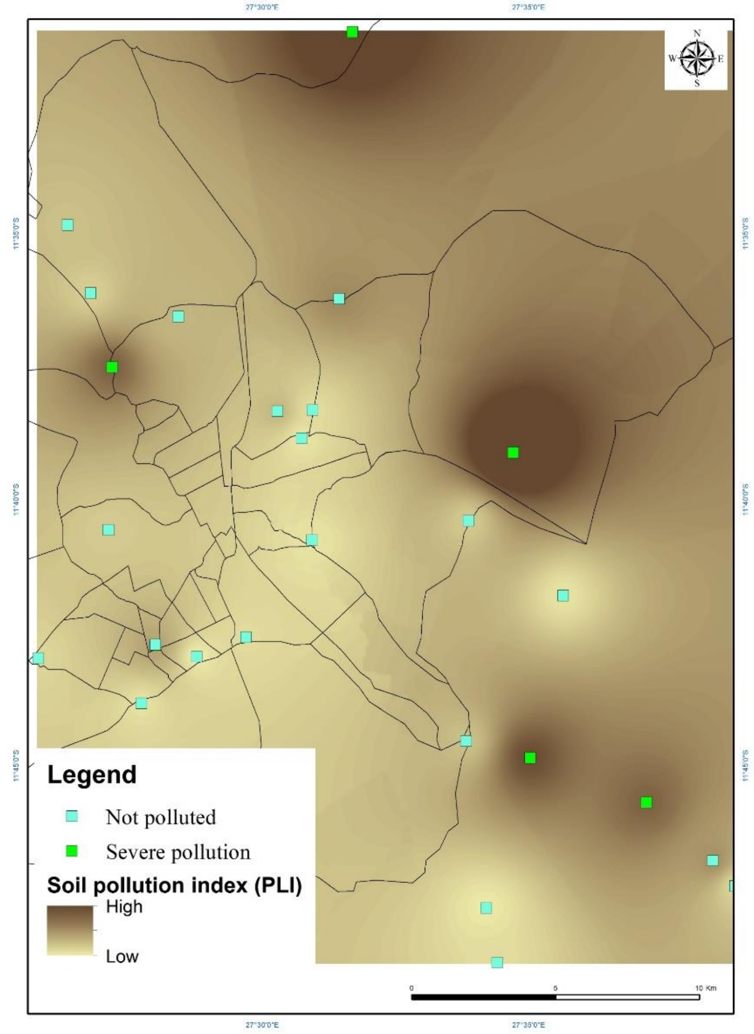


Figure 3-8. Spatial distribution of metals in the market garden soils according to their Soil pollution.

➢ Quality of crop irrigation water in the 21 selected market gardens

The laboratory results showed that nearly 57%, 52%, 19%, 10% and 5% of the water sources of the gardens were contaminated by lead, iron, copper, cadmium/cobalt and zinc, respectively. As for arsenic, no pollution effect was noted in any of the market gardens in and near Lubumbashi (Table 3-4).

The analyses showed that river waters were generally more or less contaminated than well waters: 33.3%, 23.8%, 9.5% and 4.7% of the river waters were contaminated with iron, lead, copper and cadmium, respectively, while 33.3%, 28.57% and 9.5% of the well waters were contaminated with lead, iron and copper, respectively, and 14.2%, 9.5% and 4.7% of rainwaters were contaminated with lead, iron and cadmium, respectively.

Table 3-4. Trace metal elements (mg/L) in the irrigation waters of the market garden crops of Lubumbashi gardens. Legend: Cd, cadmium; Cu, copper; Pb, lead; Co, cobalt; Al, aluminum; As, arsenic; Fe, iron; Zn, zinc; bold figures, contents above the standard.

Market Gardens	Cd	Cu	Pb	Co	As	Fe	Zn
Daipen Kisanga	0.003	0.012	0	0.012	0	0.316	0
Kafubu	0.001	3.01	0.028	0.006	0	0.381	0
Kalanda	0.002	2.51	0.049	0.012	0.02	1.175	0.002
Kalebuka	0.248	9.25	0.451	0.86	0	4.601	10.16
Kalubwe	0.002	0.019	0	0.007	0	0.782	0
Kalulako	0.001	0.129	0.038	0.018	0.027	0.185	0.065
Kamakanga	0	0.009	0.116	0.012	0	0.154	0
Kamasaka	0.002	0.014	0.017	0.007	0.022	0.144	0
Kamisepe	0.002	0.009	0.045	0.006	0.034	0.146	0
Kasungami	0.004	0.022	0.012	0.01	0.046	0.182	0.002
Katemo	0.002	0.011	0	0.008	0	0.097	0
Kawama	0.003	0.008	0.052	0.01	0	0.032	0
Kinsense	0	0.026	0.032	0.019	0.059	0.217	0.043
Kitanda	0.002	0.009	0	0.008	0.085	0.529	0.002
Maendeleo	0	0.019	0.043	0.011	0.07	0.242	0.028
Mashimikila	0.001	0.033	0.038	0.01	0	2.432	0.013
Penga-Penga	0.004	0.007	0.06	0.009	0	0	0
Sambwa	0.002	0.007	0.048	0.002	0	0.019	0
Tingi-Tingi	0	0.02	0	0.007	0	0.203	0.023

Tshamalale	0.002	0.035	0	0.005	0	1.238	0.017
Tshamilemba	0.001	2.031	0.048	0.005	0.008	0.011	0
Toxicity threshold (mg/L)	0.003	2	0.01	0.05	0.1	0.1	2

The results and their mapping showed that similar to soils, most of the contaminated waters of Lubumbashi market gardens were found along the northeast (Ruashi–Kafubu) axis of the city. Moreover, these gardens are located near a pollution cone and close to effluents discharged into the rivers (Figure 3-9–3-12). The waters of the other market gardens located along the Lubumbashi–Kasumbalesa and Lubumbashi–Kimbeimbe axes showed medium contamination levels.

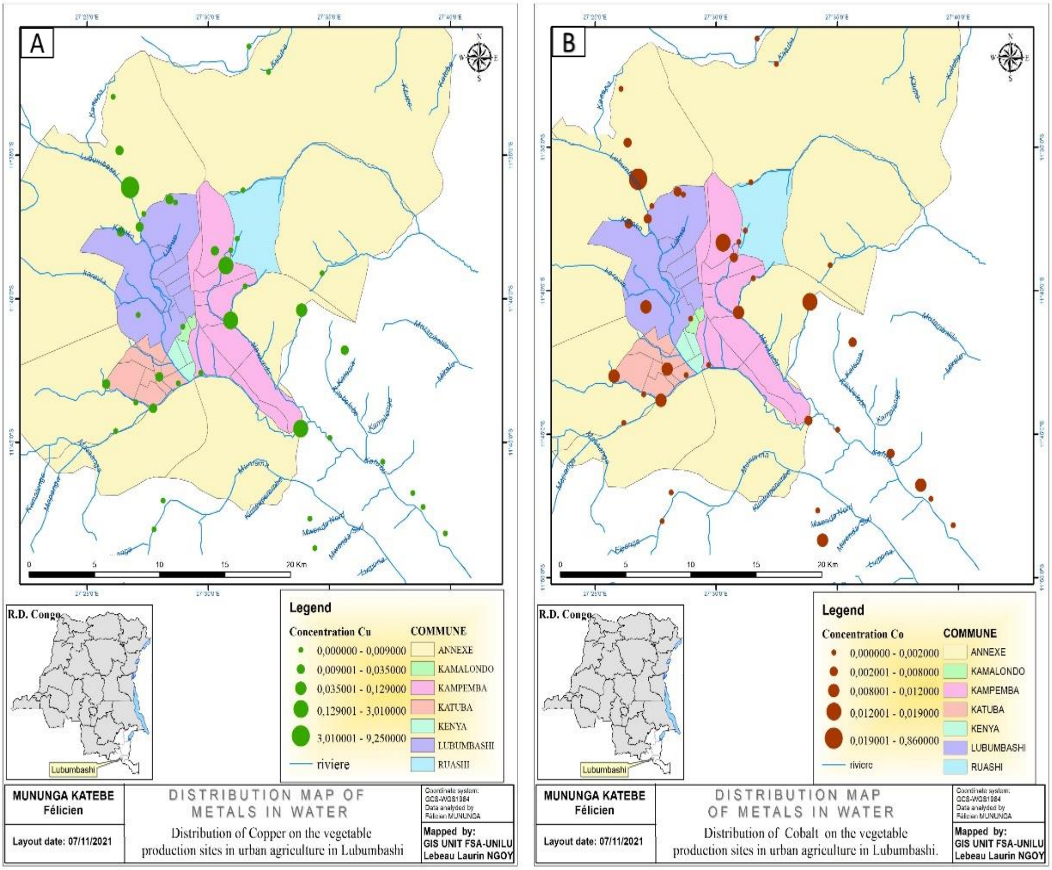


Figure 3-9. Spatial distribution of metals (Cu and Co) in the waters of Lubumbashi market gardens.

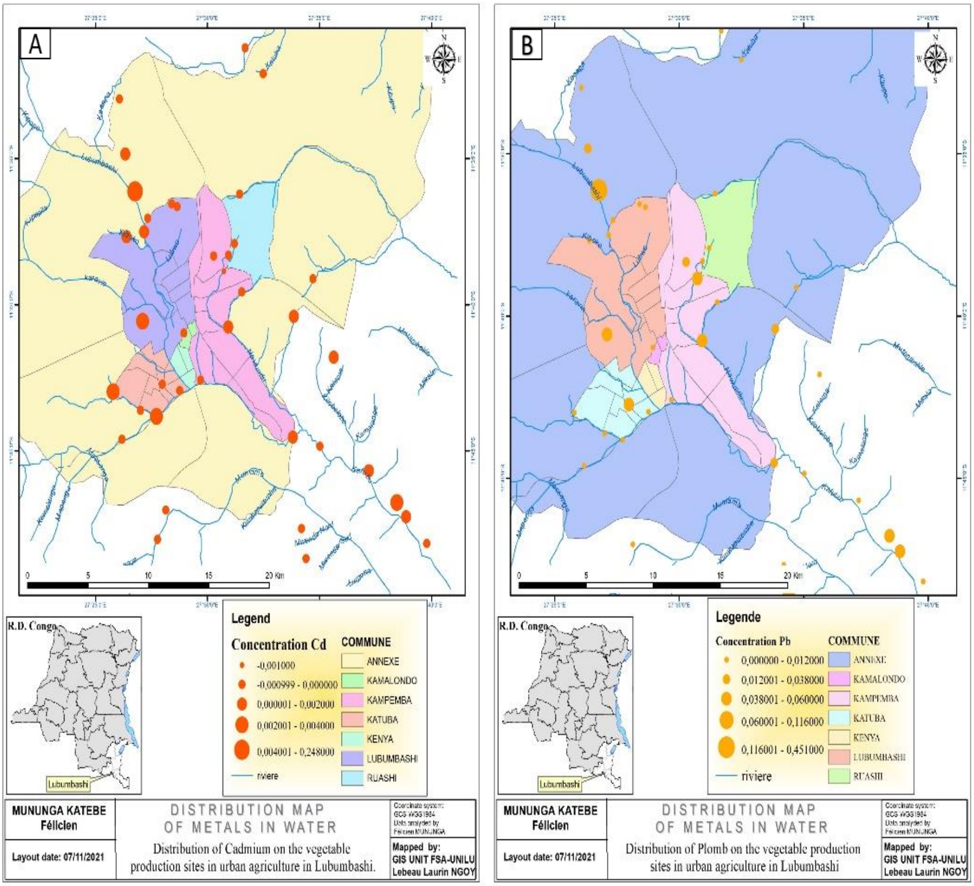


Figure 3-10. Spatial distribution of metals (Cd and Pb) in the waters of Lubumbashi market gardens.

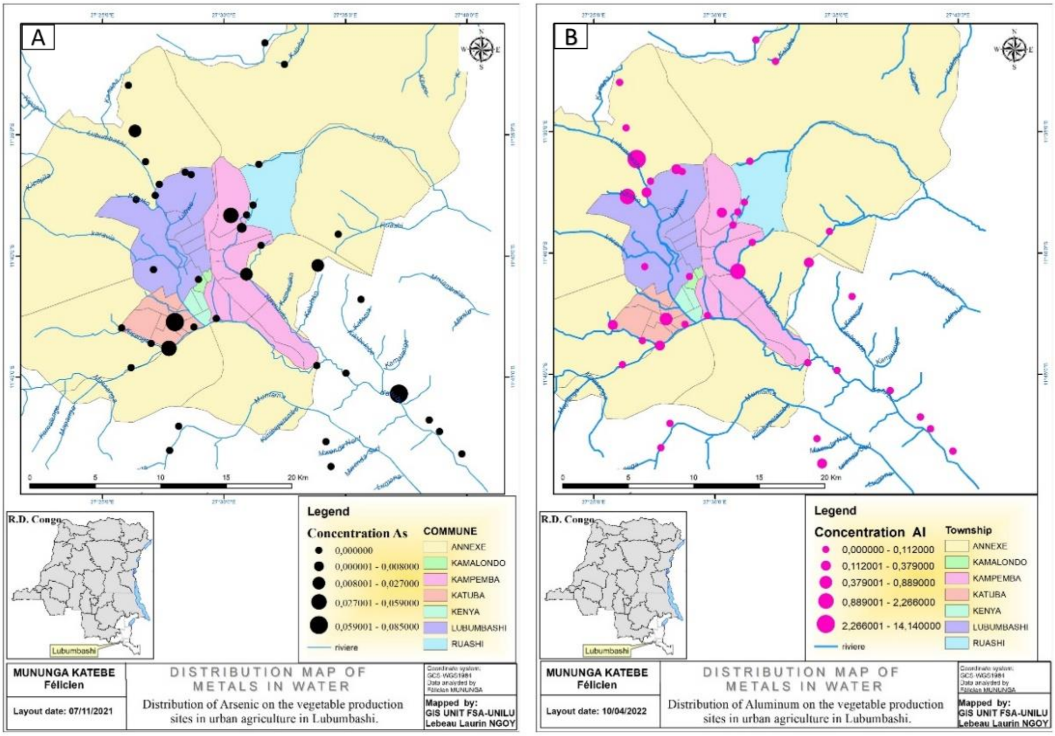


Figure 3-11. Spatial distribution of metals (As and Al) in the waters of Lubumbashi market gardens (A and B).

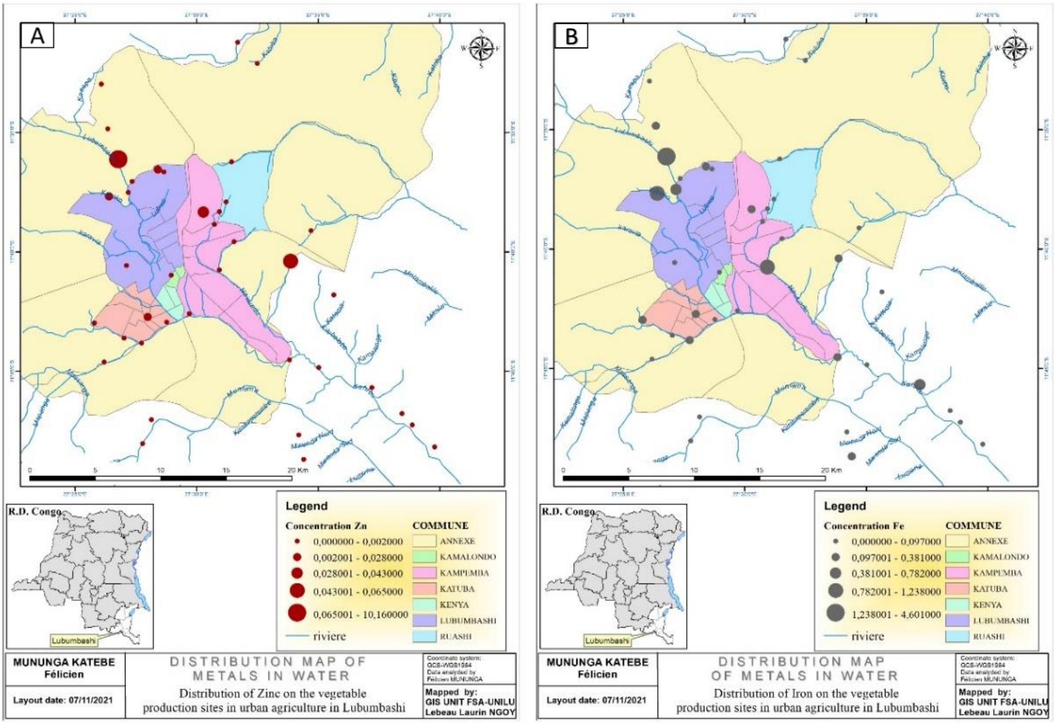


Figure 3-12. Spatial distribution of metals (Zn and Fe) in the waters of Lubumbashi market gardens (A and B).

➢ Safety of the vegetables sold in the 33 selected markets of Lubumbashi

The laboratory results showed that nearly all the vegetables sold on the 33 selected markets of Lubumbashi were contaminated with heavy metals, including Cd, Cu and Co. The analysis of variance showed that the use of several vegetables did not significantly influence the heavy metal concentrations ($p > 0.05$). However, the heavy metal concentrations remained above the contamination thresholds (Table 5). Only the Pb contents were below the WHO and AFNOR U4441 standards for vegetable consumption by humans. Among the four selected vegetables sold on Lubumbashi markets, *Brassica chinensis* presented the highest heavy metal (Cu, Cd and Co) contents, followed by *Amaranthus vulgarus*, *Spinacia oleracea* and *Brassica carinata* (Table 3-5).

Table 3-5. Mean heavy metal concentrations (mg/kg dry weight) in 4 crops sold in the 33 selected markets of Lubumbashi (AFNOR U4441 standard).

Plant Species	Co	Cd	Pb	Cu
Amaranthus vulgarus	4.41 ± 4.15 ^{a}	3.11 ± 3.56 ^{a}	1.27 ± 0.94 ^{a}	51.94 ± 61.17 ^{a}
Brassica chinensis	4.18 ± 2.65 ^{a}	2.03 ± 1.86 ^{a}	2.82 ± 2.94 ^{a}	44.93 ± 31.03 ^{a}
Spinacia oleracea	5.51 ± 11.48 ^{a}	1.25 ± 1.53 ^{a}	0.96 ± 1.22 ^{a}	21.25 ± 26.62 ^{a}
Brassica carinata	9.46 ± 18.33 ^{a}	0.82 ± 0.79 ^{a}	1.57 ± 2.49 ^{a}	27.53 ± 33.28 ^{a}
Species effects (*p*-value)	0.834	0.518	0.685	0.502

3.4. Discussion

3.4.1. Assessment of Pollution Indices, Contamination Factors and Soil Enrichment Factors in Market Gardens

We determined the extent of contamination in the various agricultural and non-agricultural soils of Lubumbashi (Lange et al., 2014; Mpundu et al., 2014; Muyumba et al., 2019; Shutcha et al., 2015). Our study is the first in the area to have data that can allow us to specifically identify each soil and its level of heavy metal pollution because none of these regional studies has been able to assess the level of pollution, contamination, and enrichment of each of the soils in this regard. Our results reveal that the soil pollution index shows nearly 80% of the gardens with no pollution risk, and 21% of the market gardens are polluted. This phenomenon can be explained by the fact that market gardens close to industrial activities show severe pollution compared to the soils of gardens far from these activities (Iyama et al., 2022; Teng et al., 2017). Most anthropogenic activities practiced in the area are hydrometallurgy and pyrometallurgy to process ore; these discharge heavy metal-laden effluent into the rivers that serve as irrigation water reservoirs for urban market gardeners and pollute the agricultural soils (Foli & Nude, 2012; Massadeh & Al-Massaedh, 2018; Thembachako et al., 2021). These hydrometallurgical or pyrometallurgical treatment processes have led to heavy metal contamination of stream sediments near a gold mine in Ghana. Similar situations have been observed in Bangladesh, where (Smith et al., 2000; Haoxian et al., 2020) have shown that the richness of the subsoil is responsible for metal contamination of the water table on the one hand and mining activities on the other.

The market gardens of Lubumbashi are close to watercourses that receive metal-rich effluents, which would cause soil pollution by watering the crops with these waters. This would be explained by the fact that organic amendments are added to the soils of the latter from former residential and mining dumps used in urban agriculture in Lubumbashi (Mpinda et al., 2016; Rai et al., 2004). Based on the soil pollution index, our results corroborate those found by (Kao et al., 2007; J. Yang et al., 2017) who showed that soils close to a pollution source had a higher pollution index than soils far from the pollution source. In all cases, the concentrations found in the water of urban market gardens came from the exploitation of Zn-enriched deposits. Similar situations were observed in Kolwezi (DR Congo), where the Dilala and Luilu rivers had high levels of heavy metals. These high concentrations of metals in the water of these rivers were due to the former activities of abandoned mining companies that were active in the city of Kolwezi (Atibu et al., 2018; T. Chen et al., 2008).

3.4.2. Chemical Quality of the Irrigation Water of the Market Gardens

The use of groundwater and recycled wastewater is the basis for the presence of metals in soils, water and plants (A. S. Abuzaid et al., 2022; S. I. Kwon et al., 2014; Yasuor et al., 2020). These corroborate our findings that 57% of the water in the market gardens of Lubumbashi is contaminated with lead, 52% with iron, 19% with copper, 10% with cadmium and 5% with aluminum. River water is often overloaded with metals released into the environment by mining companies (Akoto et al., 2008; Oguntade et al., 2015; Pekey, 2006). Furthermore, the market gardens along the Kafubu River have a high degree of Cu, Pb, and Fe pollution in contrast to the other axes along which the other market gardens are located. This is thought to be due to the fact that the land on which these rivers intersect is cupro-cobalt bearing rock (M. M. Abuzaid et al., 2020; Khalil et al., 2013). In addition, mineral processing effluents discharged by mining companies into the rivers are the main causes of water contamination/pollution. These very high metal concentrations create health and environmental problems (Atibu et al., 2018; Bandara et al., 2008; Inyinbor et al., 2019) for crop watering. High lead concentrations would mainly come from mining companies' releases into the atmosphere and water, as well as from plants (Atibu et al., 2016; S. Khalid et al., 2018; Osaili et al., 2016). Similar situations were observed by (Aboubakar et al., 2021) in the Nile Delta in Egypt, where high concentrations of Cr, Co, Cu, Pb, Ni, and Zn found in water resulted in the production of clover plants contaminated with these heavy metals, as these vegetables were watered with river water and landfill water loaded with metals had rendered plants grown on these soils unusable.

3.4.3. Safety of the Vegetables Sold in the 33 Selected Lubumbashi Markets

The safety of vegetables is a function of the quality of the agricultural soils and the irrigation water with which they are produced (Seid-Mohammadi et al., 2014). Thus, from our results, it appears that almost all of these four vegetables sampled in the markets of Lubumbashi are contaminated with copper and cobalt, and nearly 47% are contaminated with cadmium. This situation is due to the fact that the soils on which these vegetables grow are mostly contaminated by metals from mining companies, on the one hand, and from the natural richness of the subsoil, on the other hand. Our results corroborate those found in Kolwezi by (Cheyns et al., 2014; Scheen & Giet, 2012; Seid-Mohammadi et al., 2014) who found that effluent from businesses discharged into rivers was responsible for the contamination of vegetables produced and consumed in the city. Since urban agriculture in Lubumbashi is usually practiced in the dry season and on the banks of rivers, the water used to water the crops is loaded with metal pollutants, which is a very serious environmental problem. Observations made by (Atibu et al., 2016) report that effluents discharged into the rivers of Lubumbashi and the Tshamilemba canal by mining companies dating back more than a decade were the main source of contamination of the water in these rivers, as the levels of contamination found were 200 times higher than the recommended toxicity threshold for soils, and this leads to contamination of the plants growing in them.

In addition, this contamination of vegetables is thought to come from the former urban dumps of Lubumbashi that are used as market gardens in the dry season and are a reservoir of metal pollutants due to the various wastes they collect (Arukwe et al., 2012). These results corroborate those found in Kolwezi by (Arukwe et al., 2012) who report that landfills are among the most dangerous main locations for pollution, as levels found in the soil of a former landfill were above WHO standard values. Metal concentrations found in biomass were three times the standard for vegetable consumption (Antoniadis et al., 2017; Mpundu et al., 2014; Q. Song & Li, 2015). Our results confirm those of (Sharma et al., 2008; Tahir et al., 2022) which showed that the pollutant quality of soils was the basis for contamination of the six vegetables grown on these soils in the Pakistan region. Thus, of all the vegetables studied in this work, it appears that Chem-Chem amaranths are the most contaminated with heavy metals, followed by *Brassica carinata*. This would be justified by the simple fact that the soils of the market gardens and the water used to irrigate the crops at the Chem-Chem site are the most polluted in the city of Lubumbashi.

3.5. Conclusions

Our study indicated persisting heavy metal (Cu, Cd, Pb, Co and Zn) contamination of the soils, waters and market garden vegetables of Lubumbashi. Chemical analysis of heavy metals in the soils and waters revealed that the main contamination/pollution sources are most probably the naturally metal-rich soils and the metal-loaded effluents discharged into watercourses by mining companies. The quality of the soil and water of many market gardens of Lubumbashi remains poor for producing uncontaminated vegetables, and our results show that the vegetables sold on Lubumbashi markets are unfit for human consumption. In view of the currently proposed phytoremediation techniques that do not fully solve soil and vegetable pollution issues, other more advanced remediation techniques such as the composting of organic matter mixed with appropriate amounts of limestone to limit soil-to-plant heavy metal transfer should be envisaged.

Chapitre 4 :

Application of soil amendments to reduce the transfer of trace metal elements from contaminated soils of Lubumbashi (Democratic Republic of the Congo) to vegetables

L’application d’amendements organo-calcaires aux sols contaminés en élémentss traces métalliques présentée dans ce chapitre est adapté de : Mununga K.F.; Colinet G.; Kaumbu K.JM.; Mpundu M.M.; Jijakli M.H., 2024. Application of soil amendments to reduce the transfer of trace metal elements from contaminated soils of Lubumbashi (Democratic Republic of the Congo) to vegetables. *Environ Monit Assess,* https://doi.org/10.21203/rs.3.rs-3848977/v1.

Abstract: The extraction of copper and cobalt from mines has led to the contamination of agricultural soils by trace metal elements (TMEs) (e.g. Cu: 204 to 1355 mg/kg). The mining industry is one of the sources of metal discharges into the environment, contributing to water, soil, and air contamination and causing metabolic disorders in the inhabitants of the city of Lubumbashi (R.D. Congo). This study assessed the effectiveness of organocalcareous soil improvers applied to TME-contaminated soils to reduce their transfer to plants. Following a factorial design, increasing doses of organic soil improvers (chicken droppings and sawdust) and agricultural lime were applied to the soils of three market gardens (high, medium, and low Cu contamination). The experiment was monitored for 60 days. Soil physicochemical properties (pH, TOC, and total and available copper, cobalt, lead, cadmium, and zinc (mg/kg)) were determined for the three gardens and in the vegetable biomass. The daily consumption index of the vegetables was determined based on total TME content. The results show that organocalcareous soil improvers did not promote plant growth and survival on soils with high and medium levels of copper contamination. However, on soils with low copper content, organocalcareous soil improvers improved germination and plant survival and reduced the transfer of metals from the soil to the plants. The best germination and plant survival rates were obtained with the lightly contaminated market garden. In addition, the organo-limestone amendments applied to the soils slightly increased the soil pH from acidic to slightly acidic, with pH values ranging from (5.43±0.07 to 7.26±0.33). The daily vegetable consumption index obtained for cobalt in the low-contaminated garden ranged from (0.029 to 0.465 mg/60 kg/day), i.e. from 0.5 to 8.45 times higher than the FAO/WHO limit, unlike the other trace metals (Cd, Cu and Pb) for which the daily consumption index found was lower than the FAO/WHO limit. Organocalcareous soil improvers can only be applied to soils with low levels of TME contamination, but for soils with medium to high levels of metal contamination, new soilless production techniques such as hydroponics or bioponics are needed..

Keywords: daily consumption index, soil amendments, heavy metals, vegetable transfer, market gardening.

4.1. Introduction

Lubumbashi, a city in the Katanga copper belt rich in copper and cobalt, is facing environmental problems that are extremely worrying for the human health of the population, due to mineral processing activities and the intensification of mining company activities. These activities have resulted in soil, water, plant, and atmospheric pollution. The presence of important metals, such as copper, cobalt, arsenic, and cadmium, exceeds the limits set by the World Health Organization (WHO) and is found in agricultural and residential soils (Alfaro et al., 2022; M. Jiang et al., 2022; Shutcha et al., 2015). Contaminated soils transmit metals to plants, disrupting the functioning of living organisms (Briffa et al., 2020; Okereafor et al., 2020). Research carried out in Lubumbashi showed that vegetables grown in gardens and sold on various markets were contaminated with heavy metals, ranging from 13.1 to 39.3 mg/kg for copper and 0.33 to 2.94 mg/kg for cobalt (Mpundu et al., 2014; Mununga et al., 2023). Toxicity thresholds for copper and cobalt have been suggested by the WHO, namely around 10 and 1 mg/kg vegetable dry matter (Radwan & Salama, 2006). The same observations made by (Golia et al., 2023), showed that the pollution of agricultural soils and green spaces in downtown Thessalonica was due to human activities, notably rail and road passenger transport.

Soil pH, organic matter, metal, and redox levels can promote the release of Cu and Co from parent materials and their dispersion in the environment in various forms: solid, colloidal, and soluble (Hooda, 2010; Jadoon et al., 2024). In this way, the ability of metals to move in soils depends on the control of certain physicochemical parameters such as pH, total organic carbon, clays, oxides, sulfides, and carbonates. In addition, redox potential can promote the mobility and speciation of metals in soil (Hooda, 2010; Kabata-Pendias, 2004). Metals are transferred in solid, colloidal, and soluble forms. However, the distribution of plants in the natural environment is influenced by Cu and Co availability on the one hand and physicochemical conditions on the other (Faucon et al., 2011; M. Jiang et al., 2022; Lange et al., 2014; R. F. Saad et al., 2018). The mobility and bioavailability of Cu and Co can be transferred to the various components of the environment, such as water, soil, air, plants, and the food chain (Banza et al., 2009; Katemo Manda et al., 2010; Lange et al., 2014, 2016; Mwanamoki et al., 2014). The toxicity threshold for TMEs was exceeded in the urine of individuals living near ore processing facilities who were exposed to contamination by these TMEs. The TME concentrations observed were 17.8 ppm As, 0.75 ppm (Cd), 15.7 ppm (Co), 17.1 ppm (Cu), 3.17 ppm (Pb), and 0.028 ppm (U). However, the WHO recommended limits were 8, 24, 0, 20, 0, 36, and 0.008 mg/kg respectively for As, Cd, Co, and U in urine (Banza et al., 2009; Ilechukwu et al., 2021; Q. Song & Li, 2015). This situation contrasts with individuals who are far removed from sources of pollution.

There are three ways in which humans can be exposed to metal contamination, namely inhalation, ingestion, and skin contact (Acosta et al., 2014; Rajan et al., 2023). In the environment, high levels of TMEs can cause adverse consequences for human health, such as respiratory problems, DNA damage, sperm mobility, and sperm count. These metabolic problems can persist in the human body (W. Waqas et al., 2024). What's more, the effects of metals are not the same in humans. For example, mercury, and lead have an impact on the reproductive, nervous, and gastrointestinal systems (Mashyanov et al., 2017; Pratush et al., 2018; Vöröš et al., 2018). On the other hand, As, Zn and Ni can cause dysfunction in the heart, liver, and DNA (Chao et al., 2017; Sanchez et al., 2018; Stefanowicz et al., 2020). According to Izah et al (2016) and Nordberg et al (2018), Cu, Cr, and Cd impact the circulatory, pulmonary, and intestinal systems. Research in Sri Lanka has shown that consumption of cadmium-contaminated rice was responsible for the onset of kidney failure in 5,000 people living in an agricultural area (Bandara et al., 2008; Cao et al., 2020; Ghayoraneh & Qishlaqi, 2017; Gómez-Meda et al., 2017; Rahman et al., 2022). TME-contaminated soils can be sustainably treated using organic and calcareous amendments (Sarwar et al., 2017; Wan et al., 2016) to reduce the transfer of metals from soil to plants. After using organic amendments based on water hyacinth (*Eichhornia crassipes*) and agricultural lime, copper concentrations in the aerial parts of *Microchloa altera* plants decreased from (76.3 ± 22.1 mg/kg) to (25.2 ± 3.4 mg/kg) (Jaskulak et al., 2020; Lin et al., 2022; Shutcha et al., 2015). Soil pH, cation exchange capacity, and metal stability in soils were improved through the use of chicken droppings and limestone, which reduced the transfer of metals from the soil to the various plants grown on contaminated soils. However, the majority of this research demonstrates that the quantities of organic soil improvers and limestone used are extremely high. Different types of organic matter and crops need to be tested. Our research aims to validate the use of organocalcareous soil improvers in contaminated soils on the one hand and to test whether combining small quantities of different types of organic matter with lime would reduce the transfer of heavy metals (Cu and Co) from soil to plants. We expect to achieve quality vegetable production in the city of Lubumbashi. This article is part of a research project to propose solutions to the various environmental problems of urban agriculture in Lubumbashi. Firstly, we showed that garden soils were slightly, moderately, and heavily contaminated with trace metals and that vegetables bought at the market were heavily contaminated (Mununga Katebe et al., 2023a). Subsequently, this study aims to reduce the transfer of metals from soil to plants using the combination of low quantities of different organic matter and lime. The study of metal transfer from soil to plants has never focused on these types of organic matter and the vegetable crops used.

4.2. Materials and Methods

4.2.1. Study Area

The city of Lubumbashi (11° 36' 30.6" S and 27° 28' 35.7" E) currently comprises seven communes, including Annexe, Kamalondo, Kampemba, Katuba, Kenya, Lubumbashi and Ruashi (Fig.2), and covers an area of 747 km^2. Lubumbashi's climate is classified as CW6 according to the Köppen classification system and is characterized by three distinct seasons: a rainy season from November to March, a dry season from May to September, and two transitional months (April and October). Average annual rainfall in the region is estimated at around 1,200 mm, with an average yearly temperature of 20°C at an altitude of between 1,200 and 1,300 m. Soils in the Lubumbashi region belong to the ferralitic soil category, with a pH of around 5.9, and are mainly colonized by cupricolous plant species such as *Cynodon dactylon, Haumaniastrum katangense, Microchloa altera, Imperata cylindrica, and Bulbostislis pseudoperenis*.

4.2.2. Experimental Design, Soil Sampling and Crop Selection

An experiment was conducted to evaluate the efficacy of organocalcareous amendments on the transfer of metals from soil to plants, following a completely randomized factorial design. The treatments included five levels of amendment (D0: no amendment; D1: 150g sawdust; D2: 150g chicken droppings; D3: 75g sawdust and 15g agricultural lime; D4: 75g chicken droppings and 15g agricultural lime) and three types of urban market garden soils with low, medium, and high copper contamination (Kashamata, Manoah Kinsevere, and Chem-Chem), with four replications applied to the four market garden crops (*Brassica chinensis, Amaranthus vulgaris, Beta vulgaris, and Brassica carinata*).

- ✓ **Vegetable crops:** Among the twenty most cultivated and consumed species in the city of Lubumbashi, four vegetable plants (*Brassica chinensis, Amaranthus vulgaris, Beta vulgaris, and Brassica carinata*) were used in these trials. Improved seeds were purchased from local stores in Lubumbashi. After 60 days of cultivation, all plants were harvested and then dried in an oven to determine the levels of trace metals in the produced biomass and to assess the sanitary quality of the vegetables produced after applying organocalcareous amendments to soils contaminated with metals.

- ✓ **Soil**: The experiments conducted in 2019 were carried out in polyethylene pots containing 2.5 kg of soil and placed in a greenhouse in the experimental garden of the Faculty of Agronomic Sciences at the University of Lubumbashi. Three categories of market garden soils were selected based on different levels of copper contamination (204 mg/kg, 535 mg/kg, and 1355 mg/kg of copper), respectively, for the soils from the Kashamata, Manoah Kinsevere, and Chem-Chem gardens (Figure 4-1). Soil samples were taken from five different locations in each of the three urban market gardens, at a depth of 0 to 20 cm, and each batch of five samples was mixed to form a composite sample. 500 grams of the composite sample were preserved for laboratory analysis to determine the physico-chemical characteristics of the market garden soils and to minimize soil heterogeneity within the same market garden. Soil samples were air-dried for 14 days, crushed in a porcelain mortar, and sieved with a 2.0 mm sieve. The sieved soil samples were stored in polyethylene bags for 7 days before being transported to the laboratory for analysis. The pH and trace metal content of the soil samples were determined. According to the International Soil Classification, the soils of Lubumbashi belong to a group known as Ferralsoils (WRB, 2022).

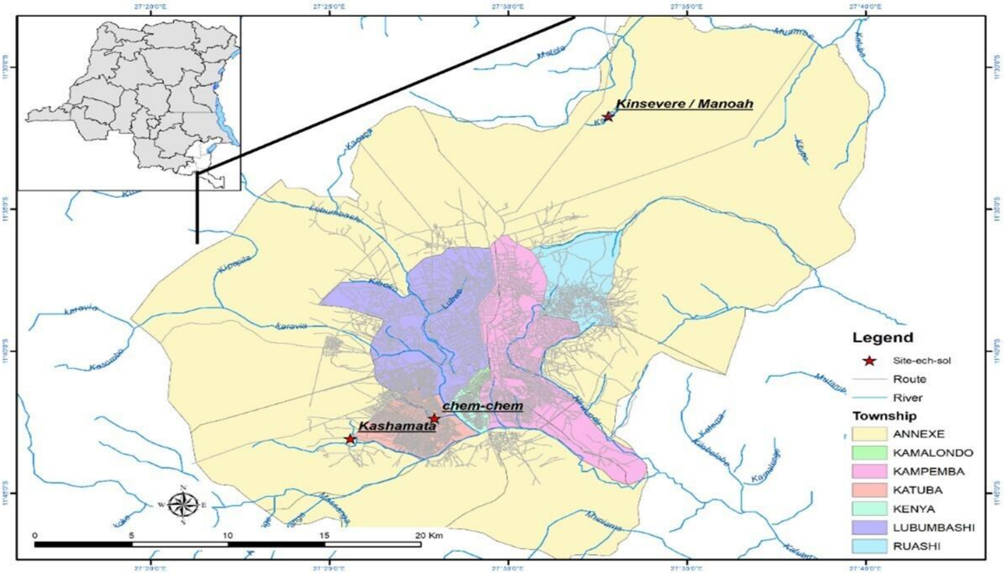


Figure 4-1. Illustration of sampled urban and peri-urban market gardens in Lubumbashi.

✓ Physicochemical characteristics of garden soils

Three types of urban market gardens (Chem-Chem; Kashamata and Manoah Kinsevere) were selected, and physicochemical characteristics were determined in each soil of these gardens (Table 4-1).

Table 4-1. Physico-chemical characteristics of soils in Lubumbashi's urban market gardens. Legend. Cu, Cd, Pb and Zn/dispo: available; <0.05: below the detection limit.

Market Gardens/Heavy metals (mg/kg)	Kashamata	Manoah Kinsevere	Chem-Chem	Toxicity threshold (mg/kg)
pH water	6,7	5,4	5,8	7
pH KCl	6,3	4,5	5	7
TOC (%)	2,54	2,3	3,14	-
Cu/total	204	535	1355	100
Cu/dispo	0,026	0,001	0,046	-
Cd/total	<0,05	<0,05	45	2
Cd/dispo	0,013	0,002	0,058	-
Co/total	Nd	Nd	Nd	30

Co/dispo	0	0,018	0,069	-
Pb/total	20	81	221	100
Pb/dispo	1,427	2,472	1,255	-
Zn/total	60	394	1470	300
Zn/dispo	0,643	0,261	1,933	-

✓ **Amendments:** In this experiment, three types of amendments were applied to soils contaminated by trace metals, including chicken droppings, sawdust, and agricultural lime. These amendments were purchased from local markets in Lubumbashi. The use of lime-based amendments on metal-contaminated soils reduces the mobility and bioavailability of metals by increasing soil pH and solubilizing oxides, resulting in the precipitation of trace metals. In addition, organic soil improvers, notably chicken droppings and sawdust, were purchased locally in Lubumbashi and composted for 15 days before sowing the crops. Organic soil improvers are renowned for their richness in organic matter, which positively influences the mobility of trace metal elements in soils by releasing organic acids that also increase soil pH.

The various organic and calcareous amendments were analyzed to determine their nutritional quality (Table 4-2). The chicken droppings were purchased from an industrial farm (Congo Oeuf) located some 15 km from the Faculty of Agronomic Sciences at the University of Lubumbashi. Agricultural lime was purchased from a lime and calcium producer in Likasi, 120 km from Lubumbashi. The sawdust was purchased from the sawmills of the Texaco market, located in the city of Lubumbashi, four kilometers from the Faculty of Agronomic Sciences.

Table 4-2. Physico-chemical characteristics of hen droppings, sawdust, and agricultural lime

Types of amendment	Mg (%)	Ca (%)	Heavy metals (mg/kg)					
			Cu	Co	Cd	Pb	Zn	Fe
Agricultural quicklime (CaCO$_3$ MgCO)$_3$	25	52	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05
Chicken droppings	0,11	7,48	80,5	5,6	0,04	0,3	321,3	654
Sawdust	0,05	0,12	22,6	2,4	0,3	1,9	21,6	1064

4.3. Measurement and analysis

The pH and TME content of the soil samples were determined. Water pH and KCl pH were determined using the potentiometric method (Lasota et al., 2020) and total organic carbon (TOC) by the Springer-Klee method. Total soil TME contents were measured using a portable X-ray fluorescence spectrophotometer (XRF, Olympus Delta Classic Plus, model DCC-4000), as described by (Mpinda et al., 2022). In addition, exchangeable TME contents were determined by the 0.01 M CaCl2 extraction method and measured by atomic absorption spectrophotometry (AAS, VARIAN 220, Agilent Technologies, Santa Clara, CA, USA) (Houba, Uittenbogaard, et al., 1996). Trace metal and major element contents were determined in chicken droppings and sawdust to determine the nutritional quality of these amendments. Extraction with aqua regia was carried out by ISO 11466:1995. For extraction, 3 g of sample and 28 ml of aqua regia were used. The extract was filtered through paper filters, diluted with demineralized water, and then digested for 20 minutes at 175°C in a microwave digestion vessel. A typical calibration method was used to determine trace metals (Cu, Co, Cad, Pb) in the different materials (chicken droppings and sawdust) using Perkin Elmer's Optima 7000 DV optical plasma emission spectrometer (ICP-OES). Plant leaves from four harvested vegetables were washed with tap water to remove soil particles, to determine only the metals absorbed by the plants. The leaves were oven-dried at 95°C for 24 hours, then ground into powder in a porcelain mortar. Plant samples rendered as powders were digested in 10 ml of $HNO_3/HClO_4$ (7:1 v/v) at 130°C, as reported by (Caçador et al., 2009; Momen et al., 2006; Otte et al., 1993). However, concentrations of trace metals such as Zn, Cu, Co, As and Cd were determined by atomic absorption spectrometry (AAS) with detection limits of 0.010; 0.10; 0.05; 0.05, and 0.05 µg/g respectively for Zn, Cu, Co, As and Cd, applying to all analytical techniques used.

4.4. Estimating the daily intake of vegetables.

To determine the level of heavy metal toxicity in plant biomass, the daily dose was estimated for vegetable consumption in the city of Lubumbashi for an individual over one day, one week, or even one month. This index also makes it possible to determine the quantities of metals ingested by a person of known body weight, and is calculated using the following relationship (Abuzed Sadee & Jameel Ali, 2023; Adefa & Tefera, 2020) :

$$\boldsymbol{EDI} = \frac{C_{mg/kg} \times Intake\left(\frac{kg}{day}\right)}{BM(kg)}$$

C_{mg} /kg is the average concentration of the metal in the vegetable, where Intake represents the quantity of vegetables to be consumed per day (kg/day), and finally, BM is the average body weight of the vegetable consumer. The WHO recommends eating 300 to 350 grams of vegetables a day. Then, an average of 0.325 kg/person/day was used to estimate the daily dose of vegetables to be consumed, and a body mass of 60 kg was chosen as the average body weight.

4.5. Statistical analysis

For each plant grown separately, vegetative parameters were subjected to a two-factor analysis of variance (ANOVA), and means were compared using a Tukey test with a significance level of 5%. Data was processed using R x64 4.1.2 and Minitab 21.3.1.0 statistical software.

4.6. Results and discussion

4.6.1. Effect of organocalcareous soil improvers on growth parameters of four vegetable crops grown on soil contaminated with heavy metals in Lubumbashi.

4.6.1.1. Germination rates of four plants grown on soil contaminated with heavy metals.

Figure 4-2 shows that plant germination rates vary from species to species and from garden to garden. Analysis of variance shows significant differences between the different types of organic material used ($p<0.05$). However, the best germination rates of *A. vulgaris* seedlings were obtained with the D2>D1>D0>D3>D4 modality. Furthermore, germination rates of *B. chinensis* plants and analysis of variance showed that the use of organocalcareous amendments significantly influenced plant germination at 7 days, with the best germination rate obtained with modality D1>D0>D2>D3>D4 ($p<0.05$). On the other hand, the highest germination rate of B. *vulgaris* plants was obtained with modality D0>D1>D4>D3>D2, and analysis of variance shows that the application of organocalcareous amendments significantly influenced chard plant germination ($p<0.05$). Finally, the highest germination rate of *B. carinata* plants was obtained with modality D1>D0>D2>D3>D4, and the analysis of variance shows significant differences between the organocalcareous amendment modalities used ($p<0.05$).

The work conducted by (Mununga et al., 2023) classified the soils of the market gardens into three categories: low, medium, and high copper contamination. They found that the vegetables sold in the markets of Lubumbashi are contaminated with trace metal elements. The results of this study show that plants did not grow well in the soils of the gardens with medium and high metal contamination. The use of organocalcareous amendments aims to increase soil pH and reduce the mobility and bioavailability of metals in agricultural soils (Alam et al., 2020; Liping He et al., 2020;

Tuan et al., 2020; Yin et al., 2016). However, analysis of variance indicates that the use of various market gardens did not significantly influence amaranth plant emergence rates. This could be attributed to the low nitrogen content of the organic matter supplied to the plants (Felix et al., 2022; D. Xu et al., 2022). Similar conclusions were drawn by (Mpundu et al., 2014) who found that the application of organocalcareous amendments to agricultural soils had no significant effect on the growth of *A. vulgaris* amaranth plants.

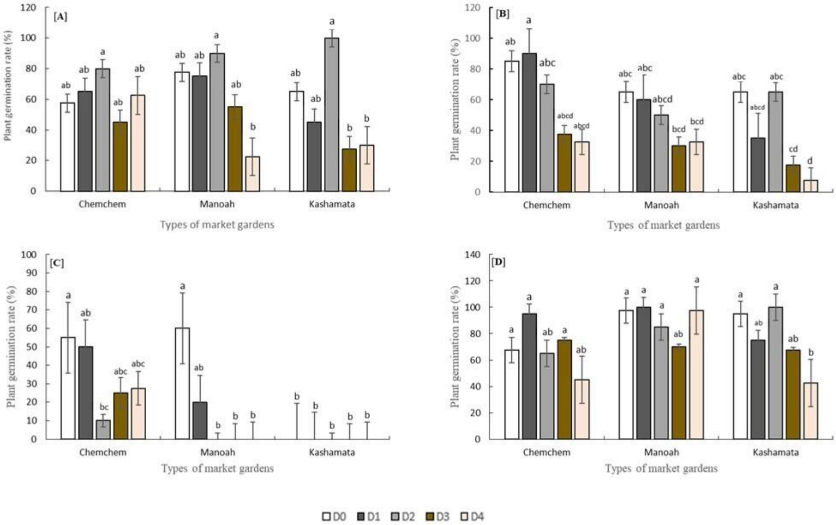


Figure 4-2. Effect of organocalcareous amendments on the germination rate of four plants grown on contaminated soils. Legend: [A]: *A. Vulgaris;* [B]: *B. chinesis*; [C]: *B. vulgaris*; [D]: *B. carinata*; D0: no amendments; D1: 150 g sawdust; D2: 150 g hen droppings; D3: 75 g sawdust + 15 g lime; D4: 75 g hen droppings + 15 g lime.

4.6.1.2. Survival of four vegetables grown in soil contaminated with heavy metals.

Analysis of variance (ANOVA) revealed that there were significant differences between the market gardens used in terms of plant survival at all observation dates ($p<0.05$), unlike the type of amendments applied to the contaminated soils which did not significantly influence amaranth plant survival, however, the Kashamata garden had given the highest survival rate, unlike the others. Thus, the interaction between market gardens and the type of organic and limestone amendments showed that there were significant differences between treatments in terms of plant survival at all observation dates ($p<0.05$), except at day 15 where the ANOVA revealed no significant difference (Figure 4-3I). The survival rate of *B. chinensis* plants ranged from 0 to 100%, with Analysis of Variance showing significant differences between market gardens at all observation dates ($p<0.05$), except at day 15, where ANOVA showed no significant difference. The best survival rate of B. chinensis plants was obtained with the Chem-Chem garden. Furthermore, analysis of variance showed that there were significant differences between the types of organic and limestone amendments applied ($p<0.05$), for *B. chinensis seedling* survival at all observation dates except day 15, where ANOVA showed no significant difference. The interaction between vegetable crops and types of organic and limestone amendments significantly influenced ($p<0.05$) *B. chinensis* seedling survival at all observation dates except day 15 th, where ANOVA revealed no significant difference (Figure 4-3II).

Regarding the survival rate of *B. vulgaris* plants, analysis of variance shows that the use of different market gardens significantly influenced the survival of B. vulgaris plants at all observation dates ($p<0.05$), with the highest survival rate obtained in the Manoah market garden. In all cases, organocalcareous soil amendments significantly influenced the survival rate of *B. vulgaris* seedlings ($p<0.05$) and, the best seedling survival rate was obtained with the modalities (D1 and D0). However, the interaction between market gardens and organocalcareous amendment types significantly influenced *B. vulgaris* seedling survival at all observation dates, except on day 15 where ANOVA revealed no significant difference (Figure 4-3III). As for the survival rate of *B. carinata* plants, it varied from (0.0+0.00 to 100.0 +0.00%), and analysis of variance reveals that there are significant differences ($p< 0.05$) between market gardens in the survival rate of *B. carinata* plants at all observation dates, with the highest survival rate obtained in the Chem-Chem garden. The application of organic and limestone amendments had a significant influence on *B. carinata* plant survival ($p<0.05$), with the best plant survival rate recorded in the Chem-Chem gardens. On the other hand, the combination of organic and limestone amendments had a significant influence on plant survival ($p<0.05$) (Figure 4-3IV).

Furthermore, amaranth plant survival was significantly influenced by market garden types, while organic matter did not significantly influence amaranth plant survival at all observation dates. Similar results were reported by (S. Ullah et al., 2023; M. Wang et al., 2023) who found that compost application on metal-contaminated soils did not significantly influence germination and survival of *Brassica juncea* plants in the Spanish region of Aznalcóllar (Alam et al., 2020). Our results can be explained by the fact that during the decomposition of organic matter, specific organic compounds can release substances that can immobilize heavy metals by forming precipitates or insoluble complexes. For example, sulfides released during the decomposition of organic matter can bind to heavy metals (Z. Chen et al., 2021; Kwiatkowska-Malina, 2018; Liu et al., 2022; Sun et al., 2021). The results obtained show that the application of organic amendments significantly influenced the pH of the market garden soils. However, an alkaline pH was observed in the soils of the lightly contaminated Kashamata garden with the cultivation of *B. vulgaris*. This phenomenon could be explained by the fact that *B. vulgaris* may alkalize its rhizosphere by excreting hydroxide ions (OH^-) or absorbing protons (H^+) at the root surface, thus facilitating the absorption of ammonium or nitrates. In contrast, other plants can acidify their rhizosphere. Our results are consistent with those of (Blossfeld et al., 2010), who showed that alpine pennycress (*Noccaea caerulescens* J. Presl & C. Presl) and ryegrass (*Lolium perenne L.*) plants alkalized their rhizosphere by approximately 1.7 and 1.5 units, respectively, while maize (Zea mays L.) plants acidified their rhizosphere.

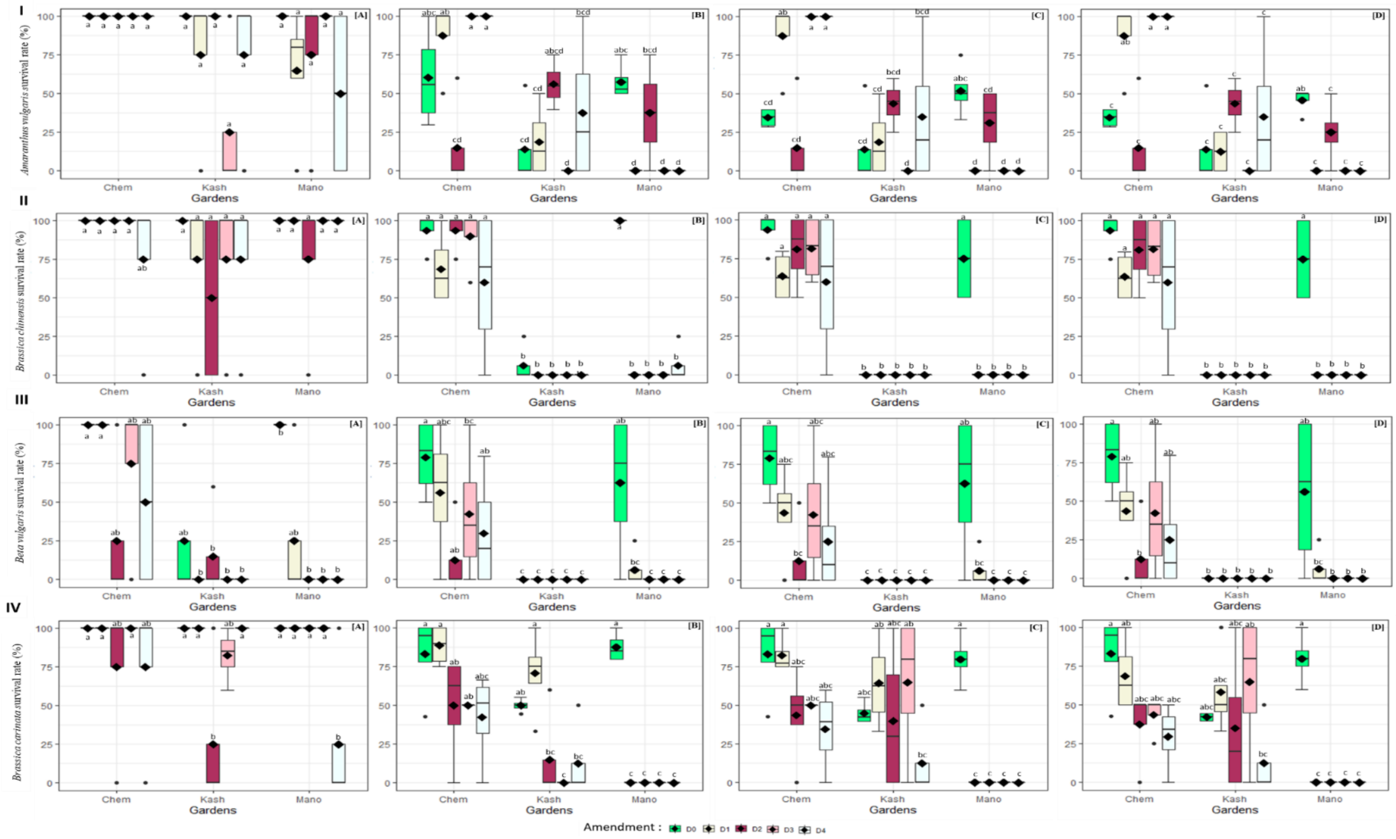


Figure 4-3. Effects of organocalcareous amendments on the survival rate of I (B. carinata); II (B. chinensis), *III (B. vulgaris and IV (B. carinata)* plants grown on soil contaminated with heavy metals. Legend: (D0: no amendments; D1: 150g sawdust; D2: 150g hen droppings; D3:75g sawdust + 15g lime; D4:75g hen droppings + 15g lime; -: extreme values; -: Mean; ◊: Median; [A]: Survival rate at 15 days; [B]: Survival rate at 30 days; [C]: Survival rate at 45 days; [D]: 60-day survival rate; Amend: Types of amendment; Chem: Chem-Chem; Kash: Kashamata Daipen and Mano: Manoah Kinsevere.

4.6.2. Effects of organocalcareous soil improvers on the pH of soils contaminated by heavy metals.

Table 4-3 shows the application of organocalcareous amendments on the three soils from the market gardens. The analysis of variance (ANOVA) indicates that there are significant differences between the three market garden soils in terms of pH for all four crops ($p<0.05$). The highest pH was obtained with the soils from the Kashamata market garden with *Beta vulgaris* as the crop. Similarly, ANOVA reveals that the applied organocalcareous amendments significantly influenced the soil pH ($p<0.05$) for all four market garden crops. The highest soil pH was obtained with treatment D4 (7.26±0.33), with *B. vulgaris* as the crop, followed by treatments D3, D2, and D1. Additionally, the interaction between the market garden soils and the applied organocalcareous amendments significantly influenced soil pH for all four market garden crops ($p<0.05$). The highest pH was obtained with treatment D4 (7.26±0.33) on the soils from the Kashamata garden with *B. vulgaris* as the crop.

Organocalcareous soil improvers are proposed as techniques for reducing the transfer of metals from soil to plants. Studies conducted by (Michel Mpundu Mubemba et al., 2014; Shutcha et al., 2015) have shown that organocalcareous amendments reduce the mobility and bioavailability of trace metals (Frick et al., 2019; Khoshru et al., 2023; Narayanan & Ma, 2023; Sarwar et al., 2017; Huifeng Wang et al., 2023; Y. J. Wu et al., 2016). However, the quantities of amendments are still very large. Our results indicate that the application of organocalcareous soil improvers reduced the transfer of trace metal elements from the soil to the plants, by forming chelates with the trace metal elements, making the soils slightly acidic (Michel Mpundu Mubemba et al., 2014; Shutcha et al., 2015).

Table 4-3. Effects of organocalcareous amendments on the pH dynamics of soils contaminated with heavy metals. Legend: (D0: no amendment; D1: 150 g sawdust; D2: 150 g hen droppings; D3: 75 g sawdust + 15 g lime; D4: 75 g hen droppings + 15 g lime.

Gardens	Amendments	pH *A. vulgaris*	pH *B. chinensis*	pH *B. vulgaris*	pH *B. carinata*
Chemchem	D0	5.69±0.03^{h}	5.69±0.07^{fg}	6.07±0.10^{de}	5.96±0.02^{de}
Chemchem	D1	5.85±0.02^{fgh}	6.05±0.06^{cd}	5.90±0.12^{de}	6.08±0.09^{de}
Chemchem	D2	6.15±0.04^{de}	6.18±0.09^{c}	6.14±0.13^{c}	6.13±0.08^{d}
Chemchem	D3	6.37±0.09^{cd}	6.18±0.14^{c}	5.85±0.15^{ef}	6.05±0.06d^{e}
Chemchem	D4	6.07±0.11^{ef}	5.82±0.06^{ef}	6.02±0.08^{de}	6.46±0.05^{c}
Manoah	D0	5.66±0.03^{h}	5.55±0.11^{g}	5.60±0.10^{ef}	5.48±0.10^{f}
Manoah	D1	5.83±0.05^{gh}	5.79±0.07^{ef}	5.58±0.10^{e}	5.43±0.07^{f}
Manoah	D2	6.33±0.08^{d}	6.16±0.05^{c}	5.78±0.06^{ef}	5.81±0.08^{e}

Manoah	D3	6.01±0.06^{efg}	5.84±0.05^{def}	5.71±0.06^{ef}	5.85±0.23^{e}
Manoah	D4	6.03±0.07^{efg}	5.93±0.13^{de}	5.93±0.13^{de}	6.05±0.06^{de}
Kashamata	D0	6.62±0.12^{b}	6.97±0.10^{ab}	6.33±0.10^{c}	6.69±0.02^{bc}
Kashamata	D1	6.77±0.04^{b}	6.81±0.09^{ab}	6.47±0.22^{c}	6.96±0.05^{ab}
Kashamata	D2	6.74±0.06^{b}	6.83±0.05^{ab}	6.69±0.19^{bc}	7.11±0.21^{a}
Kashamata	D3	6.56±0.07^{bc}	6.77±0.08^{b}	6.97±0.08^{b}	6.76±0.23^{b}
Kashamata	D4	7.22±0.22^{a}	7.02±0.07^{a}	7.26±0.33^{a}	7.21±0.18^{a}
Site effects (p-value)		0.000	0.000	0.000	0.000
Organic matter effect (p-value)		0.000	0.000	0.000	0.000
Interaction Sites x M.O (p-value)		0.000	0.000	0.000	0.000

4.6.3. Estimation of daily consumption of leafy vegetables grown in garden soils of Lubumbashi.

The estimated daily consumption of vegetables produced in Lubumbashi's urban market gardens was carried out for the Kashamata market garden, a garden with low copper contamination. In contrast, data from the Chem-Chem and Manoah Kinsevere market gardens are not presented in Table 4-4, as the majority of treatments applied did not result in sufficient biomass for analysis of metal concentration. This is due to moderate and high levels of trace metal contamination. In the Kashamata vegetable garden, the daily vegetable consumption indices are below the FAO/WHO limits for daily vegetable consumption per person for most trace metals (Cu, Cd, and Pb). However, concerning cobalt, the results indicate that the four vegetables cannot be consumed by the population of Lubumbashi, as the high quantities of metals found in the leaves exceed the limits set by the FAO/WHO for the daily consumption of vegetables for a person of 60 kg body weight. In addition, the application of organocalcareous amendments influenced the daily consumption index. Treatment D4 proved to be more effective than other treatments with fewer amendments, following the order of accumulation D4 > D3 > D2 > D1 > D0.

Our results reveal persistent problems, as the consumption indices exceed the limits set by the FAO/WHO for daily vegetable consumption, particularly about cobalt for vegetables from the Kashamata market garden (Abuzed Sadee & Jameel Ali, 2023; Adefa & Tefera, 2020; Langunu et al., 2023; Tasleem et al., 2023). This phenomenon could be explained by the fact that the soils of Haut-Katanga province in general, and the city of Lubumbashi in particular, have a pedogeochemical background enriched in copper and cobalt. In addition, the poor management of quarries and mines, as well as the discharge of effluents rich in metallic particles and aerosols containing dust, can contribute to the propensity of this environmental scourge (Bogaert et al., 2018;

Shengo et al., 2020; Shutcha et al., 2015). The recommended quantities of vegetables (300 grams/60kg of an adult) could prove very dangerous for children whose weight is less than that of adults, given the danger that the city of Lubumbashi presents in terms of copper and cobalt production. On the other hand, if we consider the other metallic trace elements (Cu, Pb, and Cd), the daily vegetable consumption index indicates that these vegetables can be consumed up to three times a week without exceeding the limits set by the FAO/WHO for daily vegetable consumption for a person of 60 kg body weight (Cherfi et al., 2016; Zhuang et al., 2009).

According to the International Soil Classification, Lubumbashi soils belong to the category of ferralitic soils characterized by the presence of over 20% clay in soil profiles A-C and A-B-C, mainly composed of Kaolinite, as well as iron and aluminum oxides (G. Chen et al., 2019). However, the clay component is mainly composed of kaolinite and is mixed with significant amounts of free oxides, resulting in a SiO_2/Al2O_3 ratio less than or equal to 2. Applying organocalcic soil improvers to ferralitic soils contaminated with trace metal elements improves soil fertility and offers a high capacity for immobilizing trace metal elements in the soil. This is due to the high reactivity of dissolved and colloidal iron in ferralsols, mixed with other elements such as Si, Ca, Mg, Na, and K introduced by the application of organo-calcium amendments on metal-contaminated soils, destabilizing kaolinite and allowing the formation of 2:1 clay mineral. These minerals then reduce the bioavailability of metals to plants (G. Chen et al., 2019; I. Mohamed et al., 2010).

Table 4-4. Daily consumption of leafy vegetables in Lubumbashi (mg/60 Kg/day). Legend : ND : not determined.

Crop types	Gardens	Types of amendment	Trace metals			
			Cd	Cu	Pb	Co
Limit WHO/FAO			**0,06**	**3**	**0,214**	**0,055**
Amaranthus vulgaris	Kashamata	D0	0,023	0,375	0,004	**0,449**
Amaranthus vulgaris	Kashamata	D1	0,007	0,182	0,005	**0,102**
Amaranthus vulgaris	Kashamata	D2	ND	ND	ND	ND
Amaranthus vulgaris	Kashamata	D3	0,002	0,461	0,013	**0,056**
Amaranthus vulgaris	Kashamata	D4	0,001	0,805	0,023	**0,101**
Brassica chinensis	Kashamata	D0	0,005	0,231	0,004	**0,177**
Brassica chinensis	Kashamata	D1	0,004	0,223	0,004	0,05
Brassica chinensis	Kashamata	D2	0,002	0,208	0,003	0,027
Brassica chinensis	Kashamata	D3	0,005	0,389	0,003	0,029
Brassica chinensis	Kashamata	D4	0,002	0,288	0,004	0,05
Brassica carinata	Kashamata	D0	0,009	0,363	0,004	**0,326**

Brassica carinata	Kashamata	D1	0,005	0,385	0,007	0,052
Brassica carinata	Kashamata	D2	0,002	1,03	**0,055**	**0,119**
Brassica carinata	Kashamata	D3	0,003	0,526	**0,029**	**0,063**
Brassica carinata	Kashamata	D4	0,002	0,947	**0,036**	**0,086**
Beta vulgarus	Kashamata	D0	0,015	0,612	0,012	**0,465**
Beta vulgarus	Kashamata	D1	0,007	0,346	0,008	**0,084**
Beta vulgarus	Kashamata	D2	ND	0,779	**0,029**	**0,075**
Beta vulgarus	Kashamata	D3	ND	ND	ND	ND
Beta vulgarus	Kashamata	D4	ND	ND	ND	ND

4.6.4. Involvement in the production of quality vegetables, and choice of urban market gardens in Lubumbashi.

In agro-environmental applications, the use of organocalcareous soil improvers has been suggested as a remediation technique for soils contaminated by heavy metals. However, few studies have been carried out in Lubumbashi to confirm or refute these techniques. These techniques are applied to moderately contaminated soils, and their effectiveness depends on the plant species used, and the types and quantities of organic amendments applied to the soil. Our results show that the majority of Lubumbashi's urban gardens are contaminated by heavy metals, mainly copper and cobalt, and that the vegetables produced there are of poor sanitary quality for human health Studies carried out by (Mununga et al., 2023) showed that the level of contamination, pollution and enrichment of each market garden was not the same, as the majority of gardens were contaminated. We, therefore, recommend that urban market gardens in Lubumbashi with extremely high levels of contamination, as well as those with exceptionally high levels of pollution, use soilless production techniques such as conventional hydroponics or bioponics to guarantee the quality of the vegetables produced in their gardens to safeguard human health (Dhawi, 2023; Gartmann et al., 2023; Magwaza et al., 2020; C. Mai et al., 2023).

The Congolese government must ensure that planning for urban agriculture in the country takes into account the implications of pollution and high levels of contamination on the potential risk posed by market gardens. To produce in quantity and quality, gardens with very severe levels of pollution and/or contamination should be prioritized for the adoption of new soilless production techniques such as bioponics or conventional hydroponics. Bioponics is a method of growing plants in an aquatic environment, where the roots are immersed in a nutrient solution derived from animal manure or plant waste, to promote both the quantity and quality of plant growth (Ezziddine, Liltved, and Seljåsen 2021; Bergstrand Karl-Johan and Hakan Asp and Malin Hulberg 2020; Resh 2013). In developing countries, where obtaining agricultural inputs is becoming increasingly difficult and expensive, adopting bioponics could prove a sustainable solution for Lubumbashi's poor urban farmers. These farmers need to adopt new techniques to grow vegetables, enabling them to reduce production costs to increase producer profits (Nsele et al., 2022).

4.7. Conclusion and outlook

Mining activities contaminate agricultural soils, water, and air, as well as plants, due to the large quantities of metals they release into the environment, posing a danger to human health. This study aimed to assess the effectiveness of organo-lime amendments applied to soils in reducing the transfer of metals from the soil to plants. Increasing doses of organic soil improvers (chicken droppings and sawdust) and agricultural lime were applied to the soils of three market gardens. Soil samples were taken from three urban market gardens in Lubumbashi, according to the level of copper contamination (high, medium, and low copper contamination). The study showed that soils heavily and moderately contaminated with copper are unable to produce quality vegetables for human consumption. On the other hand, soils with low levels of contamination (e.g., 204 Cu mg/kg) can produce vegetables that are not contaminated with copper. Organocalcareous soil improvers were incorporated at different concentrations. However, none of the tested concentrations improved germination and plant survival in soils with high and medium levels of TME contamination. The garden with low copper contamination shows that the application of organocalcareous amendments reduced the transfer of metals from soil to plants, and consequently, the vegetables produced pose no risk for consumption concerning Cu, Cd, and Pb. Plants of *B. chinensis* and *B. carinata* can be grown on soils from gardens with low levels of trace metal contamination to prove quality plants.

Vegetables grown on these soils have not absorbed large quantities of metals. This underscores the importance of determining the mechanisms of metal absorption by plants to propose appropriate remediation techniques. For example, the daily vegetable consumption index obtained for the element cobalt in the low TME-contaminated garden (Kashamata) ranged from (0.029 to 0.465 mg/60 kg/day), i.e. from 0.5 to 8.45 times higher than the FAO/WHO limit, in contrast to the other trace metals (Cu, Cd and Pb) where the daily consumption index found was below the FAO/WHO limit. Organocalcareous soil improvers can only be applied to soils with low levels of TME contamination, but for garden soils with medium to high levels of contamination, it is necessary to test other types of organic soil improvers and other plant species, as well as test new soilless production techniques such as hydroponics and bioponics.

Chapitre 5

Bioponic cultivation using chicken droppings to produce lettuce plants (*Lactuca sativa rz*) uncontaminated by trace metals.

La Culture bioponique utilisant des fientes de poulet pour produire des plants de laitue (Lactuca sativa rz) non contaminées par des métaux traces présentée dans ce chapitre est adapté de : Mununga K.F.; Iris S.; Clément B.; Mpundu M.M. and Jijakli, M.H., 2024. Bioponic cultivation using chicken droppings to produce lettuce plants (*Lactuca sativa rz*) uncontaminated by trace metals. *Horticulturae* ***2024****, 10(6), 605;* ***https://doi.org/10.3390/horticulturae10060605***

Abstract: Anthropogenic activities have denatured aquatic, terrestrial, and aerial environments throughout the world in general, and in Lubumbashi in particular, where market garden soils have become uncultivable for many plants. Thus, bioponics could be an effective means of producing uncontaminated vegetables in soilless cultivation, not only reducing the amount of fertilizer used and limiting contamination of agricultural produce but also achieving higher yields than in open-ground cultivation. The overall objective of this study was to implement a new bioponic technique for producing liquid fertilizer from chicken manure and utilize it in the organic hydroponic cultivation of lettuce (*Lactuca sativa var. Lucrecia)* installed on floating raft systems. To achieve this, two types of trials were conducted. The first was aimed at determining the quantities of organic matter to be used in the formulation of nutrient solutions. The second trial aimed to determine the optimal nitrogen concentration to be provided for hydroponic plant growth. Mineralization and/or anaerobic digestion of chicken manure were conducted for 7 days in 200 L barrels. For the first trial, nutrient solutions were created from three different concentrations of chicken manure (0.35%, 3.5%, and 7% dry matter—D.M). These solutions were then used in bioponic rafts where total ammonia nitrogen (TAN) concentrations were fixed at 150 mg/L. For the second trial, D.M was fixed at 2.5% for each tested modality, but TAN concentrations varied among them (i.e., 60, 90, and 120 mg/L TAN concentration). Modalities with low D.M concentration (0.35%) and those with low TAN concentration (60 mg/L) resulted in higher yields than bioponic modalities receiving high concentrations of dry matter or TAN, respectively, for trials 1 and 2. Although the reference chemical solutions generate the greatest yields, bioponic systems operating with chicken manure present a good alternative for the cultivation of vegetables in developing countries with heavily contaminated soils. Indeed, bioponics allows for the production of vegetables in large quantities from animal waste, which does not pose health risks for human consumption. Local vegetable species commonly grown in Lubumbashi should be tested under hydroponic conditions.

Keywords: Hydroponics, microorganisms, anaerobic, aerobic, raft.

5.1. Introduction

Soil is a source of nutrients for plants and, as a substrate, enables plant growth. However, it cannot always play this role, given its degradation mainly caused by human activities. This situation is particularly acute in arid regions and areas of intense mining activity (Michel Mpundu Mubemba et al., 2014; Muimba-Kankolongo et al., 2021b; Mununga Katebe et al., 2023a; Shutcha et al., 2015). To guarantee food security for a growing population, increasing yields with adapted techniques remains a major challenge in developing countries where access to water and suitable soil is not guaranteed and public agricultural policies are sometimes deficient in feeding their populations (Byrnes & Bumb, 2017; Marti & Puertas, 2020). This is particularly true in areas where anthropogenic activities are intense, like mining areas where soils have become less conducive to the production of quality vegetables and fruits in recent decades (Mununga et al., 2023; Treftz & Omaye, 2016).

For these areas, hydroponics could be an alternative growing technique to ensure that the grown plants are free from heavy metal contamination. Hydroponics is a soil-less cultivation technique in which plant roots are immersed in a nutrient-enriched solution and eventually maintained by a preferably inert substrate (Resh, 2013). This method, therefore, has the advantage of dissociating vegetable production and polluted soils. Three important qualities of hydroponics are (i) high yields, (ii) a 40 to 70% reduction in water consumption compared to soil-grown vegetable production, and (iii) its feasibility in areas where access to arable land is limited (due to arid conditions, or simply infertile or polluted soils) (Chandra Barman & Banu, 2016; Franco-Uría et al., 2009; Gonnella & Renna, 2021; Madeira et al., 2016; Majid et al., 2021; Putra & Yuliando, 2015).

In most hydroponics systems, plant roots are immersed in nutritive solutions made from chemical fertilizers (Resh, 2013) derived from petrochemicals. Their mining and manufacturing generate high operating costs and major environmental problems through soil, water, plant, and air pollution (Vikas Kumar et al., 2023; Udume et al., 2023). For some minerals, their purchase prices can rise rapidly, particularly when the cost of the energy required for production is unstable (Ersahin et al., 2023; L. Guo et al., 2022; Xie et al., 2022). Thus, in the face of increasing demand for fertilizers, agriculture will encounter numerous problems of fertilizer scarcity between 2050-2100, as mineral deposits are expected to be depleted (Cordell et al., 2009; Desmidt et al., 2015; Houssini et al., 2023; Sheldrick et al., 2002; Walan et al., 2014). These problems of food shortage could be exacerbated in developing countries, which are highly dependent on imports of synthetic chemical fertilizers (Abebe et al., 2022; Arancon et al., 2019; Basak et al., 2022). This dependence is set to increase over the next few years, given the depletion of the deposits from which these minerals are extracted, on the one hand, and the poverty levels of the populations living in these countries, on the other. It is therefore essential and urgent to think about innovative and sustainable techniques to overcome these global challenges of chemical fertilizer shortages, and bioponics is one such alternative technique. Also known as biological hydroponics, bioponics involves growing plants in an aqueous medium, with the roots immersed in a nutrient solution derived from the partial or total mineralization of animal manure or plant debris (Arancon et al., 2019; Bergstrand Karl-Johan & Hakan Asp and Malin Hulberg, 2020; Ezziddine & Liltved, 2021).

In developing countries, these organic fertilizers can be acquired at low cost (Feller & Beare, 1997; Franzluebbers, 2022; Gholamahmadi et al., 2023). As part of the circular economy, it would make it possible to recycle urban waste instead of making it a source of soil and air pollution and diseases (typhoid, malaria, etc.) (Holm-Nielsen et al., 2009; A. Khalid et al., 2011; Kouhounde et al., 2022). There are several techniques for producing organic fertilizers, such as compost tea (Al Jaouni et al., 2019; Alaboz et al., 2017; Liao et al., 2018; Parastesh et al., 2019; Supriatna et al., 2022) and vermicomposting (Komagbe et al., 2020; Pant et al., 2012). The use of raw materials of animal origin to make compost tea has been shown to have certain advantages, such as the suppression of certain plant diseases (Curadelli et al., 2023; Dede et al., 2023; Funes-Pinter et al., 2023; Komagbe et al., 2020; Jun Li et al., 2023; Haoxian Wang et al., 2020; M. Waqas et al., 2023).

In recent decades, poultry production has surged in response to the growing demand for meat and eggs from both urban and rural populations. The chicken droppings generated by this industry can serve as a multi-purpose resource for agriculture, offering benefits in terms of fertilization, composting, sustainability, and cost. Additionally, this high demand for chicken meat and eggs has encouraged residents to engage in poultry farming, leading to significant animal waste production. Chicken droppings can enhance crop productivity, soil health, and environmental sustainability through their rational use, while also protecting the environment from various sources of pollution (Alfa et al., 2014; Apaeva et al., 2020; Oyewole, 2010).

This study is part of a more global project, which aims to find sustainable solutions to the various environmental problems facing urban agriculture in Lubumbashi. Firstly, the contamination of soil was characterized, by water and plants in the market gardens of Lubumbashi (Mununga et al., 2023). The results showed that the gardens were low, medium, and high in trace metal contamination and that the vegetables were, therefore, highly contaminated. Secondly, organocalcareous soil improvers were applied to clean up the soil. However, vegetables grown from these soils still presented trace metals above the limits imposed by the FAO, demonstrating that the soil improvers did not help in reducing the mobility and bioavailability of heavy metals (Mununga et al., 2024).

This study aimed to analyze the impact of organic fertilizer produced from chicken droppings on yield and trace metals for lettuce grown in bioponic systems. The chicken droppings were chosen based on their availability in the Lubumbashi region, where intensive and family farming is increasingly popular with the city’s inhabitants, to offset the need for staple foods particularly poultry imported from neighboring countries. This study should help in understanding whether these fertilizers are promising for soilless crops run by populations living in the city of Lubumbashi in the D.R. Congo, which faces heavy soil pollution.

To do this, two experiments were set up. The first experiment was implemented to understand the impact of varying amounts of fresh chicken droppings on the preparation of bioponic nutrient solutions and, subsequently, its impact on lettuce yield. The second experiment consisted of determining the optimum nitrogen concentration of the bioponic nutrient solution to optimize bioponic vegetable production. Both yield and quantification of heavy metals were studied in this second experiment to better understand whether this solution is a viable alternative to grown vegetables.

5.2. Materials and Methods

For both trials performed, a bioponic system was used. The sequence of steps taking place during a bioponics production is described in (Figure 5-1). These steps were identical for both trials performed.

The difference between the trials resides in the preparation of nutrient solutions used. In the first trials, varying amounts dry matter of chicken droppings were used during the preparation of the nutrient stock solution. In the second, whilst the dry matter of chicken dropping was kept constant, the total nitrogen of each solution used was varied.

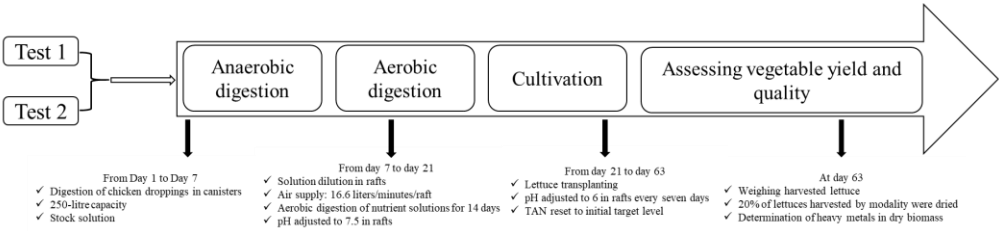


Figure 5-1. Schematic diagram of bioponic nutrient solution production

5.2.1. Plant material and growth conditions

The trials were carried out in a shadehouse located in the Biofortification, Defence, and Crop Valorization (BIODEV) research unit of the Faculty of Agronomic Sciences at the University of Lubumbashi, D.R. Congo.

The lettuce seeds (*Lactuca sativa var. Lucrecia rz*) were obtained from the Laboratory of Integrated and Urban Plant Pathology at Gembloux Agro-BioTech, Université de Liège, Belgium. These lettuce seeds were sown in 36 × 36 × 40 mm rockwool cubes, Grodan, Roermond, Netherlands. Lettuce plants were grown under ambient light conditions and at an average temperature of 20 °C (Figure A2). Eight days after germination, vigorous seedlings with 2–3 true leaves were transplanted onto 2 × 1 m floating rafts, at a rate of 36 plants per floating raft, in a 5 cm diameter hydroponic basket. Lettuces were harvested 42 days after being planted in the rafts (on Day 63 according to Figure 1). All rafts were made of recycled wood, covered with polyethylene bags containing 600 L of nutrient solution, and homogenized by a 950 L/h submersible pump in continuous operation (Sicce, Pozzoleone, Italy) (Figure 5-2).

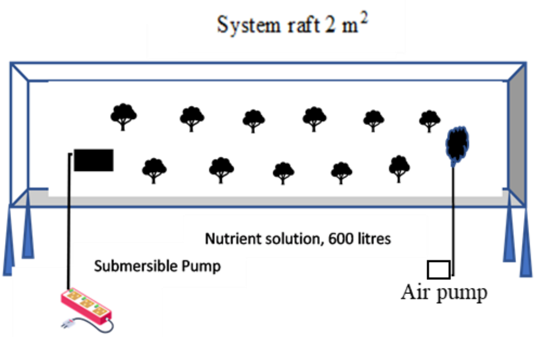


Figure 5-2. Raft system, organic hydroponic cultivation of lettuce plants.

5.2.2. Biofilter preparation

Two weeks before the anaerobic digestion of the chicken manure, bio-balls composed primarily of clay pellets, plastic caps, and biomedia (small plastic cylinders) were prepared in a 100 L capacity tank to ensure the proper development of nitrifying bacteria responsible for the nitrification process of the manure in the rafts. A mixture of 2.5 kg of well-decomposed fresh manure and 2.5 kg of mature compost was combined in 60 L of water, in which 25 L of bio-balls enclosed in a mosquito net were placed. This mixture was maintained under aerobic conditions with an airflow rate of 1.5 L/min into the tank containing the bio-balls for two weeks. The prepared 25 L of bio-balls were then divided into twelve parts, corresponding to the number of rafts (Figure 5-3).

Figure 5-3. Preparation of aerobic biofilters (biomedia, plastic plugs and clay ball).

5.2.3. Production of stock solution from chicken droppings

Thus, chicken droppings were chosen as the organic material for these experiments because it was readily available from both small and large poultry farmers in the city, and it were cheaper than mineral fertilizers (Baboy Longanza et al., 2015). The chicken droppings were purchased from an industrial poultry farm located about 15 km from the Faculty of Agricultural and Environmental Sciences at the University of Lubumbashi. For the production of nutrient solutions, all treatments (0.35%; 3.5%, and 7% dry matter D.M.) were repeated three times, i.e., three cans per treatment leading to a total of nine cans for trial 1 (Table A2). For trial 2, six repetitions (six cans) of the single modality (2.5% dry matter—D.M.) were produced (Table A3). To determine the dry weight of chicken droppings, ten 100 g samples of fresh chicken droppings were taken, weighed, and placed on aluminum plates in an oven at 40 °C for 48 h and then at 105 °C for 24 h (Table A1).

Once the stock solutions were prepared, the mineralization and/or anaerobic digestion of chicken droppings was carried out over a period of 7 days in 200 L canisters.

Following this anaerobic digestion, the nutrient solutions were filtered to remove large particles using a 500 µm mesh sieve, followed by a screening cloth. Only after this filtration process were the nutrient solutions supplied to the rafts.

These solutions were diluted to reach the desired TAN (total ammonia nitrogen). In the first trial, each stock solution was attributed to one raft. Although the chicken dropping concentration is variable (dry matter (%) in Table 1), the TAN (total ammonia nitrogen) concentration was fixed to 150 mg/L per raft before anaerobic digestion for all modalities, which was considered to be the highest concentration of nitrogen that plants can absorb in hydroponics (Resh, 2013). On the contrary, for the second trial, the initial chicken dropping concentration was identical between modalities, but TAN concentrations were fixed to three different values before anaerobic digestion (i.e., 60, 90, and 120 mg/L TAN). This information is summarized in the table below (Table 5-1).

Table 5-1. Summary of two bioponic experimental setups with lettuce cultivation (*Lactuca sativa rz*).

Types of tests	Dry matter (%)	TAN (mg/L) target
Test 1	0.35	150
	3.5	150
	7	150
Test 2	2.5	60
		90
		120

After dilution of the bioponic solutions in the twelve rafts, the latter received 2 L of biomedia and 16/6 L/min of air. Each raft then ran empty for 14 days to allow aerobic digestion to take place (from day 7 to day 21 according to Figure 5-1). For both trials, lettuce was also grown with a reference nutrient solution of Hoagland to assess the yields and quality of lettuce produced in hydroponic cultures (Resh, 2013). Given that this reference solution did not require any aerobic digestion, this one was only implemented in the rafts 14 days after the chicken-dropping prepared solutions. For this reference solution, TAN concentration was fixed at 150 mg/L for the first trial and 120 mg/L for the second trial.

5.2.4. Aerobic digestion of nutrient solutions in hydroponic raft systems before to crop transplanting: empty circulation phase.

The solution diluted in 600 L of water per raft will continue the mineralization process aerobically for 14 days in rafts covered with an impermeable polyethylene bag. Once the bioponic nutrient solution had been diluted in the rafts, the 25 L of biofilter prepared (see Section 2.2) was divided equally in each raft. The bio-balls were left in the rafts until the end of the experiment.

5.2.5. Lettuce cultivation and control of parameters

Before the cultivation phase, the water volume was restored to 600 L (i.e., the initial water level of the raft) with the chicken manure-based nutrient solutions and the reference chemical solution. Water was added here to counter the loss related to evaporation which took place. Lettuce (*L. sativa Lucrecia rz*) seedlings were then transplanted in each raft. The pH was then controlled and corrected if necessary to reach the desired pH of 6: sulfuric acid (H_2SO_4) was diluted to 10% in case of alkaline pH, and sodium hydroxide (NaOH) 3N was used when in acid pH situations. Electroconductivity (EC) was also measured using a conductivity meter. Every seven days, the desired TAN concentrations (60, 90, 120, and 150 mg/L) in the rafts were adjusted to reach the initially implemented TAN levels (Table 5-1) to ensure optimal growth of the lettuce plants until the end of the trials. The TAN adjustment was conducted after analyzing the prepared nutrient solutions with a HANNA brand spectrophotometer to determine the amount of nitrogen absorbed by the plants and the amount evaporated. Electrical conductivity, pH, and TAN concentration were monitored throughout the cultivation period. Every seven days, measurements were taken in the rafts of each of the tested treatments in trials 1 and 2, respectively, until the end of the trials.

5.2.6. Sample characterization

5.2.6.1. Trace metal quantification in chicken droppings raw material

Essential elements (Mg and Ca) and trace metals were determined at the agro-pedological laboratory of the University of Lubumbashi and the laboratory of the Office Congolais de Contrôle (OCC). The extraction consisted of taking 3 g of dried chicken droppings powder and 28 mL of aqua regia. Paper filters were used to filter the extract, which was then diluted with demineralized water and digested for 20 min at 175 °C in a microwave digestion vessel. Characterization of the chicken droppings solution can be found in Appendix A1. Quantification of trace metals (Cu, Co, Cd, Pb, Zn, Fe) in chicken droppings using Perkin Elmer's Optima 7000 DV ICP-OES spectrometer (PerkinElmer, Inc, USA) was performed according to the method developed by (Houba, Uittenbogaard, et al., 1996). The sanitary quality of the chicken manure used in the production of bioponic nutrient solutions was determined. These chicken manures contained trace metal elements; however, these levels did not exceed the limits authorized by the WHO for its use in open-field agriculture. Of all the trace metal elements analyzed, only zinc slightly exceeds the toxicity threshold of 300 mg/kg of Zn permitted for agricultural soil, unlike other trace metal elements such as Cu, Co, Pb, Cd, and Fe, which are below toxicity thresholds. Ultimately, the chicken manures used pose no risk of contamination to the nutrient solutions on the one hand and the bioponic lettuces on the other.

5.2.6.2. Physico-chemical characterization of nutrient solutions

To determine the quality of the nutrient solutions, physicochemical analyses were carried out every week, from the start of digestion to the end of the trials (harvest), using a HANNA HI83300 multiparameter spectrophotometer (HANNA Instrument, Saint Laurent de Mure, France). More specifically, these chemical analyses concerned the control of NPK in its various forms (NH_3^-N; NH_3^-; NH_4^+; NO_3^-N; NO_3^-; PO_4^3; P_2O_5; P; K; K_2O; EC; and pH) and this for all modalities for both trials. During the digestion of chicken manure, samples of highly concentrated nutrient solutions were taken. The collected solution was diluted before performing analyses with a spectrophotometer. During cultivation, the targeted TAN (total ammonia nitrogen) was adjusted weekly by adding concentrated TAN solutions to the rafts.

5.2.6.3. Heavy metals characterization in harvested lettuce

The determination of trace metals in the dry matter of lettuces harvested after the trials was carried out using the AOAC (1990) method. From a total of 36 lettuces per raft, a representative sample of each raft (20%) was dried at 105 °C for 72 h. In this way, all replicates of each modality were mixed to form a composite sample for analysis. A one-gram dry matter sample of the composite sample was taken and placed in a 250 mL digestion tube and mixed with 10 mL of concentrated HNO_3. This mixture was then boiled for 30 to 45 min to allow oxidation of all the elements. After cooling, 5 mL of 70% $HClO_4$ and the mixture were boiled until dense white fumes appeared. Next, 20 mL of distilled water was added and the mixture was brought back to a boiling state to remove the fumes. The heavy metals (Cu, Co, Cd, and Pb) present in the vegetables were determined by acid mineralization (HNO_3 + $HClO_4$), and measurements were carried out by flame atomic absorption (FAA) (Hseu, 2004; Sagagi et al., 2022).

5.2.6.4. Evaluation of lettuce crop yields

Forty-two days after lettuce transplantation, all plants from each raft were weighed on a precision scale to determine the lettuce crop yields on a per-modality basis (Figure A3).

5.2.7. Statistical analysis

Yields in both trials were analyzed using one-way ANOVA (fixed factor was % D.M. in the first trial and TAN content in the second). One-way ANOVA was also performed on heavy metals data in the second trial. When the means were significantly different ($p < 0.05$), a Tukey–Kramer test was performed. One-way ANOVA and a subsequent post-hoc test were elaborated using Minitab 19 (Minitab Inc., State College, PA, USA).

NH_3^-N; NH_3^-; NH_4^+; NO_3^-N; NO_3^-; PO_4^3; P_2O_5; P; K; K_2O; EC; and pH, on the other hand, were analyzed using a two-way mixed ANOVA (within-subject factor was time and between-subject factor was % D.M. and TAN content in the first and second trial, respectively). If a significant interaction was observed between the two factors, Bonferroni correction for multiple comparisons within each time group was performed. When this was not the case, but a significant main effect was still obtained, Bonferroni correction was also used. Two-way mixed ANOVA and subsequent post-hoc tests were performed in R (R 4.3.2 software, R Development Core Team, Boston, MA, USA).

5.3. Results

5.3.1. Assessment of the Impact of Chicken Manure Dry Matter on Bioponics (Trial 1).

5.3.1.1. Physico-Chemical Parameters of the Nutrient Solutions in the Tanks from Trial 1.

During anaerobic digestion TAN, pH, and EC were monitored in all tanks for each of the nutrient solutions modality (0.35% D.M., 3.5% D.M., and 7% D.M.). In all three cases, significant interactions between these two factors (time and % D.M.) were observed ($p < 0.05$). In the case of TAN (Figure 4a), it can be said that similar behaviors were observed on days 28, 35, and 42 between rafts that were fed with nutrient solutions of 0.35% D.M. and 3.5% D.M. On the other hand, TAN for the 7% D.M. nutrient solution was significantly greater at all times except day 49.

Electroconductivity (Figure 5-4b) appears to be the greatest for a nutrient solution at 3.5% D.M. at the beginning of the aerobic phase. Solution 0.35% D.M. gradually increases with time and becomes significantly greater than both 3.5% and 7% D.M. at day 49. Lastly, although overall stable around pH 6, it can be seen from (Figure 5-4c) that the pH obtained for solution 0.35% D.M. is several times greater than that of the other solutions (e.g., significantly greater than that of 7% D.M. at day 21, 28, and 4). Some biotic and abiotic parameters that could influence the results were not controlled, including temperature, light, and microorganisms in the nutrient solutions and rafts. This decision was made to better align our studies with the actual conditions faced by users.

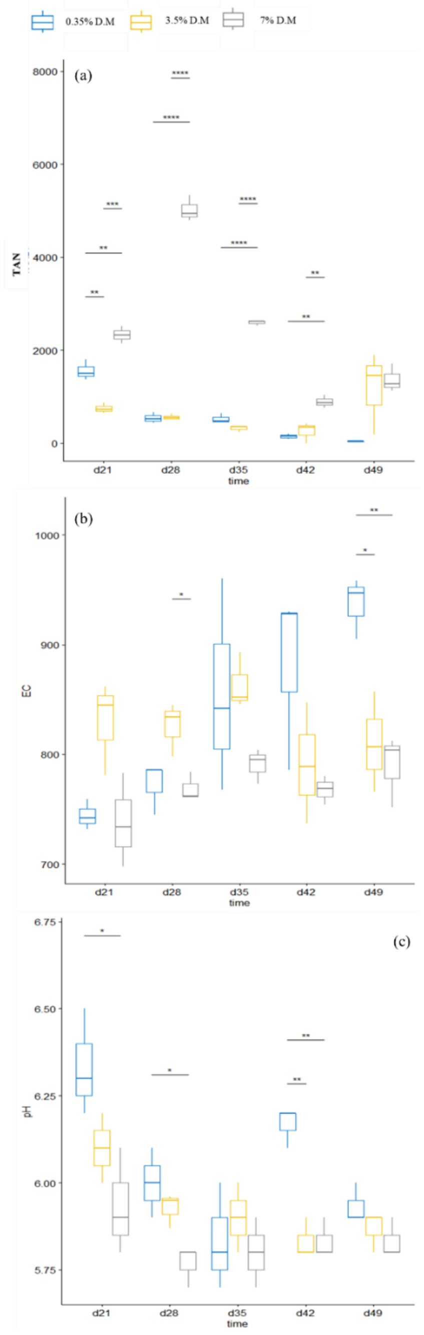


Figure 5-4. Effect of dry matter on TAN (mg/L), electrical conductivity (µS/cm), and pH of bioponic nutrient solutions manufactured from trial 1. Legend: d: days of observation; '****': $p < 0.001$: Highly significant ; '**': $p < 0.01$: Very significant; '*': $p < 0.05$: Significant; EC: electroconductivity; TAN: total ammonia nitrogen.

5.3.2. Evolution of nutrient solutions in the rafts during the cultivation of bioponic lettuces from trial 1.

The results in (Figure 5-5) showed that as the culture time increased, concentrations of NO_2-N, PO_4^{3-}, and TAN also increased until reaching their peak on the 35th day, after which concentrations decreased in all bioponic modalities except for the mineral modality (Figure 5a,e). However, treatments composed of 3.5% and 7% dry matter of chicken manure produced the highest amounts of these nutrients compared to the treatment with 0.35% dry matter. For NO_3-N, on the other hand, the highest concentration was obtained on day 21, just after transplanting, and, consequently, nitrate concentrations overall decreased with increasing days of cultivation (Figure 5-5b). Furthermore, TAN and K contents reached their peak concentrations on the 21st day and decreased as the culture time increased. The best modalities that produced high quantities in TAN were those with 7% dry matter of chicken manure (Figure 5-5d,f).

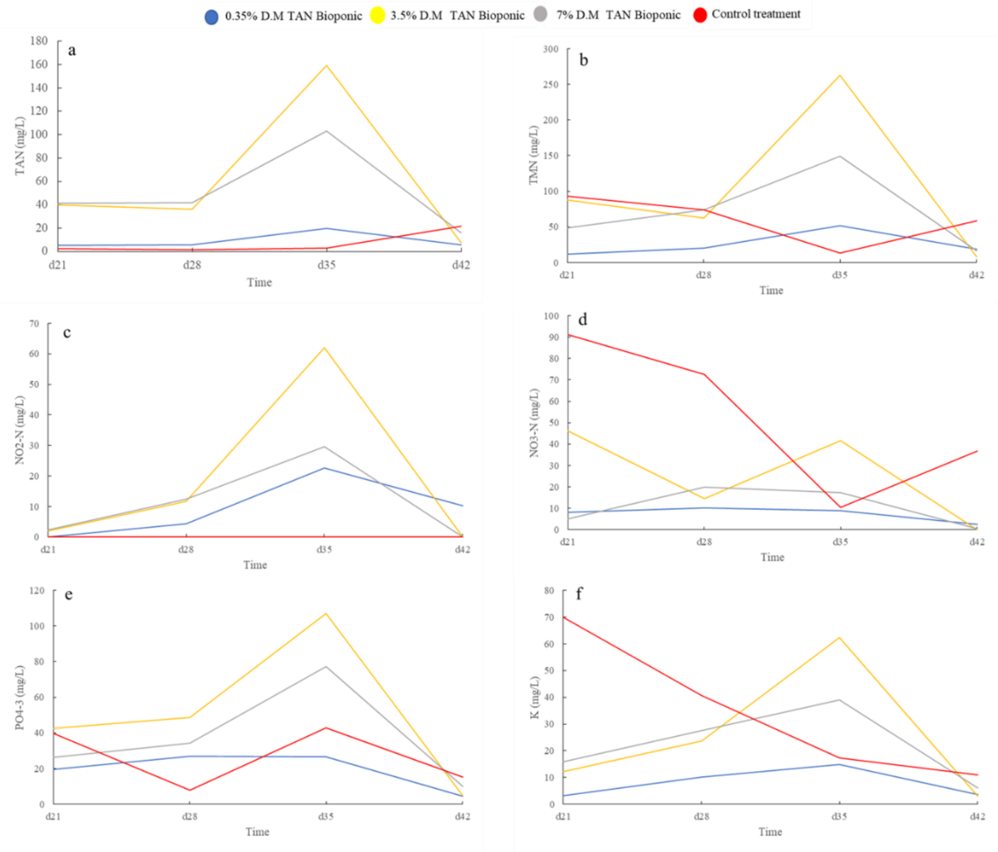


Figure 5-5. Evolution of NPK levels in the nutrient solutions in the rafts during the cultivation phase of lettuces from trial 1. Legend: d: days of observation, TAN: total ammonia nitrogen (mg/L) (a);

TMN: total mineral nitrogen (sum of NO_3-N, NO_2-N-, and TAN) (mg/L) (b); NO_2-N: nitrite nitrogen (mg/L) (c); NO_3-N: nitrate nitrogen (mg/L) (d); PO_4^{3-}: phosphate-phosphorus (mg/L) (e) and K: potassium (mg/L) (f).

5.3.3. Assessment of the yield and sanitary quality of bioponic lettuces for trace metals (TME) in trial 1.

The analysis of variance shows significant differences between the various modalities applied in hydroponic cultures ($p<0.05$) in terms of lettuce yield. The significant difference resides between the reference nutrient solution, which demonstrated higher productivity, and the nutrient solutions based on chicken manure (Table 5-2). However, the analysis of variance shows no significant difference between the modalities with chicken manure. Regarding the sanitary quality of lettuce produced in hydroponics, results show that lettuce grown with a bioponic solution poses no danger to human consumption as the levels of trace elements found in lettuce biomass are below the threshold recommended by the FAO/WHO for human consumption of vegetables. The results of this study demonstrate that variation in dry matter for the formulation of nutrient solutions does not necessarily influence the increase in crop yields. Thus, in the subsequent trial, the aim will be to test whether, for the same concentration of dry matter for the formulation of nutrient solutions, variation in TAN (total ammonia nitrogen) in the rafts could significantly influence crop yields.

Table 5-2. Effects of nutrient solutions on yield and health quality of hydroponically grown vegetables in trial 1. Legend, 0.35% dry matter; 3.5% dry matter; 7% dry matter; Mineral nutrient solution.

Treatments	Yield Trial 1 (g)	Trace metals (mg/kg)					
		As	Cd	Co	Cu	Pb	Zn
0.35% D.M	3074,16±57,1^b	0,05	1,54	0,821	8,51	3,028	18,8
3.5% D.M	1356,3±581,7^b	0,8	0,98	0,68	5,73	1,889	22,1
7% D.M	1702,8±1268,9^b	0,06	1,05	0,92	6,65	5,868	23,5
Mineral	8509,9±1405,3^a	0,9	0,88	0,56	5,89	3,145	15,9

Treatments with at least one common letter do not have a significant difference.

5.3.4. Assessment of the impact of total ammoniacal nitrogen (TAN) Concentration on Bioponics (trial 2).

As mentioned previously at the end of the first trial, the results showed that the amount of dry matter introduced during the anaerobic manure digestion did not significantly influence the lettuce crop yields. Therefore, in this second trial, it was decided to vary the TAN concentration of the nutrient solution in the rafts to evaluate its impact on lettuce crop yields. For this trial, 2.5% dry matter was chosen for the preparation of nutrient solutions using chicken manure, as previously applied by (Szekely et al., 2023). During the anaerobic phase, physicochemical parameters such as pH, EC, and TAN were monitored in the nutrient solutions (Appendix C).

5.3.4.1. Evolution of nutrient solutions in the rafts during the cultivation of bioponic lettuces from trial 2.

Following the anaerobic digestion phase, the formulated nutrient solution was redistributed in the rafts, and the TAN concentration was varied according to three modalities: 60, 90, and 120 mg/L of TAN (Table 1). During the lettuce growing phase, chemical parameters such as TAN, TMN, NO_2-N, NO_3-N, NO_2-N, PO_4^{3-}, and K in the rafts were monitored every 7 days to adjust the TAN concentration to the desired level for both bioponic modalities and the chemical reference modality (Figure 5-6).

Parameters monitored throughout lettuce cultivation are shown in Figure 5-6. Except for the results obtained for NO_2-N, TAN, and TMN, for all other results, a significant interaction was observed between the time of cultivation and TAN content.

In the case of NO_2-N, TAN, and TMN contents found in the rafts, a significant main effect of time was present. Bonferroni multiple comparison was performed to compare the overall effect of time. It appears that the impact of time is similar in all three cases, with a significant decrease between day 28 and day 35. On the other hand, observations made regarding the overall impact of the nutrient solution TAN content on the results are variable. For the NO_2-N content and the TAN content, it appeared that all TAN content modalities were significantly different from each other, with the exception of the reference solution and the chicken-dropping nutrient solution fixed at TAN 60 mg/L. No significant effect of TAN content was observed on TMN results.

For the NO_3-N, PO_4^{3-}, and K contents in the rafts during the culture period, there is an interaction between the culture time and the TAN content. In the case of PO_4^{3-}, an overall decrease in phosphate content in the raft fed with the three bioponic solutions can be observed. However, the bioponic solution with a TAN content of 90 mg/L slightly increased between days 21 and 28 before decreasing again. In the case of the mineral solution, the phosphate content remains low and ultimately increases between days 35 and 42. In the case of the potassium content, the Bonferroni multiple comparisons showed a significant difference between modalities at all culture times except on the 35th day where there are no significant differences. It is observed that there is a decrease in K as the culture time increases for all modalities except for the 60 mg/L modality. Regarding the NO_3-N content, it appears that the mineral solution displays the greatest quantities on day 21. In the following days, this one decreases and reaches NO_3-N quantities comparable to the bioponic solutions modalities. As for potassium content, it appears for the nitrate content that the mineral solution and bioponic solution both at 120 mg/L yield the greatest results (Figure 5-6).

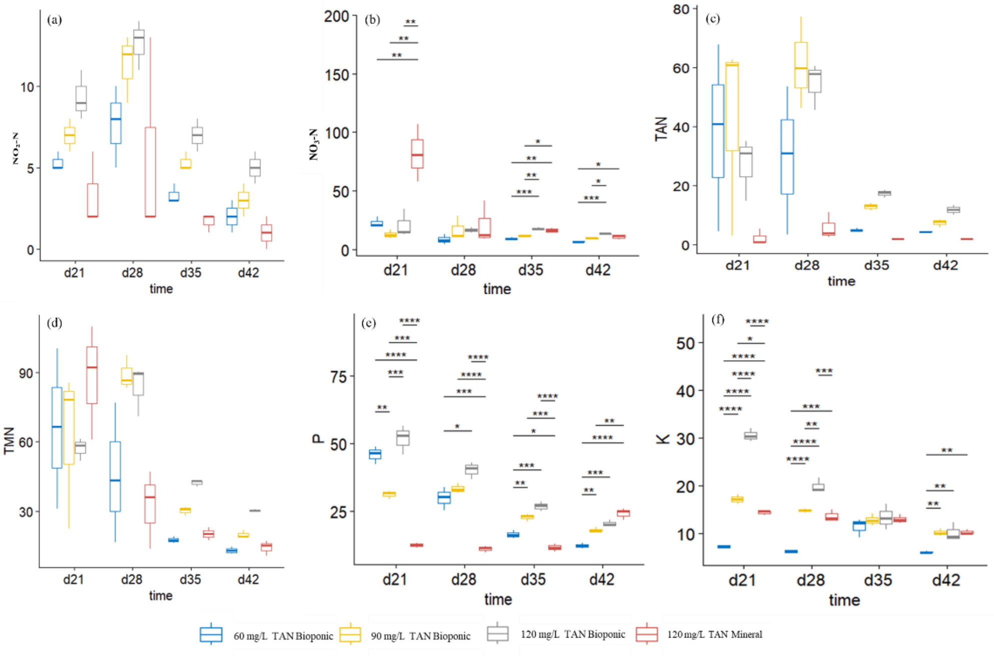


Figure 5-6. Effect of nutrient solutions and different observation dates on the chemical parameters of nutrient solutions in the rafts of trial 2. Legend: d: days of observation; '****': $p < 0.001$: Highly significant; '**': $p < 0.01$: Very significant; '*': $p < 0.05$: Significant; NO_2-N: nitrite nitrogen (mg/L) (a); NO_3-N: nitrate nitrogen (mg/L) (b); TAN: total ammonia nitrogen (mg/L) (c); TMN: total mineral nitrogen (sum of NO_3-N, NO_2-N, and TAN) (mg/L) (d); P: phosphate-phosphorus (mg/L) (e) and K: potassium (mg/L) (f).

5.3.5. Impact of nutrient solution TAN content on lettuce yields and health considerations.

The results of yield and concentrations of trace metal elements are presented in (Table 5-3). After the analysis of variance, it appears that there is a significant difference between the applied modalities (p<0.05) regarding lettuce yields. The mineral modality was found to be more productive than the bioponic modalities; however, the modality receiving low nitrogen concentrations resulted in high yields compared to the other bioponic modalities. However, no significant difference was observed between the modalities of nutrient solutions based on chicken manure. Regarding the accumulation of metals in lettuce biomass, the analysis of variance shows no significant difference between the modalities applied for the trace elements As, Pb, and Zn. However, ANOVA reveals significant differences between the modalities for the trace metals Cd, Co, and Cu (p< 0.05), with the 120 mg/L organic modality showing higher levels of these metals followed by the 90 mg/L organic modality.

Table 5-3. Effects of nutrient solutions on yield and sanitary quality of hydroponically grown vegetables in trial 2. Legend, 60 mg/l TAN biopony; 90 mg/l TAN biopony; 120 mg/l TAN bi-opony; 120 mg/l TAN Mineral solution Resh.

Treatments	Yield Trial 2 (g)	Trace metals (mg/kg)					
		As	Cd	Co	Cu	Pb	Zn
60 mg/L	6105,7±113,7^{a}	0,14±0,13^{a}	0,01±0,007^{b}	0,46±0,04^{b}	6,7±1,22^{b}	1,32±1,37^{a}	39,77±7,02^{a}
90 mg/L	5088±58,32^{a}	0,019±0,02^{a}	0,01±0,00^{b}	1,7±0,76^{a}	6,44±2,89^{a}	1,10±0,21^{a}	34,22±7,63^{a}
120 mg/L	4605±228,40^{a}	0,18±0,18^{a}	0,00±0,00^{b}	0,53±0,02^{b}	13,78±10,54^{a}	1,36±0,35^{a}	22,42±3,20^{a}
120 mg/L Mineral	11221,6±3051,5^{b}	0,054±0,07^{a}	0,07±0,01^{a}	0,32±0,08^{b}	4,71±0,79^{b}	3,27±1,93^{a}	37,1±4,84^{a}

Treatments with at least one common letter are not have a significant difference.

5.4. Discussion

5.4.1. Dynamics of pH, EC and NPK in nutrient solutions during anaerobic and aerobic digestion of hen droppings.

Numerous studies have examined the importance of chicken droppings in the production of liquid fertilizers, particularly in organic hydroponic cultivation (El-Shinawy. M.Z; Abd-Elmoniem; Abou-Hadid, 1999; Mowa, 2018; Tikasz et al., 2019). These chicken droppings are added to water in aerobic or anaerobic conditions, allowing them to ferment for one to two weeks or more, generating a digestate (Szekely & Jijakli, 2022). According to previous research, the use of highly diluted organic digestates in hydroponic cultures has yielded results similar to those of a mineral nutrient solution (Wenke et al., 2009). Conversely, nutrient solutions with a high concentration of digestate were detrimental to plants due to the high NH4+ concentrations, as mineral nitrogen is present in anaerobic conditions. When digestates are highly concentrated in nutrient solutions, there is a massive proliferation of heterotrophic microorganisms that can disrupt nitrifying bacteria if dissolved oxygen concentrations are low (Mangkoedihardjo, 2020; Prinčič et al., 1998). Both trials progressively recorded significant nitrogen losses, which can be explained by the intense development of microorganisms during the aeration phase caused by residual organic matter, as shown in Figures 5 and 6. Heterotrophic bacteria consume and assimilate all the mineral elements produced during mineralization (Finger & Strayer, 1994a; Mackowiak et al., 1996). This explains why the more concentrated digestate modalities experienced greater nitrogen losses than the less concentrated ones.

The transformation of NH_3-N, NO_2-N, and TAN into nitrate NO_3-N in both experiments demonstrates that ammonification and nitrification processes occurred in the formulated bioponic nutrient solutions. The increase in pH of the nutrient solutions can be attributed to various biochemical processes such as ammonification (conversion of inorganic nitrogen into ammonium ions NH_4^+, which absorb H^+), the removal of CO_2 resulting from the transformation of carbonate ions (CO_3^{2-}) and protons H+ into CO_2 and H_2O, and the removal of fatty acids (Mununga et al., 2023; Möller & Müller, 2012). However, under aerobic conditions, the processes of ammonification and mineralization of organic matter are significantly faster, whereas under anaerobic conditions these processes are slowed down. Therefore, in an aerobic environment, various heterotrophic microorganisms play a role in the decomposition of organic matter (Finger & Strayer, 1994a; Mackowiak et al., 1996; Stefanakis et al., 2014). On the other hand, the pH of the nutrient solutions can decrease due to the nitrification process where H^+ ions are released. Conversely, the pH of the nutrient solutions can decrease due to the nitrification process where H^+ ions are released. Consequently, aerobic heterotrophic microorganisms can utilize these ions during the oxidation of organic matter, leading to the release of dissolved CO_2 in the water, which forms carbonic acid and can lower the pH of the nutrient solution (Delaide et al., 2019; Zou et al., 2016). Nearly 80% of the anions and cations absorbed by plants come from nitrogen (NH_3-N and NO_3-N).

These different forms are responsible for the increase and/or decrease in pH of the medium via plant roots when the cation/anion ratio is greater or smaller than one, respectively. The results of this study showed that the pH of the nutrient solution remained near constant throughout the chicken manure digestion process. This could be explained on one hand by the fact that low levels of ammonia could lead to acidification of the plant growth medium, but on the other hand, the fact that the cation/anion ratio would be greater than one implies that an excess of cations in the medium can interfere with the absorption or availability of essential anions for plant growth, thus disrupting the chemical balance of elements in the medium (Dickson et al., 2016). Additionally, some microorganisms present in the environment (*Escherichia coli*, *Saccharomyces cerevisiae*) can produce organic acids or release hydrogen ions during their metabolism, capable of acidifying the medium leading to the unavailability of certain nutrients. Moreover, ammonia nitrogen in solution can be present as free NH_3 at alkaline pH, which could pose significant risks of nitrogen loss through volatilization into the atmosphere by reducing their concentrations (Ávila et al., 2017; Cleland, 1975; Dickson et al., 2016; Driscoll & Likens, 1982; Landsberg, 1981; Lea-Cox et al., 1999; Meharg, 2012; Molinari, 2015; Savvas et al., 2003; Zou et al., 2016).

In hydroponics, measuring the electrical conductivity of a nutrient solution indicates the approximate amount of mineral salts available in the solution. The total amount of ions in the solution exerts osmotic pressure on plant roots and therefore determines plant development, growth, and productivity (Ou et al., 2017). The results obtained show that as the days of mineralization increase, the electrical conductivity simultaneously increases from 2000 to over 5000 (µS/cm), which could be explained by the fact that the chicken droppings used were naturally very rich in nutrients. Similar observations have shown that chicken manure from industrial farming with balanced poultry feed had higher electrical conductivity than other animal manures or manure from traditional farming (J. Kim et al., 2010; L. Zhang et al., 2014).

5.4.2. Effects of nutrient solutions on plant growth in bioponic cultures.

In both trials, visual observation revealed that the growth of lettuce plants in the bioponic treatments was marked by a delay compared to the chemical reference treatment seven days after lettuce transplantation into the rafts. This delay in plant growth could be explained by the fact that plants need to acclimate to their new growing environment, transitioning from tap water to an organic nutrient solution (Pelayo Lind et al., 2021). However, a decrease in the levels of essential elements in the organic nutrient solutions was observed. This phenomenon could be explained by the fact that treatments with the highest concentrations of dry matter and TAN contained, on one hand, large amounts of residual organic matter, and on the other hand, they developed an intense microbial activity that would disrupt the proper functioning of nitrifiers, thus making oxygen increasingly scarce in the environment.

Consequently, essential minerals released during mineralization are often consumed by heterotrophic bacteria but also assimilated by plant roots (Finger & Strayer, 1994b; Mackowiak et al., 1996). However, organic treatments with higher concentrations of dry matter or TAN were prone to significant nitrogen losses compared to less concentrated treatments due to the formation of biofilms on the surfaces of production systems on one hand (Goddek et al., 2018). On the other hand, these biofilms may present risks by trapping or adsorbing minerals through the formation of anaerobic zones, thus leading to the denitrification process at the expense of organic matter nitrification (Alburquerque et al., 2012; Kawamura-Aoyama et al., 2014; Mackowiak et al., 1996). However, the absorption of nutrients by plants as well as the conversion of nitrites to nitrates by microorganisms can also reduce nutrient concentrations in the nutrient solution (Eck et al., 2021; Goddek et al., 2015).

Phosphorus can exist in several forms depending on the pH of the medium, and its root uptake can occur via PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^-$ ions, with the latter two forms being the most absorbed by plants. Phosphorus is more available to plants at slightly acidic pH levels (around 5) in conditions where plants are grown on inert substrates. However, when the pH of the nutrient solution becomes alkaline or very acidic, phosphorus availability decreases (Asao, 2012; Gerke, 2021). Our results showed that the pH of the nutrient solutions was alkaline during the cultivation period, while the phosphorus concentration increasingly decreased. This phenomenon could be explained by the fact that phosphorus precipitated as calcium phosphate, lead phosphate, or magnesium phosphate, forms that are less available to plants (Cheyns et al., 2012; M. J. Kwon et al., 2021; J. Y. Lee et al., 2017, 2018).

5.4.3. Yield and health quality of lettuce plants grown in bioponic cultures.

Hydroponic cultivation offers several advantages, including water economy and agricultural product quality. Additionally, it provides higher crop yields compared to conventional agricultural production techniques (Casey et al., 2022; S. Chandra et al., 2014; Goh et al., 2023; Imsande, 1986; Jesse et al., 2019; Magwaza et al., 2020; Sambo et al., 2019; Verdoliva et al., 2021). In both trials, the highest lettuce crop yields were obtained with the mineral nutrient solution modality, followed by the bioponic modality with low D.M. (in the case of trial 1) and low TAN content (in trial 2). Although not statistically significantly different, great differences are observed between the modality with low D.M. and low TAN compared to the two other bioponic modalities. This is explained by the fact the plant's need for nitrogen comes mainly from nitrate and to a smaller extent from TAN. The nitrogen uptake originating from TAN remains, however, small as this one can become toxic at high concentrations (Ilic et al., 2022; Juan Li et al., 2023; B. Liu et al., 2023; Masclaux-Daubresse et al., 2010; Yoneyama et al., 2003).

At the beginning of the lettuce growth stage (day 21 in Figures 5 and 6), high nitrate concentrations and low TAN concentrations are found for the reference solution, which, therefore, leads to optimal growth and fine high lettuce yields. In trial 1, reference treatment and bioponic solution with the lowest D.M. (i.e., 0.35% D.M.) display comparable TAN concentrations. However, this bioponic modality does not display similar NO_3-N concentrations to the reference. In other words, the initial TAN concentration for this low D.M. modality does not limit plant growth; however, NO_3-N concentrations remain low, and growth is not particularly promoted either. Although the difference in NO_3-N and TAN concentrations existing between the reference and the bioponic solutions become smaller towards the end of cultivation in both trials, it is the difference existing at the beginning of cultivation that will have the greatest impact on plant growth and impact yield. Altogether it can be said that even if bioponic solutions do not offer the same lettuce yields, the use of low D.M. and low TAN contents can offer better yields than other bioponic options for local populations wishing to use bioponics.

Additionally, lettuce plants grown through bioponic cultivation in the agro-environmental conditions of Lubumbashi pose no risks for human consumption, with metal concentrations detected in lettuce leaves being below the toxicity threshold set by the WHO/FAO for human vegetable consumption. In regions with high heavy metal concentrations, the WHO suggests that vegetables intended for human consumption should not exceed toxicity thresholds, which are set for most trace elements, notably 10-20 mg/kg Cu, 1-5 mg/kg Co, 5-10 mg/kg Pb, and 1-2 mg/kg Cd; beyond these toxicity thresholds, vegetables containing higher levels of trace metal elements are considered contaminated. Bioponics may serve as an alternative for producing quality vegetables in an environment impacted by anthropic activities, particularly mining and mineral (Magwaza et al., 2020; Sambo et al., 2019). In the context of environmental contamination and pollution in the city of Lubumbashi, the use of new technologies such as bioponics may prove to be a more efficient solution to produce quality vegetables. The use of organic fertilizers in hydroponics offers numerous economic, ecological, and environmental advantages (C. Mai et al., 2023; Maucieri et al., 2018; Treftz & Omaye, 2016). Hydroponic crops are known to be environmentally friendly because they save water resources, consume less water, and do not use too many pesticides. One of the limits consists of using synthetic chemical fertilizers. However, we, as others (Barbosa et al., 2015; S. Lee & Lee, 2015) contribute to the prospect of the possibility of using organic fertilizers derived from animal dung and plant debris as a source of nutrients for the plants. The productivity of vegetable crops such as Chinese cabbage in Lubumbashi gardens remains relatively low, with average yields estimated at around 1.9 kg/m^2. Additionally, harvest products from this conventional soil-based agriculture remain of poor sanitary quality. Harvest products from this new soilless technique are free from any metallic contamination and produce greater yields compared to soil-grown cultures (Arsène Mushagalusa Balasha and Maurice Kesonga Nsele, 2019).

5.5. Conclusion

This study aimed to develop and optimize a new bioponic technique to produce liquid fertilizer from chicken manure and implement it in the organic hydroponic (bioponic) cultivation of lettuce (*Lactuca sativa* rz). To achieve this, two types of trials were conducted under shade netting in the ambient conditions of Lubumbashi. Overall, the results are particularly promising as they demonstrate that quality vegetables can be produced, with interesting yields, exclusively using animal waste as fertilizing material. Our technique, which involves fermenting chicken droppings for hydroponic lettuce production in an environment contaminated by trace metals in Lubumbashi, has proven to be an ecological, and practically implementable approach. The results obtained indicate that the use of low percentages of dry matter from chicken manure (0.35% DM) and low concentrations of total ammoniacal nitrogen (60 mg/L total ammoniacal nitrogen) do not significantly influence crop yields compared to bioponic treatments receiving higher concentrations of dry matter and/or total ammoniacal nitrogen, respectively, in trials 1 and 2. Although the yields obtained with chemical nutrient solutions are significantly different and remain superior to bioponic treatments, chicken manure represents a potential nutrient source for plants in urban agriculture.

Additionally, lettuces grown using bioponics are safe for consumption, as they contain no trace metal levels above the FAO/WHO toxicity threshold for vegetables. However, further studies should investigate nitrogen loss mechanisms in the rafts, the role of nitrifying bacteria in organic matter, and the valorization of methane gas produced during the anaerobic fermentation process of chicken manure. Lastly, additional studies could test the cultivation of local plant species with added value and other types of organic matter in bioponic vegetable cultivation.

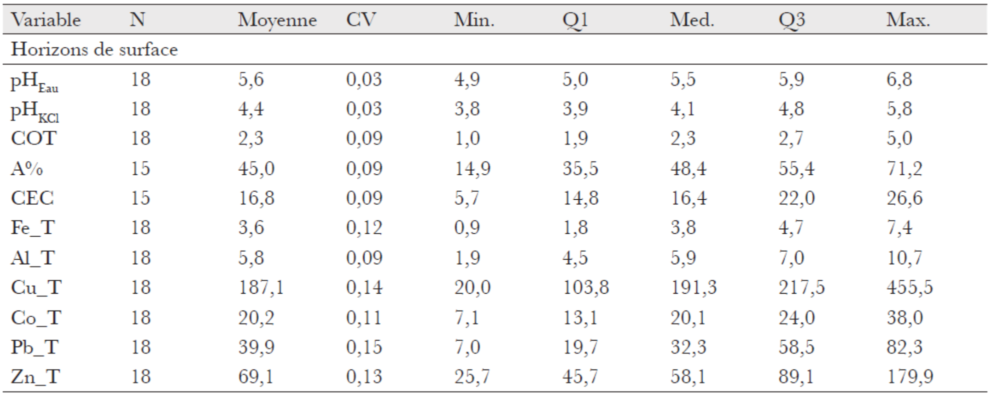
Chapitre 6 :

Discussion générale

6.1. Typologie des jardins maraîchers en fonction de la contamination, de l'enrichissement et de la pollution des sols par les métaux.

Les métaux lourds retrouvés dans les sols et les plantes proviennent principalement de deux origines notamment celle naturelle et anthropique. Les métaux issus de l'origine naturelle sont la résultante de l'altération de la roche-mère, par contre ceux d'origine anthropique proviennent des activités humaines principalement, la combustion des charbons, l'utilisation des pesticides dans les exploitations agricoles, les activités minières, etc…(Brugge & Datesman, 2023; Yizhang Liu et al., 2017). Ainsi, la connaissance des diverses sources de contamination métallique s'avère importante dans l'évaluation de la contamination environnementale, car elle permet de mettre en place des stratégies de gestion rationnelle pouvant réduire le risque de contamination de l'environnement (W. Hu et al., 2018; Peng et al., 2020). Dans l'ancien temps, cette évaluation de la contamination se reposait sur la mesure des concentrations totales des métaux lourds (Bi et al., 2009; H. Cheng & Hu, 2010), méthodes jugées insuffisantes pour une évaluation précise détectant les origines de la contamination métallique des sols ou des plantes (Komárek et al., 2008; Notten et al., 2008). C'est pourquoi des indices spécifiques ont été mis en place pour déterminer l'origine des métaux dans l'environnement notamment l'indice de géo-accumulation, le facteur de contamination, le facteur d'enrichissement, l'indice de charge polluante et le facteur de bioconcentration (Cabrera et al., 1999; W. H. Liu et al., 2005; Rezapour et al., 2019; Tomlinson et al., 1980). Pendant près de deux décennies, les travaux effectués à Lubumbashi pour déterminer la contamination de l'environnement s'est réalisée sur base des teneurs totales, rendant ainsi moins efficace cette évaluation (Mpundu et al., 2014; Ambayeba et al., 2021; Shutcha et al., 2015). Ces approches, basées sur l'observation visuelle des concentrations totales, semblent moins explicites que l'utilisation de divers indices spécifiques pour caractériser la pollution et la contamination des sols, car ces indices permettent d'évaluer la présence et l'intensité du dépôt des éléments traces métalliques (Barbieri, 2016; Borah & Deka, 2023; Chandrasekaran et al., 2015; Ferreira et al., 2022; Kowalska et al., 2018; E. Mohamed et al., 2023; Niu et al., 2019; Norani et al., 2023; Williams & Antoine, 2020). Sur base du fond pédogéochimique des sols de référence de la région du Ktanaga, une étude a été effectué afin de déterminer l'origine de la contamination, de la pollution et de l'enrichissement des sols dans les jardins maraîchers urbains et périurbains de Lubumbashi (Tableau 6-1).

Tableau 6-1. Fond Pédogéochimique des sols de référence dans la région de l'ex-province du Katanga, N : nombre d'échantillons ; CV : coefficient de variation ; Q1-Q3 : 1er et 3ème quartile ; Med. : médiane ; Max. : maximum ; Min. : minimum ; COT (%) : carbone organique total ; A% : pourcentage d’argile ; CEC : capacité d’échange cationique (cmolc.kg-1) ; _T : concentration totale (mg/kg) (Bogaert et al., 2018).



Variable	N	Moyenne	CV	Min.	Q1	Med.	Q3	Max.
Horizons de surface								
pH_{Eau}	18	5,6	0,03	4,9	5,0	5,5	5,9	6,8
pH_{KCl}	18	4,4	0,03	3,8	3,9	4,1	4,8	5,8
COT	18	2,3	0,09	1,0	1,9	2,3	2,7	5,0
A%	15	45,0	0,09	14,9	35,5	48,4	55,4	71,2
CEC	15	16,8	0,09	5,7	14,8	16,4	22,0	26,6
Fe_T	18	3,6	0,12	0,9	1,8	3,8	4,7	7,4
Al_T	18	5,8	0,09	1,9	4,5	5,9	7,0	10,7
Cu_T	18	187,1	0,14	20,0	103,8	191,3	217,5	455,5
Co_T	18	20,2	0,11	7,1	13,1	20,1	24,0	38,0
Pb_T	18	39,9	0,15	7,0	19,7	32,3	58,5	82,3
Zn_T	18	69,1	0,13	25,7	45,7	58,1	89,1	179,9

Les résultats obtenus révèlent que les sols des jardins maraîchers de Lubumbashi présentent divers degrés de contamination, allant de non contaminé, légèrement contaminé, voire moyennement ou encore très fortement contaminé par différents éléments traces métalliques. Ces contaminations sont principalement dues aux activités humaines qui ont eu un impact négatif sur les sols agricoles en milieu urbain (Mununga et al., 2023). Ces métaux sont préoccupants pour divers écosystèmes terrestres et marins, car ils peuvent se retrouver dans les eaux et les sols ainsi que la chaine trophique qu’ils supportent, tels que les poissons, les fruits et légumes des zones présentant des niveaux d'indices supérieurs à la normale et subséquemment les mammifères (L. Huang et al., 2020; D. Kumar & Khan, 2020; Mehana et al., 2020; Mng’ong’o et al., 2021; Perković et al., 2022). Nombreuses entreprises minières installées dans et autour de la ville de Lubumbashi entraîne une pollution des sols agricoles et résidentiels. Face à ces niveaux élevés de contamination des sols, des mesures ont été prises pour réduire le transfert des polluants du sol aux plantes, notamment l'épandage de chaux agricole sur tous types de sols (Liping He et al., 2020; Mei Huang et al., 2016; Y. Huang et al., 2019; Z. Li et al., 2014; Mileusnić et al., 2014; Z. Sun et al., 2018; Y. J. Wu et al., 2016; H. Zhou et al., 2022). L'absorption des éléments traces métalliques par les plantes à partir du sol est influencée par les conditions physico-chimiques du sol, le pH du sol, la présence ou l'absence d'oxygène, ainsi que le type de sol, ce qui peut également avoir un impact sur la forme sous laquelle ces éléments sont présents dans la solution (Alsaffar et al., 2015; Mei Huang et al., 2016; Kumarathilaka et al., 2018; R. F. Saad et al., 2018; Shu et al., 2017).

D'ici à 2050, les Objectifs de Développement Durable des Nations Unies, notamment les objectifs 2 et 12, visent à garantir que chaque individu sur terre puisse accéder au bien-être et à une alimentation durable. Cela soulève des questions cruciales concernant la qualité et la quantité des denrées alimentaires à consommer à l'avenir (Arora & Mishra, 2022; Fonseca et al., 2020; Y. Zhang et al., 2021).

L'industrie minière est actuellement une source d'emplois majeure dans de nombreux pays, mais elle est également à l'origine de nombreux dommages environnementaux, notamment la contamination des sols agricoles, de l'eau et de l'air, avec des conséquences significatives sur la santé humaine (Agboola et al., 2020; Du et al., 2022; Hasanuzzaman & Bhar, 2019; Mantey et al., 2020; Ofosu & Sarpong, 2023). Lubumbashi, une ville située dans la province du Haut-Katanga, est au cœur de ces problèmes environnementaux, en particulier en ce qui concerne la contamination des sols agricoles, ce qui nuit à la qualité et à la quantité des récoltes (Atibu et al., 2016; Banza Lubaba Nkulu et al., 2018; Cheyns et al., 2014; Pourret et al., 2015; Squadrone et al., 2016). Nos résultats ont permis d'établir une cartographie des marchés où au moins cinq vendeurs de légumes sont présents dans la ville de Lubumbashi. Cette cartographie offre une base solide aux décideurs du secteur public pour prendre des décisions éclairées concernant l'agriculture urbaine, notamment en ce qui concerne la nature des jardins maraîchers, leur affectation et les possibilités d'encadrement de cette forme d'agriculture urbaine (Atibu et al., 2016; C. Brown et al., 2022; Mancini et al., 2021; Mununga et al., 2023; Muteya et al., 2022; Otamonga & Poté, 2020).

Face à la pollution excessive des sols et des rivières, les entreprises minières de Lubumbashi ont adopté la pratique de l'épandage de chaux vive sur les sols contaminés afin d'immobiliser les éléments traces métalliques en augmentant le pH du sol. Des études menées par (Mpundu et al., 2014) ont révélé que la majorité des légumes (*Amaranthus vulgaris, Beta vulgaris, Brassica chinensis* etc…) vendus sur les marchés de Lubumbashi ne sont pas propres à la consommation humaine en raison de leur teneur élevée trouver dans leurs biomasses au-dessus du seuil de toxicité fixé par l'OMS pour la consommation des légumes. De même, des recherches menées en Inde par (Bempah & Ewusi, 2016; Sweta & Singh, 2022; J. Wang et al., 2021; J. Yang et al., 2018; Zwolak et al., 2019), ont montré que l'exploitation minière était responsable de la contamination de fruits et légumes car ils présenté des concentrations en éléments traces métalliques dépassant les limites recommandées pour la consommation humaine. De nombreux chercheurs soulignent que la pollution environnementale résultant des activités minières a un impact négatif sur l'ensemble de la chaîne alimentaire, et ses conséquences sont observées au fil des années (Gall et al., 2015; R. Jiang et al., 2023; Martins et al., 2023).

Les zones urbaines fortement industrialisées sont responsables de la pollution des nappes phréatiques et de l'atmosphère à l'échelle mondiale. Les rejets d'effluents dans les cours d'eau de ces régions ont des répercussions sur leur écosystème (Adamovic et al., 2022; Fayiga et al., 2018; C. Jiang et al., 2021; Kurwadkar et al., 2020; Yu Liu et al., 2021; Moyé et al., 2017; Mwaanga et al., 2019; Ruhela et al., 2022; K. Song et al., 2022; Ming Zhang & McSaveney, 2018; G. Zhu et al., 2020). Cette pollution rend également certains quartiers inhabitables en raison de concentrations élevées de contaminants dans l'air. Ces concentrations provoquent des problèmes respiratoires et cardiovasculaires chez les êtres humains (Fugiel et al., 2017; Goodkind et al., 2020; Hota & Behera, 2015; Tian et al., 2019; Ukaogo et al., 2020). Pour évaluer les effets de la pollution atmosphérique, de nombreux indicateurs de la santé environnementale sont utilisés afin de trouver des solutions alternatives pour protéger l'environnement et réduire les risques pour la santé liés à l'inhalation de ces polluants (Adimalla et al., 2020; Minjuan Huang et al., 2014; Mandal et al., 2023; L. Yan et al., 2021). À Lubumbashi, nos résultats révèlent une légère contamination pour la plupart des rivières et cours d'eau échantillonnés. Cette constatation peut s'expliquer par le fait que l'application de chaux vive dans les rivières modifie les conditions physico-chimiques en élevant le pH vers des valeurs alcalines, ce qui entraîne l'immobilisation et la précipitation de certains éléments traces métalliques (Balasha & Peša, 2023; Kalonda et al., 2017; Mununga et al., 2023).

Par ailleurs, la contamination atmosphérique a fait l'objet d'études approfondies dans la région du Haut-Katanga au cours des dernières décennies en raison de ses nombreuses conséquences, notamment l'émergence de nouvelles maladies telles que l’asthme infantile, les troubles hypertensifs augmentant ainsi le taux de mortalité des et de morbidité aux population riveraines (Flanagan et al., 2022; Ghoshdastidar et al., 2018; Joubert et al., 2020). On a également observé une contamination des sols résidentiels et la disparition de certaines plantes de la forêt claire de Miombo dans les parcelles en raison de concentrations élevées d'éléments traces métalliques notamment en cuivre, cobalt, arsenic et cadmium, etc… remplacée par une végétation basse spécialisée dans l’absorption des fortes teneurs en métaux avec les espèces comme *Microchloa aletera, Haumaniastrum katangense* (Shutcha et al., 2015 ; Chipeng*et al.*, 2009). Par conséquent, plusieurs entreprises minières testent diverses techniques de dépollution des cours d'eau, notamment la phytostabilisation, la phytoépuration ainsi que la phytovolatilisation des sols fortement contaminés par les métaux lourds (Cu et Co). Parmi les espèces végétales utilisées pour décontaminer les sols, les espèces ligneuses et les herbacées sont les plus souvent utilisées. Ces techniques de phytoremédiation des sols, prennent beaucoup de temps pour parvenir aux résultats escomptés (Y. Gao et al., 2010; Madejón et al., 2018; Vareda et al., 2019; Q. Xu et al., 2022 ; Mpundu et al., 2014; Shutcha et al., 2015; Mununga et al., 2018).

6.2. Efficacité des amendements organocalcaires sur la réduction du transfert des métaux du sol vers les plantes.

Les amendements organocalcaires sont connus pour leur capacité à réduire la mobilité et la biodisponibilité des éléments traces métalliques dans les sols (Bolan et al., 2014; Feng & Cheng, 2023; Lizhi He et al., 2019; Hong et al., 2022; Mei Huang et al., 2016; S. Li et al., 2021; Park et al., 2011; R. Zhou et al., 2017). Cependant, l'efficacité de cette réduction dépend du niveau de contamination de chaque sol ainsi que du type de sol contaminé ou pollué par ces éléments traces métalliques spécifiques (Abdu et al., 2017; Bolan et al., 2014; McBride & Li, 2023; Qin et al., 2021; J. Zhang et al., 2018). Nos résultats indiquent que l'application d'amendements organiques et calcaires réduit la mobilité et le transfert des éléments traces métalliques du sol vers les plantes. Ils corroborent les résultats trouvés par Mpundu et al., 2014, qui avaient montré que l'application simple d'amendements organiques ou calcaires ne réduisaient pas significativement le transfert des métaux, contrairement au mélange de deux amendements organique et calcaires qui avaient réduit le transfert des métaux du sol vers les plantes, quoique les teneurs trouvées étaient supérieures au seuil de toxicité de l'OMS. Cependant, le transfert des métaux du sol vers les plantes varie en fonction du niveau de contamination initial des sols. Il est intéressant de noter que pour les sols fortement pollués par les métaux, les amendements organiques et calcaires n'ont pas réussi à réduire sensiblement les concentrations en dessous des seuils de toxicité pour les quatre légumes cultivés sur les sols contaminés par les métaux (*Brassica chinensis*, *Brassica carinata*, *Beta vulgaris* et *Amaranthus vulgaris*) destinés à la consommation humaine. Toutefois, l'indice de consommation journalière trouvé pour la majorité des métaux lourds sur le sol du jardin faiblement contaminé de Kashamata était légèrement supérieur au seuil autorisé par la FAO/OMS pour une consommation humaine (Adamo et al., 2014; V. Shah & Daverey, 2020; R. H. Zhang et al., 2017; Y. Zhou et al., 2020). Nos résultats corroborent ceux trouvés par Muhammad Ahmar Amin et al., 2023, qui ont montré que l'apport de biochars aux sols contaminés par les métaux avait permis de réduire sensiblement le transfert des métaux du sol vers les plantes et l'indice de risque a été réduit sur la culture du blé (*Triticum aestivum L.*).

Les amendements organocalcaires appliqués aux sols contaminés par les éléments traces métalliques ont un double effet. D'une part, le carbonate de calcium augmente le pH du sol, agissant comme un amendement alcalin comme les acides organiques qui neutralisent les éléments traces métalliques tels que le plomb, le cuivre et le cadmium (Adamczyk-Szabela et al., 2015; Awad et al., 2020; R. Y. Kim et al., 2015; Rocco et al., 2018). D'autre part, l'ajout de matière organique augmente la capacité d'échange cationique du sol, ce qui permet de retenir les ions métalliques, réduisant ainsi leur mobilité dans les sols et facilitant les échanges de cations.

Ces amendements organiques appliqués aux sols agricoles contaminés par les métaux libèrent des substances telles que les acides organiques, les acides humiques et fulviques, les polysaccharides etc…peuvent servir de source importante de carbone, alimentant ainsi les microorganismes du sol. Ceux-ci peuvent décomposer les différents contaminants du sol d'une part ou l'immobilisation des métaux d'autre part (Agrelli et al., 2020; Daldoul et al., 2015; Igalavithana et al., 2017). En conséquence, les plantes absorbent les métaux de manière différenciée dans leurs tissus en fonction de leurs mécanismes, ce qui permet de les classer en différents groupes, notamment les hyperaccumulatrices, les accumulatrices, les tolérantes, et les excluantes. Quoi que les espèces végétales de la famille de Brassicacée, soient dans la catégories des hyperaccumulatrices, certaines plantes comme la poirée bette (*Beta vulgaris*), la carotte sont des accumulatrices, contrairement aux laitues qui sont exclueuses des métaux (A. Ahmed et al., 2021; Ghuge et al., 2023; I. Khan et al., 2021; Srinivasan, 2000; Xia et al., 2020 ; Y. Jiang et al., 2015; Zhuang, 2005; M.J. McLaughlin et., 2015).

6.3. Fabrication des solutions nutritives organiques et leur utilisation en culture hydroponique

La qualité des solutions nutritives dépend de plusieurs facteurs, notamment leur composition chimique, leur biodisponibilité, leur stabilité, leur pH, la qualité de l'eau, ainsi que leur qualité microbiologique (Alexopoulos et al., 2021; Ciriello et al., 2021; Ding et al., 2018; Resh, 2013; Szekely et al., 2023; Wortman, 2015). Après de nombreux essais, nous avons réussi à élaborer des solutions nutritives à base de fientes de poules adaptées au contexte de Lubumbashi. Les rendements des cultures obtenus avec ces solutions bioponiques se rapprochent de ceux obtenus avec des solutions nutritives chimiques de référence, en particulier dans le cadre du deuxième essai. Il est important de noter que les plantes de laitue produites n'ont pas montré de contamination métallique de leurs parties aériennes. La fabrication de solutions nutritives par la bioponie implique la transformation des matières organiques riches en substances azotées, favorisant une meilleure croissance des plantes (Gartmann et al., 2023; Wongkiew et al., 2021, 2022, 2023). Cependant, ces matières organiques sont sujettes à des pertes importantes en azote dans les solutions nutritives, ce phénomène pourrait être attribué à divers facteurs notamment la volatilisation de l’ammoniac, la dénitrification, l’absorption par les plantes et l’immobilisation microbienne induisant ainsi une altération de la qualité de l’eau, la déficience nutritionnelle des plantes enfin des faibles rendements des cultures (Dsouza et al., 2021; Thomas & Bose, 2023; Wongkiew et al., 2021). E. Epstein, A. Bloom, 2005; S.R. Grattan et al., 1999; Z. Rengel, 2015; Roger Knowles, 1982; Mark A. Sutton et al., 2011).

Nos résultats indiquent que lorsque les solutions nutritives contiennent de grandes quantités de matière organique (7% de matière sèches) ou de fortes concentrations en azote (150 mg/kg de TAN), elles perdent davantage d'azote ce qui est en accord avec les résultats précédemment trouvés (Gentile et al., 2008; Scott & Rothstein, 2014; Soto et al., 2015; Szekely et al., 2023; Terman, 1980; van Kessel et al., 2009). Ces mêmes auteurs ont montré que l’apport au sol des fortes quantités de compost et d’azote minéral avaient causé des pertes d’azotes dans le sol agricole. Les solutions nutritives produites en bioponie peuvent être suffisamment riches en éléments majeurs pour permettre une production de légumes en quantité et en qualité (Szekely & Jijakli, 2022; Wongkiew et al., 2023). Ces fortes concentrations en azote, phosphore et potassium sont généralement attribuables à l'alimentation équilibrée en protéines et vitamines des poules dont proviennent les fientes (Azeez & Van Averbeke, 2010; Delve et al., 2001; Leitner et al., 2021; Mkhabela & Materechera, 2003). Afin de garantir la biodisponibilité des éléments nutritifs pour les plantes, le pH des solutions nutritives a été maintenu à 6, car c'est autour de cette valeur que les éléments sont le plus accessibles aux plantes (Arancon et al., 2019; Rusmanta et al., 2019; Y. Zhu et al., 2021), contrairement aux environnements très acides ou très alcalins. Cependant, lors de la fermentation anaérobie des solutions nutritives dans les bidons-citernes, le pH avait tendance à devenir légèrement acide à très acide, ceci pourrait expliquer les faibles rendements des modalités bioponiques par rapport à la modalité de référence (Boe et al., 2010; C. liu; X. Y. G. Z. W. L. J. Li, 2008; H. Li et al., 2012; Rawoof et al., 2021).

La qualité de l'eau utilisée peut affecter la présence et l'activité des microorganismes essentiels impliqués dans le processus de minéralisation. C'est pourquoi, pour nos essais, nous avons utilisé de l'eau de ville (RESIDESO) que nous avons laissée reposer à l'air libre pendant 72 heures sans traitement, afin de permettre l'élimination de substances telles que le chlore qui pourraient inhiber les bactéries et les champignons. Des études antérieures (Karlidag et al., 2011; LeChevallier et al., 1988) ont montré que le chlore était responsable de la perte de diversité biologique dans les eaux traitées au chlore. Les bactéries pendant la digestion des matières organiques, jouent un rôle essentiel dans le processus de nitrification, elles peuvent avoir des effets antagonistes sur les solutions nutritives et les plantes si elles parviennent à utiliser les nitrates produits, comme source d’énergie (Bruni et al., 2023; Martínez-Sánchez et al., 2006; X. Wang et al., 2023).

6.3.1. Cycles des nutriments et processus microbiologiques en culture hydroponique

Les rendements des laitues dans les deux essais ont été déterminés. Il est apparu que la modalité de référence chimique avait des rendements très élevés par rapport aux modalités bioponiques. Il faut souligner que les modalités bioponiques avec de faibles concentrations de matière sèche et d'azote ammoniacal total (TAN) avaient des rendements plus élevés que les modalités avec de fortes concentrations de matière sèche et de TAN, ceci pourrait s'expliquer par la présence de phytohormones de croissance telles que les auxines, les gibbérellines, les cytokinines et certains acides humiques dans les boues bioponiques composées principalement de déjections animales, et pourrait être la cause principale de l'augmentation des rendements de laitue pour les modalités ayant les plus faibles concentrations de matière sèche et d'azote ammoniacal total (Arancon et al., 2019; Charoenpakdee, 2014; Giménez et al., 2020; Mowa, 2018).

La faible productivité des modalités bioponiques dans le cas de concentration élevées de matière sèche et/ou de TAN (azote ammoniacal total) par rapport à la modalité de référence chimique peut s'expliquer par le fait que ces concentrations élevées induisent un stress osmotique, une toxicité ionique et un déséquilibre des nutriments dans les rafts, rendant ces solutions nutritives très concentrées et par ricochet moins assimilables par les plantes. Par contre, la faible productivité peut etre dûe à des faibles concentrations en minéraux d’une part, mais par le manque de ratios optimaux entre les différents minéraux d’autre part (Fallovo et al., 2009; T. Hu et al., 2006; Kartseva et al., 2021; Soundy et al., 2001). Cependant, cette absorption des nutriments par les plantes peut également être due à des conditions agro-environnementales défavorables, notamment le pH, la luminosité et la température, qui peuvent augmenter ou diminuer les flux de nutriments dans les radeaux (Ndoung et al., 2021; Solomou & Sfougaris, 2021).

➢ Nitrification

L’ajout d’un biofiltre dans un raft hydroponique pendant la minéralisation aérobique des solutions bioponiques permet d’accélérer la transformation du NH4+ en NO3-N par le processus de nitrification, forme selon laquelle la plupart des plantes absorbent. Le nitrate et l'ammonium sont les deux formes d'azote prélevées par les plantes, en fonction de la physiologie de la plante mais aussi de la concentration de l'élément en solution (Roosta, 2024; Yajuan Xing et al., 2024; G. Xu et al., 2012). La nitrification peut donc être définie comme une phase de transformation dans laquelle l'ammoniac/ammonium NH3/NH4 passe au stade de nitrite, pour finir en nitrate, un mécanisme réalisé par des bactéries aérobiques chimio-synthétiques autotrophes. La phase de conversion de l'ammoniac en nitrite est réalisée par des bactéries oxydant l'ammoniac du genre *Nitrosovibrio ; Nitrosococcus, Nitrosospira, Nitrosolobus et Nitrosomonas*. Alors que la phase de conversion du nitrite en nitrate est réalisée par des bactéries oxydant le nitrite du genre *Nitrococcus, Nitrobacter, Nitrospina* et *Nitrospira* (Rurangwa et Verdegem 2013 ; Timmons et Ebeling 2013 ; Wongkiew et al. 2017).

Toutes les bactéries n'ont pas la même efficacité lors de la nitrification ; les bactéries du genre *Nitrospira*, par exemple, sont réputées pour être des nitrifiants complets de la matière organique (Daims et al., 2015; C. Li et al., 2019; H. Liu et al., 2021; Yanan Wang et al., 2023). Dans la bioponie, les nutriments pour les végétaux proviennent principalement des débris végétaux, des déchets ménagers, des excréments d'animaux, etc...(Jijakli, 2024; Pelayo Lind et al., 2021; Szekely et al., 2023). L'azote produit dans ces différentes matières organiques se présente en grande partie sous la forme d'ammoniac NH_3^-, qui est transformé en nitrite puis en nitrate par des microorganismes comme décrit ci-dessus (Szekely et al., 2023 ; Sugita et al., 2005). Les ions ammoniac et ammonium peuvent être toxiques pour les plantes lorsque les quantités de ces nutriments deviennent très élevées, mais il est conseillé de ne pas dépasser 30 mg/l d'ammonium et de nitrite dans une solution nutritive contenant des plantes. Au-delà de ces concentrations, l'ammonium et les nitrites entraînent une réduction de la hauteur des plantes, du rendement et du nombre de feuilles, ainsi qu'une accentuation de la décoloration des racines (Esteban et al., 2016; Hoque et al., 2008; Phipps & Cornforth, 1970).

➢ Processus de solubilisation du phosphore

Le phosphore est un macronutriment qui joue un rôle crucial dans le cycle de croissance et de développement des plantes, en particulier dans la régulation des réponses physiologiques et l'amélioration de la tolérance aux stress abiotiques tels que la salinité, la sécheresse, la chaleur, l'humidité, la toxicité du CO_2 élevé et la toxicité des métaux lourds. La forme de phosphore absorbée par les plantes est l'orthophosphate ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) (F. Khan et al., 2023; Resh, 2013).

Cependant, la solubilité du phosphore dépend du niveau de pH ; lorsqu'il est alcalin, il facilite la précipitation du phosphore en solution, ce qui le rend indisponible pour les plantes (Yildiz et al., 2017). Dans les environnements alcalins, le phosphore peut précipiter sous forme de struvite (phosphate de magnésium ou d'ammonium) (Le Corre et al., 2005).

- **Processus de solubilisation du potassium**

Le potassium appartient à la catégorie des nutriments connus sous le nom de macronutriments. Les engrais potassiques sont principalement dérivés de deux minéraux rocheux, la sylvite (KCl) et la carnallite ($KCl{\cdot}MgCl_2{\cdot}6H_2O$) (SOUMARE et al., 2023). Le potassium est impliqué dans de nombreux processus métaboliques tels que la photosynthèse, la synthèse des protéines, l'activation des enzymes, ainsi que l'équilibre cation-anion (Hasanuzzaman et al., 2018; Schwartz et al., 2019). Cependant, la carence en potassium peut être un facteur limitant de la production végétale, ainsi pour réduire les pénuries de potassium, certains mécanismes existent déjà, notamment l'utilisation de micro-organismes solubilisant le potassium tels que Bacillus circulans, Acidithiobacillus ferrooxidans, *Pseudomonas spp*, *Aspergillus spp*, *Bacillus edaphicus* etc…, le rendent disponible pour les plantes (Vivek Kumar et al., 2017). Le potassium peut être disponible pour les plantes en fonction du degré d'altération des roches, mais d'un autre côté, le cation potassium peut être disponible en fonction des quantités relatives d'autres cations tels que le calcium et le magnésium présents dans l'environnement. Cependant, le cation potassium peut agir comme un antagoniste d'autres cations tels que le calcium et le magnésium, par exemple, l'augmentation de la teneur en magnésium inhibe l'absorption du potassium et du calcium (Fageria & Moreira, 2011; Singh, 2000) par un mécanisme de compétition. Le potassium améliore également l'efficacité de l'absorption de l'azote par les racines, mais réduit également la concentration de nitrate (NO_3^-) dans les parties foliaires des plantes, de sorte que le potassium peut également s'opposer à l'ion ammonium (NH_4^+).

6.4. Implication de la bioponie dans la production maraîchère de Lubumbashi

Le transfert et l'adoption de nouvelles techniques ou pratiques agricoles dans une région donnée exigent une étude socio-économique approfondie qui tient compte des conditions locales spécifiques. Cela nécessite également une évaluation des pratiques agricoles existantes dans la région, une adaptation des nouvelles pratiques agricoles, la formation et la sensibilisation des agriculteurs, la disponibilité et l'accessibilité des intrants agricoles localement, un accompagnement technique, le suivi et l'évaluation des techniques mises en œuvre, ainsi qu'une évaluation de la faisabilité économique et de la durabilité des nouvelles pratiques agricoles proposées (Andati et al., 2022; Carayannis, 2018; Fosso & Nanfosso, 2016; Silva et al., 2011; M. M. Smith et al., 2021). La bioponie pourrait alors contribuer à une production des légumes de qualité dans un environnement pollué d'une part mais elle peut se pratiquer sur toute l'année d'autre part (Desire Djidonou et al., 2019). Pour répondre aux besoins des agriculteurs en matière d'adaptation à cette nouvelle technique, nous avons utilisé des matériaux locaux recyclés. Nous avons, par exemple, fabriqué des rafts (plates-formes hydroponiques) à partir de matériaux disponibles localement. De plus, pour la fabrication des solutions nutritives organiques, nous avons testé l'utilisation de fientes de poules achetées localement (Caputo et al., 2020; Gonnella & Renna, 2021; Gumisiriza et al., 2022; Hasan et al., 2018; Mandal et al., 2023; Michelon et al., 2020; Obirikorang et al., 2021; Souza et al., 2023; Spina et al., 2021) (Figure 6-1).

Figure 6-1. Construction et démonstration de la mise en place des dispositifs pilotes aux producteurs de Lubumbashi.

La diffusion et l'enseignement ont été employés pour promouvoir la nouvelle technique de production bioponique que nous avons développée à l'Université de Lubumbashi. Un total de 80 participants, principalement des agriculteurs maraîchers de Lubumbashi, ont suivi une formation de deux jours dans la salle ARUPE de Lubumbashi, au cours de laquelle les intervenants principaux étaient Monsieur Félicien Mununga et Madame Iris Szekely (Figure 6-2).

Figure 6-2. Formation des agriculteurs urbains et visites des dispositifs pilotes à l'Université de Lubumbashi.

Après les sessions de formation et de sensibilisation des agriculteurs, huit ménages de producteurs ayant suivi la formation ont installé des dispositifs pilotes. Les autres producteurs avaient également la possibilité de visiter ces dispositifs pour mettre en pratique les concepts appris lors de la formation. Chaque participant a reçu un manuel (Annexe 1). Un suivi régulier a été effectué chaque semaine dans les huit ménages pilotes pour s'assurer que les plateformes fonctionnaient correctement. De plus, une pesée a été réalisée pour déterminer le poids des légumes récoltés. Dans le but de relever le défi économique des producteurs de Lubumbashi, nous avons choisi de cultiver la laitue (*Lactuca sativa*), une culture considérée comme prestigieuse, généralement consommée par les populations plus aisées et ayant une bonne demande sur le marché. Lors de la récolte de ces légumes, les producteurs ont réussi à vendre chaque pied de laitue jusqu'à 2.000 Francs congolais, soit l'équivalent d'un euro à l'époque. Cela était exceptionnel, car aucun autre légume en saison sèche n'atteignait ce prix. En comparaison, les autres légumes étaient vendus à 500 Francs congolais, soit 0,25 euro.

Cette expérience encourage à se tourner vers les cultures à haute valeur marchande, produites en qualité et en quantité à moindre coût. Il est important de noter que les coûts de production des légumes, tels que l'achat d'intrants, le désherbage, les pesticides et la main-d'œuvre, représentent plus de 70 % des bénéfices. En revanche, les techniques de culture hors-sol bioponiques sont moins coûteuses à mettre en place, utilisent des matériaux locaux de production tels que les fientes de poules, le bois recyclé, les plaques de polystyrène, etc., et nécessitent moins de main-d'œuvre (Figure 6-3).

Figure 6-3. Production bioponique des laitues dans la ville de Lubumbashi.

Chapitre 7 :

Conclusion générale et perspectives

Conclusion générale et perspectives

Toutes les activités minières ont un impact sur l'environnement, notamment sur le sol, l'eau, les plantes, l'air et la santé humaine. D'où l'émergence de certaines hypothèses selon lesquelles tous les sols des jardins maraîchers de Lubumbashi seraient contaminés par les métaux lourds. Des dysfonctionnements métaboliques sont causés par la contamination des différentes composantes de l'environnement, tels que le sol, l'eau, les plantes et les animaux. Cette thèse visait à élaborer de nouvelles techniques de production de légumes de bonne qualité sanitaire et non contaminés par les métaux.

Dans un premier temps, nous avons mené une étude caractérisant la contamination des sols des jardins maraîchers urbains à Lubumbashi et ses environs. Des échantillons de sol, d'eau et de plantes ont été prélevés dans les jardins maraîchers et les marchés urbains de Lubumbashi contenant au moins cinq producteurs et cinq vendeurs de légumes. Les teneurs en métaux contenus dans le sol, l'eau et les plantes ont été déterminées à partir de ces échantillons acheminés au laboratoire. Les indices de contamination, de pollution et d'enrichissement ont permis de déterminer l'origine et le niveau de contamination des sols de chaque jardin maraîcher en se basant sur ces teneurs totales. Les résultats ont montré que les sols des jardins maraîchers de Lubumbashi sont contaminés par les métaux lourds tels que le cuivre, le cobalt, le cadmium, le plomb, l'arsenic et le zinc, et que les quatre légumes cultivés sur ces sols contaminés présentaient des teneurs au-dessus des seuils recommandés par l’OMS, pour la consommation humaine des légumes.

Ensuite, nous avons évalué l'efficacité des techniques de dépollution des sols contaminés par les métaux lourds en utilisant des amendements organocalcaires disponibles dans la région. Les amendements organiques d'origine animale (fientes de poules) et végétale (sciures de bois) mélangés à de la chaux agricole ont été utilisés pour réduire le transfert des métaux lourds de sols vers les plantes (*Brassica chinensis, Amaranthus vulgaris, Beta vulgaris* et *Brassica carinata*). Les résultats démontrent que l'application d'amendements organocalcaires aux sols contaminés en ETM a permis de réduire le transfert de ces métaux du sol vers les plantes.

Notre étude confirme les conclusions d'autres chercheurs, soulignant que la réduction de ce transfert nécessite des quantités plus importantes d'amendements organiques et calcaires, qui sont rarement disponibles sur toute l’année dans la ville de Lubumbashi. Cela pose un défi quant à la mise en œuvre de cette technique. En outre, parmi les trois jardins sélectionnés en fonction du niveau de contamination en cuivre, l'indice de consommation journalière des légumes pour une personne de 60 kg trouvé, indique qu'il dépasse les limites fixées par l'OMS/FAO pour une consommation quotidienne de légumes provenant du jardin maraîcher faiblement contaminé en cuivre, pour ce qui est du cobalt. Les deux jardins maraîchers (Manoah et Chem-Chem) n'ont pas produit de biomasse suffisante pour l'analyse et par conséquent, l'indice de consommation journalière des légumes n'a pas pu être déterminé, mais il dépasserait probablement les limites de l'OMS/FAO en raison des quantités élevées de cuivre retrouvées dans les sols.

Enfin, nous avons développé des solutions nutritives bioponiques qui ont été utilisées pour les cultures hydroponiques. Étant donné les problèmes de contamination des sols, nous avons exploré les techniques de culture hors-sol, en particulier l'hydroponie organique. Deux expériences ont été réalisées afin de déterminer le pourcentage en matières sèches approprié d'une part et la teneur en azote ammoniacal totale d'autre part, pouvant produire en quantité et en qualité les plantes en bioponie. Quarante et deux jours après la mise en culture, les plants de laitue (*Lactuca sativa*) ont été récoltées, pesées et séchées à l'étuve pour déterminer le rendement des cultures d'une part et la qualité sanitaire des laitues produites hydroponique organique d'autre part. Les résultats ont montré que les solutions nutritives fabriquées à partir de fientes de poules ont fourni des éléments nutritifs nécessaires pour la croissance des plantes en hydroponie d'une part. D'autre part, l'augmentation de pourcentage en matière sèche tout comme celle de TAN dans les rafts n'augmentent pas proportionnellement les rendements des cultures. Enfin, les légumes produits en culture bioponique ont présentaient des teneurs en éléments traces métalliques en dessous du seuil de toxicité de l'OMS autorisé pour la consommation humaine des légumes.

À la suite de cette thèse, nous suggérons aux autorités politico-administratives de réaffecter à d'autres usages des jardins maraîchers fortement contaminés par les métaux d'une part. Que la mise en place de la bioponie sur les sols de jardins maraîchers fortement contaminés en métaux devienne une urgence afin de permettre aux agriculteurs urbains de Lubumbashi de produire de légumes de qualité et en quantité d'autre part. Que les futures expériences mettent l'accent sur les cultures maraîchères locales à haute valeur ajoutée que les espèces locales à faible valeur ajoutée cultivées dans les jardins maraîchers urbains de Lubumbashi. Afin d'augmenter les rendements des cultures bioponiques comparables aux rendements hydroponiques standards, il serait bien de tester les bactéries commerciales pouvant accélérer la nitrification des fientes des poules et minimiser les pertes d'azote dans les rafts pendant la mise en culture d'une part, mais de tester d'autres matières organiques comme les herbes de pélouse, des bouses de vaches, des crottes de chèvres, etc… d'autre part.

Annexes

A.1. Names of the 40 identified urban market gardens of Lubumbashi.

Table A1. Urban and peri-urban gardens identified in Lubumbashi.

Urban and peri-urban market gardens
Bombeki
Bongonga
Camps-assistant
Camps-scout
Campus-Unilu
Chem-chem
Daipen-Kisanga
Ferme konde
Ferme nkonde
Inera-Salongo
Kabetsha
Kafubu
Kakonkania
Kalebuka
Kalubwe
Kalulako
Kamakanga
Kamatete
Kamilombe

Kamisepe
Kantumbwi
Kasamba
Kashamata
Kashimbala
Kasungami
Katemo
Kawama
Kilobelobe
Kinsense
Kitanda
Luano
Maendeleo
Kinsevere/Manoah
Mwenda
Naviundu
Penga-penga
Sambwa
Tingi-Tingi
Tshamalale
Tshamilemba

A.2. Names of the markets of the city of Lubumbashi (Democratic Republic of the Congo).

Table A2. Urban markets of Lubumbashi.

Market	Municipality
Antenne Ruashi	Ruashi
Camp Prefabrique	Kampemba
Double Poteau	Lubumbashi
Eureka	Lubumbashi
Kabulamenshi	Lubumbashi
Kalebuka	Annexe
Kamatete	Annexe
Kansoko	Annexe
Karavia	annexe
Kasangulu	lubumbashi
Katuba 1	Katuba
Katuba 2	Katuba
Kenya (zone)	Kenya
Kigoma	Kampemba
Kilobelobe	Annexe
Kimuti	Kampemba
Lido	Lubumbashi

Manoah Nsoko	Ruashi
Marche Ciné	Annexe
Météo	Annexe
Mimbulu	Katuba
Moise	Annexe
Mwimbila	Kenya
M'zee	Lubumbashi
Njanja	Kenya
Pande	Kampemba
Peage Kimuti	Katuba
Radem	Kampemba
Rail	kampemba
Rose Tshakwiza	Annexe
Tabac	Kampemba
Tshamalale	Annexe
Zambia	Ruashi

Table A.3. Contamination levels of urban and peri-urban garden soils according to the contamination factor.

Market gardens	**Fe contamination level**	**Cu contamination level**	**Pb contamination level**	**Zn contamination level**
Bongonga	Low contamination	Low contamination	Low contamination	Low contamination
Chem-chem	Low contamination	Moderate contamination	Moderate contamination	Very strong contamination
Daipen/Kashamata	Low contamination	Low contamination	Low contamination	Low contamination
Kabetsha	Low contamination	Low contamination	Low contamination	Low contamination
Kafubu	Low contamination	Low contamination	Low contamination	Moderate contamination
Kalebuka	Low contamination	Low contamination	Low contamination	Low contamination
Kalubwe	Low contamination	Moderate contamination	Low contamination	Moderate contamination
Kalulako	Low contamination	Low contamination	Low contamination	Low contamination
Kamakanga	Low contamination	Low contamination	Low contamination	Low contamination

Kamatete	Low contamination	Low contamination	Low contamination	Low contamination
Kamilombe	Low contamination	Moderate contamination	Low contamination	Significant contamination
Kamisepe	Low contamination	Low contamination	Low contamination	Low contamination
Kantumbwi	Low contamination	Low contamination	Low contamination	Low contamination
Kasungami	Low contamination	Low contamination	Low contamination	Low contamination
Katemo	Low contamination	Low contamination	Low contamination	Low contamination
Kawama	Low contamination	Moderate contamination	Low contamination	Moderate contamination
Kilobelobe	Low contamination	Low contamination	Low contamination	Moderate contamination
Kinsense	Low contamination	Low contamination	Low contamination	Low contamination
Kinsevere-Manoah	Significant contamination	Moderate contamination	Low contamination	Moderate contamination
Kitanda	Low contamination	Moderate contamination	Low contamination	Significant contamination

Luano	Low contamination	Low contamination	Low contamination	Moderate contamination
Maendeleo	Low contamination	Moderate contamination	Low contamination	Moderate contamination
Mwenda	Low contamination	Low contamination	Moderate contamination	Low contamination
Penga-penga	Low contamination	Low contamination	Low contamination	Low contamination
Sambwa	Low contamination	Low contamination	Low contamination	Low contamination
Tingi-Tingi	Low contamination	Low contamination	Low contamination	Low contamination
Tshamalale	Low contamination	Low contamination	Low contamination	Low contamination
Tshamilemba	Low contamination	Low contamination	Low contamination	Low contamination

Table A.4. Metal enrichment levels of the urban and peri-urban market gardens of Lubumbashi.

Market gardens	**Cu**	**Pb**	**Zn**
Bongonga	No enrichment	No enrichment	No enrichment

Chem-chem	Enrichment Medium High	Moderate Enrichment	High Enrichment
Daipen/Kashamata	Low Enrichment	No enrichment	Low Enrichment
Kabetsha	No enrichment	No enrichment	No enrichment
Kafubu	Low Enrichment	No enrichment	Moderate Enrichment
Kalebuka	Moderate Enrichment	No enrichment	Low Enrichment
Kalubwe	Low Enrichment	No enrichment	Low Enrichment
Kalulako	Low Enrichment	No enrichment	Low Enrichment
Kamakanga	No enrichment	No enrichment	No enrichment
Kamatete	No enrichment	No enrichment	Low Enrichment
Kamilombe	Low Enrichment	No enrichment	Enrichment Medium high
Kamisepe	Low Enrichment	No enrichment	Low Enrichment
Kantumbwi	No enrichment	No enrichment	No enrichment
Kasungami	No enrichment	No enrichment	No enrichment
Katemo	No enrichment	No enrichment	No enrichment

Kawama	Low Enrichment	No enrichment	Low Enrichment
Kilobelobe	Low Enrichment	Low Enrichment	Moderate Enrichment
Kinsense	Low Enrichment	No enrichment	Low Enrichment
Kinsevere-Manoah	No enrichment	No enrichment	No enrichment
Kitanda	Low Enrichment	No enrichment	Enrichment Medium-high
Luano	Low Enrichment	Low Enrichment	Moderate Enrichment
Maendeleo	Low Enrichment	Medium High Enrichment	Enrichment Medium-high
Mwenda	No enrichment	No enrichment	Low Enrichment
Penga-penga	No enrichment	No enrichment	No enrichment
Sambwa	Low Enrichment	Low Enrichment	Low Enrichment
Tingi-Tingi	Low Enrichment	No enrichment	Low Enrichment
Tshamalale	No enrichment	No enrichment	No enrichment
Tshamilemba	No enrichment	No enrichment	No enrichment

Table A.5. Pollution levels of the urban and peri-urban market gardens of Lubumbashi.

Market garden name	Pollution level
Bongonga	Not polluted
Chem-chem	Severe pollution
Daipen/Kashamata	Not polluted
Kabetsha	Not polluted
Kafubu	Not polluted
Kalebuka	Not polluted
Kalubwe	Severe pollution
Kalulako	Not polluted
Kamakanga	Not polluted
Kamatete	Not polluted
Kamilombe	Severe pollution
Kamisepe	Not polluted

Kantumbwi	Not polluted
Kasungami	Not polluted
Katemo	Not polluted
Kawama	Not polluted
Kilobelobe	Not polluted
Kinsense	Not polluted
Kinsevere-Manoah	Severe pollution
Kitanda	Severe pollution
Luano	Not polluted
Maendeleo	Severe pollution
Mwenda	Not polluted
Penga-penga	Not polluted
Sambwa	Not polluted
Tingi-Tingi	Not polluted

Tshamalale	Not polluted
Tshamilemba	Not polluted

Table A6. XRF determination of metals in 29 urban and peri-urban market gardens of Lubumbashi (mg/kg). Limits of quantification: 0,05 mg/Kg.

Market gardens	**Fe**	**Cd**	**Cu**	**Pb**	**Cr**	**Zn**
Bongonga	3,31	0,05	59	0,05	0,05	30
Chem-Chem	4,08	45	1,355	221	67	1,47
Daipen/Kashamata	2,13	0,05	204	20	45	60
Kabetsha	2,19	0,05	113	0,05	45	42
Kafubu	2,34	236	146	0,05	0,05	181
Kalebuka	1,12	0,05	226	0,05	38	53
Kalubwe	4,97	40	850	0,05	58	301
Kalulako	1,84	0,05	239	0,05	0,05	85

Kamakanga	3,33	0,05	78	0,05	66	44
Kamatete	3,55	0,05	206	26	0,05	138
Kamilombe	4,23	56	656	0,05	69	716
Kamisepe	1,87	0,05	208	0,05	63	73
Kantumbwi	1,81	0,05	45	0,05	46	28
Kasungami	1,9	0,05	102	0,05	47	38
Katemo	3,23	19	56	0,05	0,05	35
Kawama	4,18	0,05	598	39	0,05	262
Kikula/Sambwa	1,57	0,05	201	18	45	88
Kilobelobe	3,71	0,05	344	48	75	284
Kinsense	3,7	0,05	270	34	51	136
Kinsevere (Manoah)	33,43	0,05	535	81	0,05	394
Kitanda	4,96	0,05	826	47	59	652
Luano	4,05	0,05	346	80	46	300

Maendeleo	2,7	0,05	493	184	57	409
Mashimikila	2,46	0,05	1,043	73	0,05	230
Mwenda	1,28	0,05	66	0,05	43	42
Pengapenga	4,31	0,05	183	0,05	49	50
Tingi-Tingi	2,57	0,05	160	0,05	45	66
Tshamalale	2,73	0,05	50	0,05	0,05	34
Tshamilemba	2,46	0,05	51	0,05	0,05	33
Toxicity threshold (mg/Kg)	NT	2	100	100	150	300

Table A7. Physico-chemical characteristics of chicken droppings

Chicken droppings	Essential elements		Heavy metals (mg/Kg)					
	Mg (%)	Ca (%)	Cu	Co	Cd	Pb	Zn	Fe
	0.11	7.48	80.5	5.6	0.04	0.3	321.3	654

Table A8. Physico-chemical properties of bioponic nutrient solutions from trial 1, stock solutions before dilution in rafts on day 7, after dilution on day 21 of vacuum aerobic circulation pH; EC: electroconductivity (µS/cm); TAN: total ammonia nitrogen (mg/L); N-NO_3: nitric nitrogen (mg/L); N-NO_2: nitrite nitrogen (mg/L); TMN: total mineral nitrogen (sum of N-NO_3, N-NO_2, and TAN) (mg/L); P-PO_4^{3}: phosphate-phosphorus (mg/L) and K-potassium (mg/L). Legend, T1: 0.35% dry matter; T2: 3.5% dry matter; T3: 7% dry matter.

Parameters	Stock solutions (mg/kg)			Solution after aerobic digestion (mg/L)					
				T1		T2		T3	
	T1	T2	T3	7	21	7	21	7	21
pH	6.9	6.9	6.7	7.4	7.2	7.4	7.4	7.3	7.3
EC	726.5	795.3	747.3	546	591.4	654	696.8	944	959.4
TAN	225.06	994.26	2112	25.4	3.72	30.83	19.17	89.13	37.12
NO_2 -N	4.3	28	84.6	0	0	0	1.33	0	2.33
NO_3 -N	3.4	61.6	472	3.53	7.07	0.83	2.83	4.13	4.2
TMN	232.8	1083.8	2668.6	29	10.78	31.67	23.33	93.27	43.65
PO_4^{3-}	37.3	49	184	51.7	67	13	62.33	22	40.33
K	81.6	333.3	1666.6	8.8	8.83	12	20.17	21.17	13.67

Table A9. Physico-chemical properties of bioponic nutrient solutions from trial 2, stock solutions before dilution in rafts on day 7, after dilution on day 21 of vacuum aerobic circulation pH; EC: electroconductivity (µS/cm); TAN: total ammonia nitrogen (mg/L); N-NO_3: nitric nitrogen (mg/L); N-NO_2: nitrite nitrogen (mg/L); TMN: total mineral nitrogen (sum of N-NO_3, N-NO_2, and TAN) (mg/L); P-PO_4^3: phosphate-phosphorus (mg/L) and K-potassium (mg/L). Legend, T1: 60 mg/l TAN biopony; T2: 90 mg/l TAN biopony; T3: 120 mg/l TAN biopony; T4: 120 mg/l TAN Mineral solution Resh.

Parameters	Stock Solution	Solution after aerobic digestion (mg/L)					
		T1		T2		T3	
		7	21	7	14	7	14
pH	6.4	7.7	7.5	8	7.5	7.9	7.9
EC	3818.8	508	611	579.1	837.6	873	1125.3
TAN	960.8	5.37±1.52	1.60±0.34	5.60±0.34	48.20±33.33	8.04±1.78	124.67±34.82
NO2 -N	114.4	30±16.3	211.6±20.95	10.00±1.41	250±96.26	25.00±2.16	110±57.15
NO3 -N	301.1	18.0±4.81	36.67±7.41	52.83±20.09	40.67±9.88	24.07±4.65	40.50±29.15
TMN	1376.4	53.37±19.84	249.93±13.80	68.43±19.50	338.86±63.62	57.10±5.52	275.17±51.25
PO43-	182.4	38.23±12.5	77±20.51	60.6±18.95	43.33±21.93	86.33±19.07	48.00±9.09
K	240.4	7.23±3.51	31.33±5.56	13.03±4.58	49.00±5.35	11.20±5.37	56.83±17.46

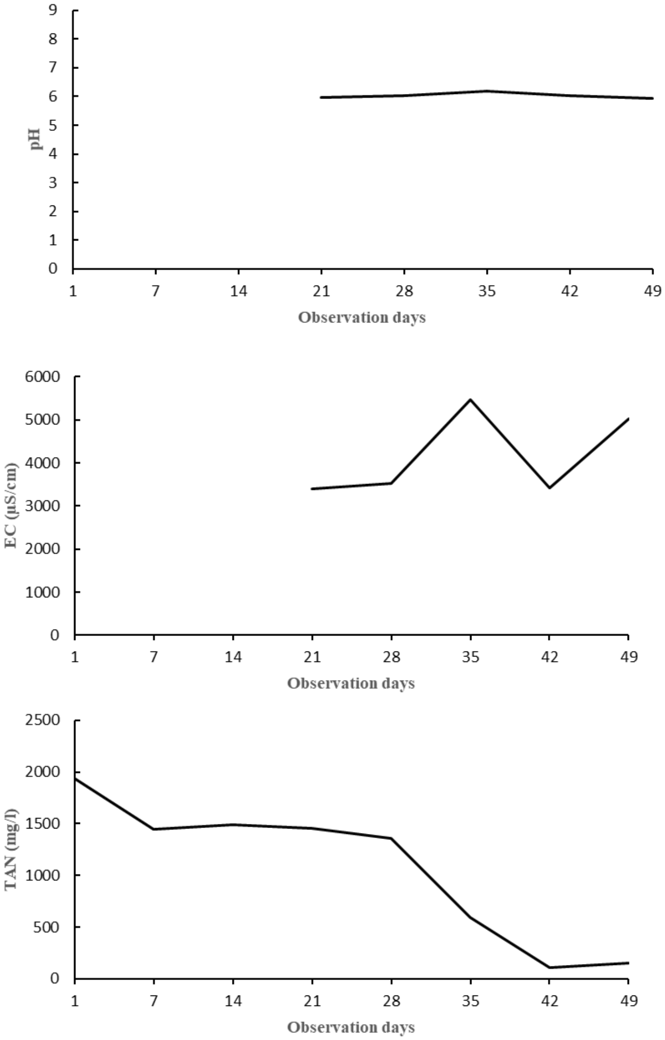


Figure A1. Figure 6: Effect of dry matter on the quality of nutrient solutions derived from chicken manure in trial 2.

Figure A2. Illustration of lettuce sowing in rockwool cubes and cultivation.

Figure A3. Illustration of bioponic lettuces produced in an impacted environment in Lubumbashi.

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