中文摘要

本研究計畫之目的在於發展一新穎之生物為基礎機率風險評估整合架構，以研析九孔暴露於含鋅水域、吳郭魚暴露於含砷水域以及人食用受砷污染養殖海鮮及飲用地下水之健康風險。此機率模式包含結合生物動力與資源-消耗者動態模式之一階雙區塊生物累積模式，描述九孔暴露於含鋅水域之動態行為。並採用生理為基礎之藥理動力及動態（PBPK/PD）模式，除用以描述吳郭魚暴露於含砷水域之暴露分析外，亦用於人體健康風險評估上。研究中探討養殖九孔受鋅和吳郭魚受砷污染下之各標的組織濃度曲線，並藉由重新建立以生物為基礎之劑量與反應關係，來預測九孔成長抑制/死亡風險及吳郭魚之死亡風險，並推估人攝取受砷污染之養殖海鮮及地下水之非致癌/致癌風險。本研究以機率風險評估架構來描述特定年齡族群居民於烏腳病盛行區（食用養殖吳郭魚、虱目魚及豆仔魚）與蘭陽平原（飲用地下水和食用養殖海鮮（如：香魚及草蝦））之無機砷暴露風險。本研究亦以造成人體潛在致癌風險為基礎，推估人可攝取無機砷之飲食忠告。

在九孔暴露於含鋅水域之風險分析結果顯示，位於臺灣北中南的頭城、口湖及安平三地養殖池水中之含鋅量，對九孔造成存活影響之風險機率較低。此外，預測抑制九孔成長之危害商數（growth hazard quotient），第 90 百分位潛在風險值分別為頭城：1.94、口湖：0.47 及安平：0.51。推估九孔死亡之預期風險分別為頭城：0.46、口湖：0.36 及安平：0.29。本研究結果指出，台灣口湖與安平兩地之養殖九孔暴露於含鋅水域並無顯著之風險；而相較之下，頭城養殖池則有較高之抑制九孔成長風險，應提出警訊。靈敏度分析結果指出，水域中鋅濃度為影響藻類及九孔體內鋅濃度之最主要因子，其變異貢獻範圍為 82.85–91.87%。

由吳郭魚暴露於含砷水域之風險分析結果指出，以風險值為 0.1 為例，10%

以上機率因吳郭魚各標的器官受到砷污染後，約有 10^{-9} 到 10^{-6} %吳郭魚會受到死亡之影響。吳郭魚各標的器官如魚肉、鰓及肝之預期死亡超越風險分別為 0.3、0.1 及 0.3，顯示烏腳病盛行區暴露於含砷水域之吳郭魚存活率約有 70–90%，其受到死亡危害之風險較不顯著。

此外，本研究探討烏腳病盛行區及蘭陽平原當地孩童（4–12 歲，暴露時間：8 年）、青少年（13–20 歲，暴露時間：16 年）與成年人（21–65 歲，暴露時間：61 年）攝食養殖海鮮及飲用地下水之健康風險。研究分析指出攝取來自慢性砷中毒盛行區受到砷污染之養殖海鮮及地下水，可能會增加威脅當地所有居民得到皮膚病變及成年人得到皮膚癌之盛行率，並增加成年人因受砷所誘導肺癌及膀胱癌而導致死亡之潛在發生率。由研究結果發現蘭陽平原當地居民得到皮膚病變與皮膚癌之病症，及誘導成肺癌及膀胱癌所導致死亡之風險皆較烏腳病盛行區當地居民高。

本研究並以最保守風險分析為基礎之飲食忠告，求得當地居民最大可接受之風險值。在致癌風險考量下，建議烏腳病盛行區之當地青少年（13–20 歲，暴露時間：16 年）每月最大允許養殖海鮮攝食量（中位值）為不超過 15–28 餐（或每日 25–46 公克），當地成年人（21–65 歲，暴露時間：61 年）每月攝食量則建議需少於一餐（或每日 0.19–0.30 公克）。在蘭陽平原一帶，本研究建議當地青少年（13–20 歲，暴露時間：16 年）每月攝食量為不超過 4–7 餐（或每日 6–11 公克），當地成年人（21–65 歲，暴露時間：61 年）每月攝食量則需少於一餐（或每日 0.08–0.12 公克）。

關鍵詞：九孔；吳郭魚；年齡別；鋅；砷；機率；生理為基礎之藥理動力及藥理動態；模式為基礎之風險評估；飲食忠告

Abstract

The purpose of this dissertation is to develop a novel biologically-based probabilistic risk assessment (PRA) integrated framework for abalone Haliotis diversicolor supertexta exposed to waterborne zinc (Zn), arsenic (As) exposure estimates for tilapia Orechromis mossambicus, and age-specific human health risks through consumption of As-contaminated farmed seafood and groundwater. The probabilistic models implemented include linking a first-order two-compartment bioaccumulation model, with biokinetic and consumer−resource dynamic models for abalone exposed to waterborne Zn and employing a physiologically based pharmacokinetic/pharmacodynamic (PBPK/PD) model not only for describing As exposure in tilapia, but also assessing human health risks. Target organ metal (Zn or As) concentration profiles in aquatic organisms (abalone or tilapia) and human follow a reconstructed dose-response relationship to predict growth and mortality risks of abalone, mortality risk of tilapia, and morbidity and fatality risks for human. This study carries out PRA framework to characterize age-specific exposure risks to ingested inorganic As in BFD-endemic area (through farmed tilapia, milkfish, and large-scale mullet) and in Lanyang Plain (through drinking groundwater and farmed seafood such as smelt and grass shrimp). This study also determines the consumption advice for inorganic As based on the estimates of potential carcinogenic risks.

Risk analysis indicates that abalone reared near Toucheng, Kouhu, and Anping, respectively, in north, central, and south Taiwan region show a relative low likelihood that survival is being affected by waterborne Zn. The predicted 90th percentiles of growth HQ (GHQ) for potential growth risk were estimated as 1.94 (Toucheng), 0.47 (Kouhu), and 0.51 (Anping). Expected risks of mortality for abalone were estimated as 0.46 (Toucheng), 0.36 (Kouhu), and 0.29 (Anping). These findings indicate that

waterborne Zn exposure poses no significant risk to farmed abalone in Kouhu and Anping, yet a relative high growth risk in Toucheng is alarming. Sensitivity analysis indicated that the key parameter in estimating Zn in algae and abalone is water Zn content that contribution to variance ranged from 82.85 91.87%. Risk analysis demonstrates that the probabilities that 10% or more of the tilapia muscle, gill, and liver (risk=0.1) affected ranged from 10^{-9} to 10^{-6} %, whereas the expected exceedence risk of mortality for tilapia muscle, gill, and liver were calculated to be 0.3, 0.1, and 0.3, respectively, indicating less significant adverse effect for tilapia major organs exposed to waterborne As from selected tilapia farms in the BFD-endemic area.

This study performs the health risk for children (4– 12 yrs, exposure duration: 8 yrs), adolescents (13– 20 yrs, exposure dur ation: 16 yrs), and adults (21– 65 yrs, exposure duration: 61 yrs) consumption of farmed seafood and groundwater by residents in BFD-endemic area and in Lanyang Plain. Risk analysis indicates that consumption of As-contaminated farmed seafood and groundwater from arseniasis-endemic areas may increase threat to prevalence ratios of arsenicosis for all residents and skin cancer for adults, whereas increase potential incidence rates from As-induced lung and bladder cancer for adults. Here this study shows a higher morbidity for arsenicosis and skin cancer and fatality for lung and bladder cancers for residents living in Lanyang Plain.

The analysis of the most restrictive risk-based consumption advice, which reflects the highest risks, suggest that the median farmed seafood consumption rate of carcinogenic effects for adolescents (13– 20 yrs, exposure duration: 16 yrs) is no more than 15 – 28 meals mon-1 (or 25 – 46 g d^{-1}), whereas less than one meal mon-1 (or 0.19– 0.30 g d^{-1}) for adults (21– 65 yrs, exposu re duration: 61 yrs) in BFD-endemic area. In Lanyang Plain, we suggest that the median consumption rate

for adolescents (13− 20 yrs, exposure duration: 16 yrs) is no more than 4 − 7 meals mon-1 (or 6− 11 g d^{-1}), whereas less than one meal mon-1 (or 0.08 − 0.12 g d^{-1}) for adults (21 − 65 yrs, exposure duration: 61 yrs).

Keywords：Abalone;Tilapia; Age-specific; Zinc; Arsenic; Probabilistic; PBPK/PD; Model-based risk assessment; Consumption advice