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the case for Thailand

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Published in:
The International Journal of Life Cycle Assessment

Link to article, DOI:
[10.1007/s11367-022-02094-1](https://doi.org/10.1007/s11367-022-02094-1)

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Mankong, P., Fantke, P., Phenrat, T., Mungkalasiri, J., Gheewala, S. H., & Prapasongsa, T. (2022). Characterizing country-specific human and ecosystem health impact and damage cost of agricultural pesticides: the case for Thailand. *The International Journal of Life Cycle Assessment*, 27, 1334–1351.
<https://doi.org/10.1007/s11367-022-02094-1>

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Characterizing country-specific human and ecosystem health impact and damage cost of agricultural pesticides: the case for Thailand

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Received: 10 May 2022 / Accepted: 6 September 2022 / Published online: 6 October 2022
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Abstract

Purpose Existing emission and toxicity characterization models in life cycle assessment are currently not suitable for assessing pesticide-related impacts of crop cultivation in tropical regions. This study aims to parameterize the scientific consensus model USEtox for Thai environments to derive toxicity characterization factors of pesticide emissions from agricultural systems in Thailand. Potential human toxicity and ecotoxicity impacts and related damage costs of pesticides used on nine crops cultivated in Thailand are quantified.

Methods Considering country-specific conditions, USEtox was adapted by applying the landscape and consumption parameters specific to Thailand. Related Thai-specific characterization factors of identified pesticides used in Thai agriculture were quantified. Four emission inventory models were applied to determine pesticide emission fractions in different environmental compartments. The consistent combination of pesticide emission mass and associated characterization factors yielded potential toxicity impact scores. Pesticide impact-related damage costs (external costs) on human health and ecosystem quality were quantified using valuation factors for Thailand. The crops with the highest total damage costs were selected and compared with the annual net incomes of the respective crop production systems.

Results and discussion Pesticide toxicity impacts assessed by using Thai-specific factors were different from the use of global average factors ranging from 1 to 169% (human toxicity) and from 0.1 to 3587% (ecotoxicity). Our results indicated the variability in impact scores influenced by emission modeling choices. Following PestLCI consensus emission estimation model, mango cultivation showed the highest human toxicity impacts of 0.07 DALY/ha, resulting in high human health damage costs mainly caused by Propineb (93%). Rice cultivation with a dry direct-seeded system exhibited the highest ecotoxicity impacts (3934 PDF m³ day/ha) and associated damage costs mainly caused by Oxadiazon (92%). Pesticides used in cultivation of nine crops resulted in total damage costs of 7188 and 3.01 million THB/crop-year for human health and ecotoxicity, respectively. Mango and rice production accounted for 70% and 17% of the total damage costs, which were 36% and 20% of the respective crops' annual net income.

Responsible Editor: Masaharu Motoshita

Highlights

- Thai-specific toxicity characterization factors of 166 pesticides are quantified.
- Pesticide-related emissions, toxicity impacts, and damage costs are quantified.
- Influence of emission modeling choices on toxicity impacts is illustrated.
- Pesticides used for nine crops cause total damage costs of 7.2 billion THB/crop-year.
- Pesticide damage costs are 36% of the annual net incomes for mango production.

Extended author information available on the last page of the article

Conclusions Our study illustrates the ranking of pesticides applied throughout the crop calendar causing toxicological impact and related damage costs on human health and ecosystem quality. This helps identify crops and the main contributors to pesticide-related toxicity impacts in Thailand. Our study highlights the need for proper emission quantification and for the use of characterization factors locally parameterized to increase accuracy. Our results will be useful for future improvement toward more sustainable pesticide use.

Keywords PestLCI · USEtox · Characterization factor · Human toxicity · Ecotoxicity · Life cycle impact assessment

Abbreviations

BAHY	Biodiversity adjusted hectare year
CF	Characterization factor
CVC	Current value of cost
DALY	Disability-adjusted life year
FVC	Future value of cost
PAF	Potentially affected fraction of species
PDF	Potentially disappeared fraction of species
Rice-DD	Rice cultivation with a dry direct-seeded system
Rice-PD	Rice cultivation with a pre-germinated direct-seeded system
THB	Thai baht

1 Introduction

Pesticide use remains a challenging issue for many countries to handle. The global goal of reducing the negative impacts of chemicals and waste by 2020 has not been accomplished (UNEP 2021). Asia is the world's leading user of pesticides, accounting for more than half of global use in 2018 (FAO 2021). Thailand plays a significant role in the total consumption between 98 and 198 million kilograms of pesticides during the period 2011 to 2020 (DOA 2020). Since Thailand is a global producer and exporter of agricultural products. Half of the total area in Thailand is agricultural land (LDD 2019). To supply local and global demand, Thai farmers usually use pesticides and other agrochemicals to ensure high productivity (Wanwimolruk et al. 2017). Various pesticides (e.g., insecticides, herbicides, fungicides) are mainly applied in Thailand using a knapsack sprayer and a high-pressure pump sprayer for a high crop (PPRD 2020), and more than 80% used a motorized backpack sprayer in rice farming (Sombatsawat et al. 2022). However, many farmers in Thailand used pesticides over existing guidelines such as Good Agricultural Practices (GAP) (Grovermann et al. 2013; Laohaudomchok et al. 2020). In this regard, numerous studies reported pesticide residues in fruits and vegetables distributed in Thailand's markets (Wanwimolruk et al. 2015a, b, 2016, 2017, 2019; Phopin et al. 2017; THAI-PAN 2019).

The use of pesticides is a global concern due to adverse effects on human health and the environment (Kosnik

et al. 2022; Persson et al. 2022). Ordinarily, agricultural workers and (residential) bystanders are showing higher health risks because of their vicinity to pesticide sprayed areas (Ryberg et al. 2018). Sombatsawat et al. (2022) reported that some Thai farmers still lack the use of personal protective equipment such as masks, gloves, shoes, and goggles during pesticide application. Therefore, many studies demonstrated a wide range of adverse health issues caused by agricultural pesticides used in Thailand (Nankongnab et al. 2020; Sapbamrer et al. 2020, 2019; Sapbamrer and Nata 2014). Nonetheless, available health effect studies in Thailand have primarily focused on a single substance as a biomarker of pesticide exposure, despite the fact that many pesticides are applied throughout the crop calendar depending on pest species and crops (Laohaudomchok et al. 2020; Wongta et al. 2018). Pesticides sprayed in Thai agricultural areas are then contaminating the soil and water environments (Jaipieam et al. 2009; Kruawal et al. 2005; Aungudornpukdee 2019). Pesticide use on a large scale can reduce biodiversity and cause bioaccumulation in the food chain (Carvalho 2017; Chagnon et al. 2015; Gilbert 2016). Multi-disciplinary organizations in Thailand have worked to reduce the usage of pesticides in the country. Paraquat (herbicide) and chlorpyrifos (insecticide), two key pesticides used in Thailand (accounted for 30% of the total mass of pesticides imported to Thailand in 2018 (DOA 2020), were banned in 2020 (Laohaudomchok et al. 2020; Ministry of Industry 2020). The potentially harmful effects of any possible replacements are currently unclear. To address Thailand's use of improper pesticides, policymakers require proper information to make better decisions and provide recommendations for reducing the impacts of pesticides.

Modeling pesticide distribution in plants is a key tool for limiting pesticide overuse and quantifying human exposure (Jacobsen et al. 2015). Life cycle assessment (LCA) is a standardized tool that aims to quantify the potential environmental impacts of a product throughout its life cycle, including the application of toxic compounds (ISO-14040 2006). USEtox is a scientific consensus model developed under the UNEP-SETAC Life Cycle Initiative to characterize human toxicological and ecotoxicological impacts of chemical emissions in LCA (Rosenbaum et al. 2008; Westh et al. 2015). This model is recommended in various methods for human toxicity and freshwater ecotoxicity characterization (Hauschild et al. 2013). In order to model

toxicity impacts from pesticide use, it is important to identify the emission compartments for each applied substance. Different approaches are available to estimate the emission fractions of sprayed pesticides into environmental media. For example, in the Ecoinvent database, the most widely used background life cycle inventory (LCI) database, 100% of the applied dose is assumed to be emitted to the agricultural soil (Fantke 2019). In contrast, the PestLCI Consensus model (<https://pestlciweb.man.dtu.dk>) is a state-of-the-art pesticide emission model whose input parameters can be defined according to pesticide application characteristics (Rosenbaum et al. 2015). However, Gentil et al. (2020b) highlighted that existing emission inventory and characterization models are not completely appropriate for evaluating pesticide emission distributions and related impacts for crops cultivated in tropical regions (e.g., Thailand). Under tropical conditions, environmental processes related to pesticide emission distributions illustrate an increase in degradation and volatilization rates due to high temperatures, and high rainfall and loose soils typically increase runoff and leaching behavior (Sanchez-Bayo and Hyne 2011; Daam et al. 2019). Considering LCI models adapting to tropical conditions, there are many specific features that have to deal with including tropical cropping systems (i.e., soil types, climate conditions, crops, and adding active ingredients of pesticides), tropical pesticide application techniques (i.e., drift curves), and better address leaching rates in tropical systems (Gentil-Sergent et al. 2021). Nevertheless, existing studies related to pesticide dissipation in the field in Thailand are limited (Ciglasch et al. 2006; Abdullah et al. 2001). Pesticide emission patterns under the tropics and their impacts are not as well known or verified by observations as in temperate regions causing data and model parameters for the assessment to be limited (Sanchez-Bayo and Hyne 2011; Fantke et al. 2017a). Models should hence be adapted and parameterized using the best available data and knowledge before application because they are usually designed based on temperature conditions associated with the environmental mechanisms of the substances (Gentil-Sergent et al. 2021). Moreover, although USEtox is capable of high-throughput simulations of impact scores for pesticides, it is based on default or generic global/continent-level inputs, such that regional-specific (e.g., tropical regions) applications are currently not available. In addition, more spatialized approaches, such as Pangea (Wannaz et al. 2018a, b), can provide impact scores with high spatial resolutions. However, intensive calculations are required, which are not easily performed by many users (e.g., regulators). Therefore, a user-friendly, high-throughput, regional-specific modeling approach is a useful intermediate solution.

Hence, the present study aims (1) to parameterize the existing toxicity characterization model USEtox for the Thai environment to derive Thai-specific toxicity characterization

factors of pesticide emissions from agricultural systems in Thailand, and (2) to quantify and compare the potential human toxicity and ecotoxicity impacts and the related damage costs (so-called external costs, which are costs that are not included in market prices of products) of pesticide application during food crop cultivation in Thailand. Nine crops (rice, cabbage, chili, cucumber, tomato, watermelon, tangerine, durian, and mango) were considered based on high consumption in Thailand (ACFS 2016), high pesticide residues reported (Thai-PAN 2019), and existing pesticide application data. Different existing emission inventory approaches were used to determine the pesticide emission distribution. These were then coupled to the life cycle impact assessment (LCIA) model USEtox based on broad recommendations (Gentil et al. 2020a; Nemecek et al. 2022), and related characterization factors (CFs) of pesticides parameterized for Thai environmental conditions were derived by adapting relevant landscape parameters. Following this approach, the most important substances contributing to the impacts of pesticide applications were identified. Quantifying the damage costs of pesticides used in crop cultivation will ultimately help to identify which crops may have a greater impact on the overall impacts in the country's context.

2 Methodology

2.1 Quantifying toxicological impacts

The toxicological impacts of agricultural pesticides on human health and ecosystem can be characterized in terms of impact scores for an impact category (Fantke et al. 2018a; Fantke 2019; Juraske et al. 2009; Juraske and Sanjuán 2011; Peña et al. 2019, 2018) as shown in Eq. 1.

$$IS = \sum_{i,j} (m_{i,j} \times CF_{i,j}) \quad (1)$$

where $m_{i,j}$ is the emission mass of pesticide j from crop cultivation into a given environmental compartment i per unit area treated ($\text{kg}_{\text{emitted}}/\text{ha}$), and $CF_{i,j}$ is the respective CFs for human health damages ($\text{DALY}/\text{kg}_{\text{emitted}}$) or for ecosystem quality damages ($\text{PDF m}^3 \text{ day}/\text{kg}_{\text{emitted}}$). The human toxicity CFs (cancer and non-cancer) at damage level are expressed as disability-adjusted life years (DALY) per kilogram (kg) pesticide emitted into any environmental compartment (Fantke et al. 2021, 2018b). The ecotoxicity CFs at the damage level are expressed as a potentially disappeared fraction (PDF) of ecosystem species integrated over the exposed environmental compartment and time per kg pesticide emitted into any environmental compartment (Fantke et al. 2018a). Impact scores, IS (DALY/ha for human health,

and PDF $\text{m}^3 \text{ day/ha}$ for ecotoxicity) resulting from all pesticides applied throughout a crop round are quantified from the summation in relation to 1 hectare (ha) treated.

2.2 Pesticide emission quantification

The emission mass can be derived from the mass of a pesticide active ingredient applied to a crop cultivation, $m_{\text{app},j}$ ($\text{kg}_{\text{applied}}/\text{ha}$) and the emission fraction into a particular environmental compartment $i, f_{i,j}$ ($\text{kg}_{\text{emitted}}/\text{kg}_{\text{applied}}$) (Fantke 2019) as shown in Eq. 2.

$$m_{i,j} = m_{\text{app},j} \times f_{i,j} \quad (2)$$

2.2.1 Pesticide application dose derivation

Nine food crops cultivated in Thailand were considered, including rice (two cultivation methods), four vegetables (cabbage, chili, cucumber, and tomato), and four fruits (watermelon, tangerine, durian, and mango). Rice is a major economic crop in Thailand. Rice cultivation with a dry direct-seeded system (Rice-DD) and a pre-germinated direct-seeded system (Rice-PD) are the most popular practices in Thailand, representing 40% of total agricultural land in 2018 (OAE 2020a). Pesticide application data in Thailand were obtained from Bayer Crop Science Thailand (Bayer Crop Science Thailand 2019a, b). The data source provided the characteristics of individual pesticides (e.g., trade name, formula, target class, amount of active ingredient), and the guidelines for pesticide application, such as application doses, application methods, and application frequencies following the plant growth calendar. Additional guidelines of sprayed volumes for pesticide preparation specifically with a crop type and/or growth stages published by Plant Protection Research and Development Office (PPRD), Department of Agriculture (DOA), Thailand, were applied to correctly derive the mass of pesticide active ingredients applied per cultivated area in Thailand (PPRD 2020). The mass of pesticide active ingredients applied to crop cultivation in Thailand is calculated as shown in Eq. 3.

$$m_{\text{app},j} = \sum_x (D_{\text{app},j,x} \times A_x) \quad (3)$$

where $D_{\text{app},j,x}$ is the pesticide application dose ($\text{kg}_{\text{applied}}/\text{ha}$), A_x is the treated area (ha), and their product is summed over x treatments in cases when dosage and treated areas might vary. The derivation of individual pesticide application doses is detailed in the Electronic Supplementary Material-1 (ESM1), Section S-1.

2.2.2 Pesticide emission fractions

Four emission inventory models were applied to determine the consequences of different choices in modeling initial pesticide dispersion into different environmental compartments. Three generic approaches widely used in LCA according to World Food LCA Database (WFLDB) (Nemecek et al. 2019) and Fantke (2019) are Ecoinvent ((Nemecek and Kägi 2007; Nemecek and Schnetzer 2011), US LCI (USDE 2012), and Neto et al. (2013). The respective assumptions of emission fractions after applied pesticide are 100% emitted to agricultural soil in the Ecoinvent database: 95% and 5% emitted to air and surface water in US LCI; 75% and 25% emitted to agricultural soil and air in the study of Neto et al. The emission fractions into different environmental compartments can, however, vary with crop and application method, and are hence further derived using the PestLCI Consensus model (Nemecek et al. 2022). This model determines the pesticide emission dispersions into different environmental compartments at two levels including primary distribution (some minutes after pesticide application) and secondary emission (1 day after pesticide application) when additional transport and degradation processes of the substances after application have been considered (Gentil et al. 2020a). The specific information on crop cultivation and pesticide application within the country (e.g., climate, soil types, pesticide application methods, crop seasons, the months of application) was additionally sought from relevant official documents in Thailand and applied as model inputs. More details on inputs for the PestLCI Consensus web tool (<https://pestlciweb.man.dtu.dk>) are shown in the ESM1, Section S-2. Emissions to off-field surfaces are expressed in the fraction area of Thailand (e.g., agricultural soil, natural soil (including urban areas and miscellaneous land), freshwater area) to consistently combine with the CFs for environmental emissions from USEtox (see details of emission fraction conversion to fraction area of Thailand in the ESM1, Section S-3).

2.3 Toxicological characterization factors

USEtox version 2.12 (<https://usetox.org>) was applied to quantify the CFs for human toxicity and ecotoxicity of the pesticides used in Thai agriculture. The endpoint CFs, $CF_{i,j}$ of pesticide j are derived by combining four terms (Fantke 2019; Gentil et al. 2020a; Rosenbaum et al. 2008) as shown in Eq. 4.

$$CF_{i,j} = FF_{i,j} \times XF_{i,j} \times EF_j \times SF_j \quad (4)$$

where $FF_{i,j}$ ($\text{kg}_{\text{in compartment}} \text{ per kg}_{\text{emitted}}/\text{day}$) is the fate factor linking the increase of pesticide mass in a given environmental compartment due to emission in any compartments,

XF_{ij} is the exposure factor linking pesticide mass taken in via human exposure routes (e.g., inhalation, ingestion) ($\text{kg}_{\text{intake/day}}$ per $\text{kg}_{\text{in compartment}}$) or dissolved pesticide mass in the receiving exposure compartment ($\text{kg}_{\text{dissolved}}/\text{kg}_{\text{in compartment}}$), EF_j is the effect factor linking the exposure to human toxicological effect (disease cases/day per $\text{kg}_{\text{intake}}/\text{day}$) or to ecotoxicological effect for determining potentially affected fraction (PAF) of species ($\text{PAF m}^3/\text{kg}_{\text{dissolved}}$), and SF_j is the severity factor linking toxicological effects to human health damage (DALY/day per disease cases/day) or ecosystem quality damage (PDF/PAF).

2.4 Parameterization for Thai environmental conditions

Up to now, the USEtox model contains the dataset of default settings, 16 sub-continent, and 8 continental regions. Any of the regions belonging to the USEtox model can be independently selected by a user, but are primarily intended as a sensitivity analysis of the global default values (Fantke et al. 2017b). For users who aim to introduce their own regions, it can be challenging to provide the related parameterized input data.

2.4.1 Thai-specific data into the USEtox model

Consequently, the USEtox model version 2.12 was adapted by applying the landscape and consumption parameters to Thailand conditions according to parameterization methods guided by Fantke et al. (2017b), to obtain Thai-specific CFs used for the impact assessment. The parameters have been adjusted and calculated at different scales (e.g., urban, continent, and global) relying on available state-of-the-art data and previous studies in Thailand. It is necessary to recalculate global parameters in context of the differences between the values for the new region and the global average (Fantke et al. 2017b; Bratec et al. 2019). The description and calculation methods of all parameters are shown in Table S1 of the Electronic Supplementary Material-2 (ESM2). In the USEtox model, a parameterized region named “Thailand” was created by adding a new row in the “Landscape & indoor data” sheet, which was populated with Thai-specific data based on the values provided in Table S1, ESM2. Eventually, executing USEtox calculations for Thailand by entering the respective region row number in the “Run” sheet yielded Thai-specific results. More details on how to recalculate global parameters and to incorporate the Thai-specific data into the USEtox model are provided in the ESM1, Section S-10.

2.4.2 Identification of pesticides used in Thailand

Pesticides used in Thai agriculture were identified from various sources including the pesticides imported in 2018 (DOA 2020), pesticides used in the cultivation processes of oil palm (Silalertruksa et al. 2017) and kale (Thai-PAN 2013), pesticide residues in fruits and vegetables distributed within Thailand’s markets (cabbages, tomatoes (Wanwimolruk et al. 2017); watermelon, durian (Wanwimolruk et al. 2015a); Chinese kale (Wanwimolruk et al. 2015b); mangosteen (Phopin et al. 2017); Chinese kale, pakchoi, morning glory (Wanwimolruk et al. 2016); guava (Wanwimolruk et al. 2019)), and also the survey report of pesticide residues monitored by the Thailand Pesticide Alert Network (Thai-PAN) (Thai-PAN 2019). The CAS Registry Numbers (CAS-RN) of the identified pesticides were then searched from the list of hazardous substances in 2013 published in the Notification of the Ministry of Industry in 2013, Thailand (Ministry of Industry 2013).

2.4.3 Updating the degradation rate parameters in USEtox

The half-life value of pesticides in the environment is one of the important parameters used in the quantification of CFs factors derived from USEtox (Fantke et al. 2014, 2012b). The half-life values in the water phase of the identified pesticides were updated by obtaining values from relevant databases such as the Pesticide Properties Database (PPDB) (University of Hertfordshire 2020b), Bio-Pesticides Database (BPDB) (University of Hertfordshire 2020a), and CompTox Chemicals Dashboard, US EPA (US EPA 2021). The updated water degradation rate constant, $k_{\text{deg},w}$ (s^{-1}), of pesticides is calculated from the corresponding reported half-life value, $t_{1/2}$ (d) as shown in Eq. 5.

$$k_{\text{deg},w} = (\ln(2)/t_{1/2})/C_{s\text{-to-d}} \quad (5)$$

with $c_{s\text{-to-d}}$ as unit conversion factor of 86,400 s/day. The updated water degradation rate constants of the pesticides and their difference with default values are shown in the ESM1, Section S-4.

2.4.4 Characterization factors derivation

Matching tests with CAS-RN between the identified pesticides and the organic substances database underlying the USEtox 2.12 model were done to calculate the CFs. Thus, 157 pesticides were matched, accounting for 92% of the total mass of pesticides imported to Thailand in 2018 (DOA 2020). However, 65 out of the 157 matched pesticides do not have

the human toxicity CFs due to the absence of the human toxicological effect factors (EF_{human}) in the default USEtox model. These missing data were hence derived in our study using the toxicological data from the CompTox Chemicals Dashboard, US EPA. The methodology for EF_{human} quantification relies on USEtox (Fantke et al. 2017b) (see ESM1, Section S-5). From these matched pesticides, we identified the important pesticides used in Thailand to evaluate the difference between obtained endpoint CFs from adapted and default USEtox. There were 15 pesticides consisting of the top five in each pesticide target class (herbicides, fungicides, and insecticides) representing 70% of the total pesticide mass imported to Thailand in 2018 (DOA 2020). More details of the percent difference in each pesticide and calculation methods are shown in the ESM1, Section S-6. However, based on the case study in this work, the USEtox inputs for missing substances were additionally derived for nine pesticides used in food crop cultivation in Thailand according to Bayer Crop Science Thailand's recommendations, as indicated in the ESM1, Section S-7.

2.5 Damage cost assessment

Damage cost, DC in Thai baht (THB) per crop year, are derived by multiplying a toxicity impact score from Eq. (1) by the valuation factor, VF , and the treated area per year, A (ha/crop-year) as shown in Eq. 6.

$$DC = IS \times VF \times A \quad (6)$$

where DC , IS , and VF are different for human health and ecosystem quality. The total treated area for a specific crop in Thailand in 2018 was primarily based on the Office of Agricultural Economics (OAE) (OAE 2020a), and the Department of Agriculture Extension (DOAE) (DOAE 2019a, b) (see the total treated area of each crop in the ESM1, Section S-9). The valuation factor of 591,788 (THB/DALY) for human health and 1.02 (THB/PDF m^2 year) for ecosystem quality was projected due to inflation according to Haputta et al. (2020) as shown in Eq. 7.

$$FVC = CVC_{2011} \times (1 + r)^{(t-2011)} \quad (7)$$

where current value of cost, CVC_{2011} , is the Thai people's budget to pay for avoiding 1 DALY of 512,000 THB in 2011 and in 1 PDF in m^2 during 1 year of 0.88 THB in 2011 (derived from 8800 THB/BAHY, and 1 BAHY = -10,000 PDF m^2 year) estimated by Kaechan and Gheewala (2017), r is the average inflation rate of Thailand between 2011 and 2019 relying on the obtained inflation rate (GDP deflator) from The World Bank Group (2021), that is 1.83%, and t is the reference year of currency used in the valuation (i.e., 2019). Eventually, in ecosystem quality damage cost assessment, applying a conversion factor of 1 year is 365.25 day

(NASA Official. (n.d.)) and dividing the PDF m^2 year with mean of mean depth of thirty-three large water resources in Thailand of 19.05 m (Department of Fisheries 2016).

3 Results and discussion

3.1 Pesticide emission distributions

Table 1 shows the average emission fractions of multiple pesticides applied in the cultivation of nine food crops modelled by using the PestLCI Consensus model. For the primary distribution (some minutes after pesticide application), all food crops show that the main fractions are emitted to field soil and field crop surface. Six crops, namely rice, cabbage, cucumber, tomato, watermelon, and tangerine, show a similar trend with pesticides being mainly emitted to the agricultural soil (53% to 84%) followed by the crop surface (9% to 40%). Three other crops including chili, durian, and mango show that the main emission compartments of pesticides are the crop surface (48% to 61%) followed by the agricultural soil (33% to 45%). Similarly, for the secondary emission (1 day after pesticide application), agricultural soil and crop uptake compartments are the main distribution channels of pesticides applied to all food crops. Removal through degradation shows a wide range from 2 to 21% in the secondary emissions. The results indicate that the emission fractions varied widely for emissions to agricultural soil and crop compartments. On the other hand, the small emission fractions to air and off-field surfaces are slightly different. The dominant compartments in pesticide emission distributions found in this study are agricultural soil and crops which is consistent with previous studies (Fantke et al. 2012a; Fantke and Jolliet 2016).

The primary distribution process determines the fraction deposited on leaves and soil, and the emission fractions to air and off-field surfaces by wind drift. After that, secondary emission processes take place on leaves and in soil (Birkved and Hauschild 2006; Dijkman et al. 2012). Hence, to carry out the PestLCI Consensus model, the fraction of pesticide intercepted by leaves is a significant factor in determining the main distribution compartments for sprayed pesticides. This study defines the fraction of pesticide intercepted by leaves (range 0–1) following the crop growth stages recommended by Linders et al. (2000) and in relation to the cultivation process provided by Bayer Crop Science Thailand. The crop growth stages of fruits and vegetables mainly include leaf development, flowering, fruit development, and ripening/senescence, depending on the crop types (Linders et al. 2000). The variability of primary distribution depends on application time during crop growth stages (Gentil et al. 2020a). Consequently, pesticides that are applied throughout the crop growth stages result in high

Table 1 Average emission fractions (%) into environmental compartments of pesticides applied to different food crop cultivation in Thailand evaluated by the PestLCI Consensus model

Emission to	Average emission fractions ^a (% k _g -emitted/k _g -applied) among pesticides applied to									
	Rice-DD ^c	Rice-PD ^c	Cabbage	Chili	Cucumber	Tomato	Watermelon	Tangerine	Durian	Mango
Primary distribution (some minutes after application)										
Air	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Field soil surface	83.85	80.74	61.33	45.03	73.20	60.56	81.52	52.79	44.72	32.61
Field crop leaf surface	9.32	12.42	31.83	48.13	19.96	32.61	11.65	40.37	48.45	60.56
Off-field surface	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Agricultural soil (off-field) ^b	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Natural soil (off-field) ^b	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Freshwater (off-field) ^b	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Secondary emission (1 day after application)										
Air	6.00	6.01	6.03	6.03	6.01	6.01	6.00	6.04	6.00	6.02
Field soil surface	65.14	60.64	51.06	38.35	67.09	56.41	80.95	39.80	40.44	28.51
Field crop leaf surface	0.21	3.56	4.01	7.33	2.35	1.35	0.68	12.07	1.10	4.01
Field crop leaf uptake	8.84	7.92	24.22	37.31	16.37	30.13	9.91	25.54	44.00	52.47
Groundwater	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Degradation in field crop and soil	18.98	21.04	13.85	10.15	7.34	5.26	1.62	15.71	7.63	8.15
Off-field surface	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Agricultural soil (off-field) ^b	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Natural soil (off-field) ^b	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Freshwater (off-field) ^b	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

^aIndividual pesticide emission fraction applied to each crop is shown in the Electronic Supplementary Material-1 (ESM1), Section S-3

^bThe emissions to off-field surfaces are expressed in the fraction area of Thailand which are 56% agricultural soil, 41% natural soil (including urban areas and miscellaneous land), and 3% freshwater (LDD 2019)

^cRice cultivation methods with a dry direct-seeded system (Rice-DD) and pre-germinated direct-seeded system (Rice-PD) represent 43% and 40% of the total rice cultivation area in Thailand in 2018 (OAE 2018a, b)

crop deposition due to the pesticide intercepted by leaves. For example, pesticides such as insecticides and fungicides are sprayed through the growth stages from leaf development until the ripening stage in chili cultivation. Likewise, several pesticides (including insecticides and fungicides) are applied from new leaf development until the flowering stage in durian and mango cultivation. On the other hand, some pesticides are mainly applied to soil causing high field soil deposition. Examples include herbicide application against weeds at the beginning of cultivation and insecticide application against soil insects. An insecticide (imidacloprid) is applied for seed protection from soil pests in the cultivation process of cucumber, watermelon, and Rice-DD. Some herbicides are applied for weed control at the beginning of rice cultivation. More details on individual pesticide emission fractions are shown in the ESM1, Section S-3.

3.2 Characterization factors for Thai environmental conditions

This study provides the human toxicity and ecotoxicity CFs of 166 pesticides used in Thailand including 48 herbicides, 49 fungicides, 57 insecticides, and 12 pesticides in other target classes (e.g., acaricide, molluscicide, fumigant, and plant growth regulator) in the ESM1, Section S-4. Table 2 shows the endpoint (i.e., damage-level) CFs for human toxicity and ecotoxicity of important pesticides used in Thai agriculture. The endpoint human toxicity CFs of the important pesticides indicate a wide range from 10^{-12} to 10^{-2} DALY/kg_{emitted}. The pesticide emissions to freshwater compartments exhibit the highest endpoint ecotoxicity CFs in the range of 91 to 1.5×10^6 PDF m³ day/kg_{emitted}. A regionalized assessment considers geographical differences using parameters related to pesticide emission conditions such as territory, wind speed, temperature, runoff, rain rate, etc. that are generally considered to present the sensitivity of pesticides in the environment or refer to pesticide residues in the crops (Fantke 2019; Giusti et al. 2022). To quantify the sensitivity of important pesticides in environments associated with spatial parameters of Thailand, the obtained endpoint CFs from the adapted USEtox with Thailand-specific data illustrate the differences when compared with the global average factors, ranging from 1 to 169% for human toxicity CFs and from 0.1 to 3587% for ecotoxicity CFs (Table 2). Additionally, updated degradation rates in the water phase of 105 out of 157 pesticides are calculated. The difference between default and updated degradation rates ranges from 0 to 3 orders of magnitude (see the percent difference of each pesticide in the ESM1, Section S-4). CFs describe the expected impacts due to environmental emissions of toxic compounds. Pesticides with lower potential toxicity effects were hence identified by ranking endpoint CFs for emissions

to agricultural soil in the ESM1, Section S-4 as an illustrative case.

3.3 Toxicological impacts on humans and ecosystems

Pesticide emission fractions and CFs in a given environmental compartment are combined to quantify potential impact scores. Four emission inventory models are applied to determine the pesticide emission distribution. PestLCI Consensus model is the only LCI approach considering an emission fraction that reaches the crop which will be consumed and lead to additional human impacts. The emissions to crops have not been considered in the other three approaches (Ecoinvent, US LCI, Neto et al.). LCA practitioners can define the parameter values specifically with the characteristics of the country's agriculture and pesticide application related to time and growth stages in the PestLCI Consensus model. Primary emission fractions from the PestLCI Consensus model are fully consistent with USEtox applied for impact calculations (Gentil et al. 2020a). Therefore, the PestLCI Consensus model is chosen as the main emission inventory approach to illustrate the obtained impact scores compared with three fixed approaches widely used in LCA.

Seventeen pesticide types are distributed across nine crops during the cultivation processes of rice, vegetables, and fruits, with application rates ranging from 0.01 to 0.50, 0.01 to 14.44, and 0.02 to 21.88 kg per hectare, respectively. The combination of emitted mass and CFs yields potential toxicity impact scores, plotted along diagonal equi-impact lines in Fig. 1. The equal impact is indicated by data points on the same diagonal line, which can be influenced by emission mass, CFs, or a combination of both.

3.3.1 Impacts on human health and related substance contributors

Figure 1a indicates that a large pesticide emission to crops, along with a high CF, results in the highest human health impact scores for Propineb used in mango, chili, and tangerine cultivation. This demonstrates an important consideration of the fraction of pesticide emissions to crop compartments in LCA. Based on the results from the PestLCI Consensus model in Fig. 2a, all food crops show total human health impact scores in the range of 5.2×10^{-5} to 6.9×10^{-2} DALY/ha. Mango has the highest human health impact scores of 6.9×10^{-2} DALY/ha, followed by chili (3.7×10^{-2} DALY/ha) and tangerine (1.5×10^{-2} DALY/ha) at the same order of magnitude. High amounts of several pesticides are applied to mango cultivation in the range of 1.6 to 21.9 kg_{applied}/ha. Pesticides are sprayed using a high-pressure knapsack sprayer through the mango's seasonal fruit development, which generally contains a lot of crop leaves (PPRD

Table 2 Characterization factors of important pesticides used in Thai agriculture

Pesticides ^a			Emission to ^b					% different ranging ^c
CAS-RN	Common name	Target class	Rural air	Freshwater	Sea water	Nat soil	Agri soil	
Adapted-Endpoint human health characterization factor (DALY/kg_{emitted})^d								
38,641–94-0	Glyphosate-isopropylammonium	Her	1.5E-04	3.6E-04	1.5E-07	1.5E-04	1.5E-04	-
1910–42-5	Paraquat dichloride	Her	4.4E-07	1.3E-06	3.8E-09	1.0E-07	1.0E-07	9–93
2008–39-1	2,4-D-dimethylammonium	Her	9.9E-02	3.5E-04	2.2E-07	1.6E-04	2.1E-04	-
834–12-8	Ametryn	Her	1.4E-04	7.0E-04	7.0E-06	4.3E-05	8.4E-05	-
1912–24-9	Atrazine	Her	3.2E-06	1.2E-05	4.0E-08	1.1E-06	3.0E-06	49–78
12,071–83-9	Propineb	Fun	2.6E-07	2.3E-07	4.2E-10	6.6E-09	2.2E-07	57–84
8018–01-7	Mancozeb	Fun	7.2E-08	6.8E-09	3.4E-12	3.2E-10	1.4E-07	57–84
10,605–21-7	Carbendazim	Fun	5.3E-08	1.8E-07	2.1E-10	1.1E-08	7.9E-08	57–83
57,837–19-1	Metalaxyl	Fun	1.6E-07	4.5E-07	4.3E-10	1.3E-07	2.7E-07	57–79
133–06-2	Captan	Fun	8.2E-08	2.9E-08	5.0E-10	3.7E-10	6.8E-09	47–94
65,195–55-3	Abamectin	Ins	1.4E-04	1.7E-04	4.7E-06	6.5E-08	7.8E-08	57–96
2921–88-2	Chlorpyrifos	Ins	4.2E-06	4.6E-05	1.4E-06	3.8E-07	4.9E-07	34–98
55,285–14-8	Carbosulfan	Ins	2.9E-06	4.8E-05	1.5E-06	3.2E-07	3.8E-07	44–109
120,068–37-3	Fipronil	Ins	6.9E-06	1.2E-04	3.8E-06	3.8E-06	4.2E-06	1–93
52,315–07-8	Cypermethrin	Ins	1.0E-06	1.4E-07	9.5E-09	2.6E-09	5.0E-09	57–169
Adapted-Endpoint ecotoxicity characterization factor (PDF m³ day/kg_{emitted})								
38,641–94-0	Glyphosate-isopropylammonium	Her	7.4E+01	3.0E+02	4.5E-07	1.3E+02	1.3E+02	1–105
1910–42-5	Paraquat dichloride	Her	7.6E+01	1.2E+03	2.4E-08	9.5E+01	9.5E+01	7–470
2008–39-1	2,4-D-dimethylammonium	Her	2.1E+02	8.6E+02	9.3E-10	4.0E+02	4.0E+02	1–101
834–12-8	Ametryn	Her	2.3E+03	4.8E+04	5.6E-02	2.9E+03	2.9E+03	25–221
1912–24-9	Atrazine	Her	3.7E+03	5.7E+04	8.9E-02	5.2E+03	5.2E+03	30–218
12,071–83-9	Propineb	Fun	3.0E+00	9.1E+01	3.7E-08	2.6E+00	2.6E+00	0.1–145
8018–01-7	Mancozeb	Fun	1.4E+01	1.9E+02	6.8E-14	9.1E+00	3.1E+01	0.1–200
10,605–21-7	Carbendazim	Fun	4.8E+03	1.0E+05	1.6E-04	6.4E+03	6.2E+03	5–183
57,837–19-1	Metalaxyl	Fun	1.4E+02	8.3E+02	3.6E-03	2.4E+02	2.4E+02	31–187
133–06-2	Captan	Fun	1.1E+01	6.8E+02	8.7E-06	8.3E+00	8.3E+00	0.4–159
65,195–55-3	Abamectin	Ins	4.4E+02	3.3E+04	6.4E-22	1.3E+01	1.3E+01	2–381
2921–88-2	Chlorpyrifos	Ins	2.9E+02	3.6E+05	6.6E-01	2.4E+03	2.4E+03	3–472
55,285–14-8	Carbosulfan	Ins	8.0E+00	3.7E+03	1.1E-03	2.4E+01	2.4E+01	2–535
120,068–37-3	Fipronil	Ins	1.8E+04	5.7E+05	1.1E-01	1.7E+04	1.7E+04	6–266
52,315–07-8	Cypermethrin	Ins	8.1E+03	1.5E+06	1.2E+00	2.0E+04	2.0E+04	9–3587

^aThere are the top five of each main pesticide target class imported to Thailand in 2018 including 73% herbicides (Her), 12% fungicides (Fun), and 10% insecticides (Ins) (DOA 2020)

^bSee more details of characterization factors for human toxicity (cancer and non-cancer) and ecotoxicity at midpoint and endpoint levels of 166 pesticides in the Electronic Supplementary Material-1 (ESM1), Section S-4

^cPercent difference ranging between obtained endpoint characterization factors from adapted and default USEtox model except for the three pesticides (–) whose characterization factors are derived in this study

^dAll endpoint human toxicity characterization factors of these pesticides are presented for non-cancer effects except for Atrazine and Captan for which total values (cancer and non-cancer) are shown

2020). Mango thus shows the highest pesticide emission fractions to the crop leaf surface (61% as shown in Table 1) in the primary distribution process. Moreover, 3 of the 5 pesticides used in mango cultivation show higher endpoint human toxicity CFs in the crop compartment (i.e., emission to archetype crop as apple) than other environmental

compartments (e.g., air, soil, water) in the range of 3 to 6 orders of magnitude, since crop residues reach humans more efficiently as compared to environmental emissions (shown in the ESM1, Section S-8). Propineb (> 90% share) is the largest contributor to the potential human health impacts on these three crops (mango, chili, and tangerine), as stated

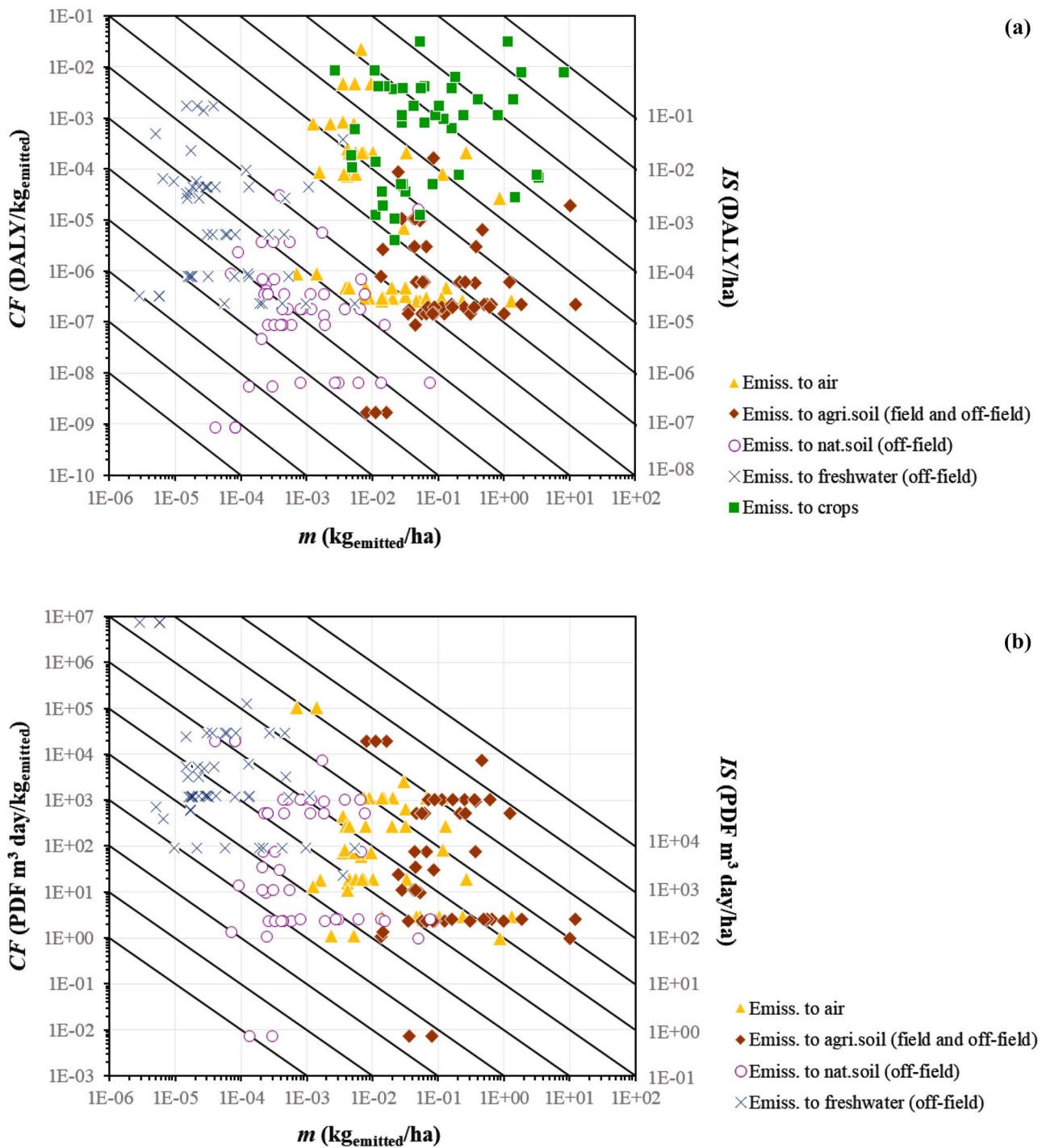


Fig. 1 Characterization factors (left-side y-axis) for **(a)** human toxicity (DALY/kg_{emitted}) and **(b)** ecotoxicity (PDF m³ day/kg_{emitted}) for emitted mass of pesticides applied to different food crop cultivation in

Thailand (x-axis) (kg_{emitted}/ha) with diagonal equi-impact lines (right-side y-axes), respectively illustrating impact scores for human toxicity (DALY/ha) and ecotoxicity (PDF m³ day/ha)

in Table 3. This is due to the high doses of Propineb used in the cultivation process (21.9, 1.75, and 3.94 kg_{applied}/ha in mango, chili, and tangerine, respectively), causing high emissions. Propineb is also the predominant substance contributor (> 70% share) in the cultivation processes of cabbage and cucumber. This is the main fungicide used in Thai

agriculture that shows the highest import mass annually (DOA 2020). Dominating pesticides related to human health impacts from the fruit and vegetable cultivation (e.g., cabbage, chili, cucumber, tangerine, durian, mango) and Rice-DD method are fungicides such as Propineb and Tebuconazole. Insecticides (e.g., Ethiprole and Imidacloprid) also

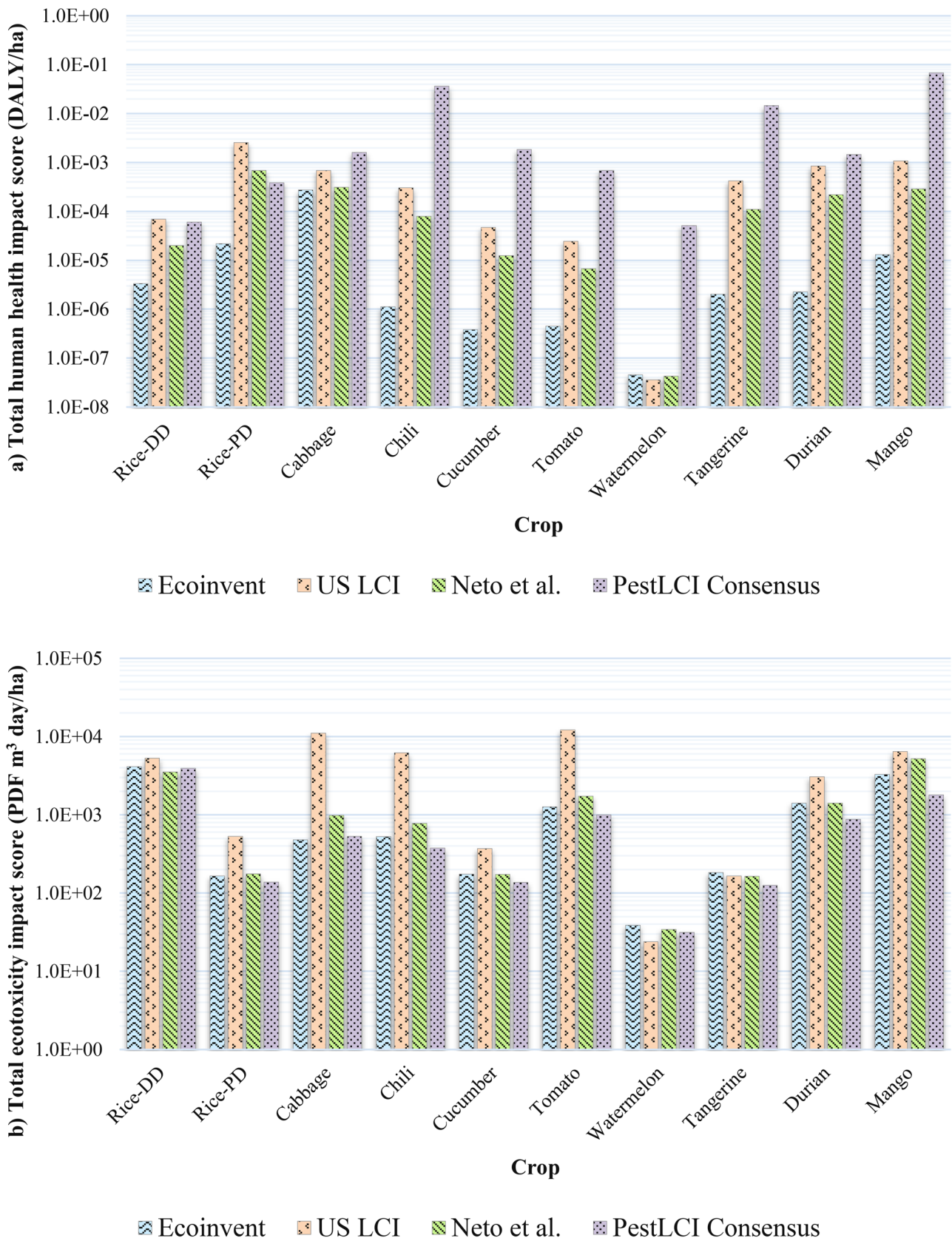


Fig. 2 (a) Total human health impact scores (DALY/ha) and (b) total ecotoxicity impact scores (PDF m³ day/ha) of pesticides applied to different food crop cultivation in Thailand based on various assumptions for emission distributions

contribute to the impacts from the cultivation processes of Rice-PD, tomato, and watermelon (Table 3). The results show a trend of fungicides and insecticides having a greater overall impact on human health.

3.3.2 Impacts on ecosystem and related substance contributors

Figure 1b shows that the ecotoxicity impact scores are mainly associated with high pesticide emission fractions to agricultural soil coupled with high CFs resulting in the maximum impact scores for Oxadiazon used in Rice-DD cultivation. Agricultural soil is the main channel of pesticide release into the environment contributing to ecotoxicity impact scores. Small amounts of other pesticide use (e.g., Betacyfluthrin) are compensated by higher CFs emission to freshwater channels. Based on the results from the PestLCI Consensus model in Fig. 2b, all food crops show total ecotoxicity impact scores in the range of 31 to 3934 PDF m³ day/ha. Rice-DD method illustrates that the highest ecotoxicity impact scores are mainly caused by Oxadiazon (92% share) (Table 3). This cultivation method confronts a weed problem after sowing the rice seeds directly in dry soil and waiting for the rainy day to germinate (Rice Department 2016). On the other hand, Rice-PD method has ecotoxicity impact scores (138 PDF m³ day/ha) that are lower than Rice-DD method by one order of magnitude. Tebuconazole is the predominant substance contributor to

the ecotoxicity impacts with a 93% share (Table 3). The rice seed is allowed to germinate before planting on wet soil in the Rice-PD method causing problems related to microorganisms (Rice Department 2016). Rice cultivation indicates the highest pesticide emission fractions to agricultural soil compared with other crops: 84% for Rice-DD and 81% for Rice-PD methods in the primary distribution process (shown in Table 1). The endpoint ecotoxicity CFs of Oxadiazon in agricultural soil and other compartments (e.g., air, freshwater, natural soil) are higher than for Tebuconazole (shown in the ESM1, Section S-8). Furthermore, in the fruit group, mango cultivation shows the highest ecotoxicity impact scores of 1803 PDF m³ day/ha (Fig. 2b). The three main pesticides contributing to the ecotoxicity impacts are Imidacloprid (38% share), Trifloxystrobin (29% share), and Tebuconazole (29% share) (Table 3). Mango cultivation uses a higher amount of Imidacloprid at 2.19 kg_{applied}/ha than other fruits (including watermelon, tangerine, and durian) which is in the range of 0.07 to 0.54 kg_{applied}/ha. In the vegetable group, the highest ecotoxicity impact score of 1002 PDF m³ day/ha is from tomato cultivation (Fig. 2b). Betacyfluthrin (41% share) and Metribuzin (37% share) are the main substance contributors to ecotoxicity impacts from tomato cultivation. Additionally (Table 3), Betacyfluthrin is also the major contributor to the ecotoxicity impacts in the cultivation process of cabbage and chili. USEtox shows the maximum endpoint ecotoxicity CFs of Betacyfluthrin compared with all pesticides applied through the four vegetables

Table 3 The most important substances contributing (% share) to potential toxicological impact scores from different food crop cultivation in Thailand based on four emission approaches

Crop	Most substance contributor (% share) ^a							
	Human health impact score (DALY/ha)				Ecotoxicity impact score (PDF m ³ day/ha)			
	Ecoinvent	US LCI	Neto et al.	PestLCI	Ecoinvent	US LCI	Neto et al.	PestLCI
Rice-DD	B (96) [#]	G (50) ^{&}	G (45) ^{&}	F (85) ^{&}	B (91) [#]	B (83) [#]	B (89) [#]	B (92) [#]
Rice-PD	I (85) [*]	I (95) [*]	I (95) [*]	I (64) [*]	F (94) ^{&}	F (72) ^{&}	F (90) ^{&}	F (93) ^{&}
Cabbage	D (100) ^{&}	D (94) ^{&}	D (96) ^{&}	E (72) ^{&}	H (95) [*]	H (99) [*]	H (98) [*]	H (97) [*]
Chili	K (56) [*]	K (91) [*]	K (91) [*]	E (98) ^{&}	F (49) ^{&}	H (89) [*]	H (61) [*]	H (68) [*]
Cucumber	C (49) ^{&}	G (55) ^{&}	G (54) ^{&}	E (91) ^{&}	F (74) ^{&}	F (86) ^{&}	F (77) ^{&}	F (74) ^{&}
Tomato	A (68) [#]	G (98) ^{&}	G (94) ^{&}	J (37) [*]	A (39) [#]	H (91) [*]	H (56) [*]	H (41) [*]
Watermelon ^b	J (100) [*]	J (100) [*]	J (100) [*]	J (100) [*]	J (100) [*]	J (100) [*]	J (100) [*]	J (100) [*]
Tangerine	K (47) [*]	K (100) [*]	K (99) [*]	E (99) ^{&}	J (94) [*]	J (64) [*]	J (92) [*]	J (95) [*]
Durian	K (73) [*]	K (87) [*]	K (86) [*]	F (64) ^{&}	F (80) ^{&}	F (91) ^{&}	F (82) ^{&}	F (83) ^{&}
Mango	C (45) ^{&}	G (85) ^{&}	G (83) ^{&}	E (93) ^{&}	F (59) ^{&}	F (74) ^{&}	G (39) ^{&}	J (38) [*]

Symbols refer to a pesticide target class including ([#]) herbicide, ([&]) fungicide, and (^{*}) insecticide

^aMost substance contributors are shown with a pesticide name's code as follow as A (Metribuzin: 21,087–64-9), B (Oxadiazon: 19,666–30-9), C (Fluopyram: 658,066–35-4), D (Propamocarb HCL: 25,606–41-1), E (Propineb: 12,071–83-9), F (Tebuconazole: 107,534–96-3), G (Trifloxystrobin: 141,517–21-7), H (Betacyfluthrin: 68,359–37-5), I (Ethiprole: 181,587–01-9), J (Imidacloprid: 138,261–41-3), K (Spiromesifen: 283,594–90-1)

^bOnly imidacloprid is used throughout the cultivation process

in this study. Consequently, the toxicity impacts on ecosystems from the fruit and vegetable cultivation (e.g., cabbage, chili, tomato, watermelon, tangerine, and mango) are mainly caused by insecticides such as Betacyfluthrin and Imidacloprid (Table 3). This demonstrates that, despite using lower insecticides in crop cultivation, it has a significant impact on overall ecotoxicity. Fungicide as Tebuconazole is contributed to the cultivation processes of some crops such as Rice-PD method, cucumber, and durian. Herbicide such as Oxadiazon contributes to the potential impacts of the Rice-DD method. For overall impact reduction, the main substance contributors should be considered when identifying possible substitutes with lower toxicity.

3.3.3 Influence of modeling choices on impact score results

The results indicate a high difference between varied and fixed inventory modeling for human toxicity impact assessment in the range of 1 to 4 orders of magnitude (Fig. 2a). PestLCI Consensus model provides the highest total human health impact scores for all food crops except for rice cultivation when compared with generic emission distributions. Various pesticides applied to crop cultivation illustrate the highest endpoint CFs for human toxicity in the archetype crop compartment in the USEtox. On the other hand, the lowest total human health impact scores are found when the Ecoinvent assumption is applied for all food crops except for watermelon. However, when more environmental compartments are considered according to Neto et al. and US LCI assumptions, then additional impact scores are obtained. Total human health impact scores based on different emission approaches are compared with Ecoinvent in percent relative comparison as shown in Fig. S1(A) in the ESM2.

The higher estimated emission to soil and water shows higher ecotoxicity impacts. Figure 2b illustrates a trend of obtained ecotoxicity impact scores from various emission approaches at the same order of magnitude in six crop cultivation (Rice-DD, Rice-PD, cucumber, tomato, watermelon, tangerine, and mango). US LCI shows significant highest ecotoxicity impact scores compared with other approaches at 1 to 2 orders of magnitude in all crops except for watermelon and tangerine. The endpoint CFs for ecotoxicity of several pesticides applied to crop cultivation show the highest values when they are emitted to the freshwater channels. The fixed model US LCI has defined 5% of applied pesticides emitted to the freshwater compartment while not exceeding 0.1% average are emitted to the freshwater evaluated by the PestLCI Consensus model (shown in Table 1). The ecotoxicity impact scores based on different emission approaches are compared with Ecoinvent in percent relative comparison as shown in Fig. S1(B) in the ESM2.

3.4 Total damage costs on human health and freshwater quality

Since variability in toxicological impact scores is based on emission inventory approaches, we follow the PestLCI Consensus model to demonstrate our results (Table 4). Total damage costs on human health and freshwater ecotoxicity of numerous pesticides applied during nine crop cultivation in Thailand are 7188.37 and 3.01 million THB/crop-year, respectively. The total damage costs for human health are two thousand times higher than total damage costs for freshwater ecotoxicity. Mango cultivation shows the highest human health damage costs of 5005.13 million THB/crop-year with a 70% contribution to the total damage costs. Meanwhile, Rice-DD method shows the highest freshwater ecotoxicity damage costs of 2.87 million THB/crop-year with a 95% contribution to the total damage costs. The results indicate that the relevance of higher impact scores is resulting in high damage costs. Mango and Rice-DD cultivation have the highest impact scores for human toxicity and ecotoxicity, respectively (shown in Fig. 2). Furthermore, higher damage costs are influenced by the cultivation area. For example, Rice-PD method shows a 15% contribution to total human health damage costs even though it has lower human health impacts than chili and tangerine by two orders of magnitude. This is due to large cultivation areas of Rice-PD method with 4.63 million hectares accounting for 19% of the total agricultural area in Thailand in 2018 (OAE 2020a). On the other hand, chili and tangerine cultivation accounted for less than 1% of Thailand's total agricultural area in 2018 (OAE 2020a).

The damage cost assessment of pesticide applications during cultivation on human health and freshwater ecotoxicity is quantified for a crop round per total treated area per year. As a result, the damage costs at the national level are represented. According to the highest damage costs found in mango and rice cultivation, these crops are then chosen to demonstrate how total pesticide application damage costs are related to annual net incomes from the specific crop production. Mango is a crop growing across Thailand due to suitable circumstances. Thailand can produce mango throughout the year including out of the season (June to February) (DOA 2018). Thailand intends to enhance the mango production procedures in order to achieve high quality and safety, as well as to satisfy the market, have less environmental impacts, and have an increased net income (DOA 2018). Meanwhile, rice is a major crop in Thailand with the largest cultivation area of around 68.5 million rais or 11 million ha during the crop year 2019/2020, ranked as one of the top ten countries of global producers and exporters (OAE 2021).

Table 4 Total damage costs to human health and freshwater quality of pesticides applied throughout the treated area per year based on four emission approaches

Crop	Emission models and % share of total damage costs							
	Ecoinvent	% share	US LCI	% share	Neto et al.	% share	PestLCI	% share
Human health damage costs (million THB/crop-year)								
Rice-DD	9.85	13.6	204.97	2.8	59.04	3.0	178.68	2.5
Rice-PD	60.12	83.1	7029.33	95.0	1888.72	94.9	1055.88	14.7
Cabbage	1.17	1.6	2.93	0.0	1.33	0.1	6.86	0.1
Chili	0.02	0.0	5.58	0.1	1.46	0.1	670.57	9.3
Cucumber	0.0014	0.0	0.17	0.0	0.05	0.0	6.80	0.1
Tomato	0.0016	0.0	0.085	0.0	0.023	0.0	2.38	0.0
Watermelon	0.0002	0.0	0.00013	0.0	0.00015	0.0	0.19	0.0
Tangerine	0.02	0.0	4.03	0.1	1.06	0.1	140.66	2.0
Durian	0.19	0.3	70.43	1.0	18.35	0.9	121.21	1.7
Mango	0.96	1.3	78.80	1.1	21.20	1.1	5005.13	69.6
Total	72.33		7396.34		1991.23		7188.37	
Freshwater ecotoxicity damage costs (THB/crop-year)								
Rice-DD	3,009,427	93.6	3,852,736	86.7	2,569,597	91.2	2,866,734	95.1
Rice-PD	111,539	3.5	360,075	8.1	118,838	4.2	93,678	3.1
Cabbage	504	0.0	11,663	0.3	1035	0.0	559	0.0
Chili	2379	0.1	28,029	0.6	3530	0.1	1704	0.1
Cucumber	158	0.0	335	0.0	157	0.0	124	0.0
Tomato	1077	0.0	10,358	0.2	1472	0.1	855	0.0
Watermelon	34	0.0	21	0.0	30	0.0	28	0.0
Tangerine	435	0.0	392	0.0	391	0.0	298	0.0
Durian	29,170	0.9	62,847	1.4	29,075	1.0	17,972	0.6
Mango	59,538	1.9	116,473	2.6	93,913	3.3	32,526	1.1
Total	3,214,261		4,442,929		2,818,036		3,014,478	

Based on the existing data of Nam Dok Mai production, a mango species mainly planted in Thailand (accounted for 39% of the total area of mango cultivation in 2020), annual production costs, prices at farm gate, and net incomes of mango cultivation in 2020 were 6696, 20793, and 14096 million THB/crop-year, respectively (OAE 2020b; DOAE 2022). Mango cultivation results in total damage costs from human toxicity and ecotoxicity impacts of 5005 million THB/crop-year. As a consequence, total damage costs from the pesticides used in mango cultivation are 36% of the total net incomes. In the crop year 2018/2019, annual production costs, prices at farm gate, and net incomes of rice cultivation (all systems) were 294,103, 300,358, and 6,255 million THB/crop-year, respectively (OAE 2021). The total damage costs from human toxicity and ecotoxicity impacts caused by two main rice cultivation systems in this study (Rice-DD and Rice-PD) are 1238 million THB/crop-year, accounting for 20% of the annual net incomes of rice cultivation (all systems) in Thailand. More details on the derivation and reference of the annual production costs, prices at farm gate, and net incomes are documented in the ESM1, Section S-9.

Pesticides used in these two crops are showing high environmental costs, requiring suitable actions to limit the toxicity impacts. These are external costs associated with the impact of pesticides on health and the environment that should be minimized to ensure more sustainable and economically viable crop production systems. To debate the net benefits provided by pesticides used, the internal costs (e.g., purchase and application of pesticides) and external costs (e.g., potential impacts on human health and the environment) should both be consistently considered (Bourguet and Guillemaud 2016). Hence, the current study substantially supports a thorough evaluation comparing the external costs with the annual net revenue (divergence of production costs and price at the farm gate) of each crop. Currently, to develop relevant pesticide policies, Laohaudomchok et al. (2020) suggested to include information on the economic impacts of workers' injuries and illnesses, and the ecological consequences of pesticide use. Since toxicity impacts related to damage costs can be considerably influenced by the choice of pesticides, further pesticide guidelines should recognize the damage costs of exposure to multiple pesticides for decision-making.

4 Conclusions

Our study illustrates the ranking of toxicological impact scores and related damage costs on human health and fresh-water quality resulting from pesticides applied during the cultivation processes of nine food crops according to existing guidelines in Thailand. The differences in the toxicity impacts of important pesticides in Thailand when using Thai-specific factors in comparison with the global average factors are ranged from 1 to 169% (for human toxicity) and from 0.1 to 3587% (for ecotoxicity).

Our results indicate that the variability in toxicological impact scores is influenced by emission inventory approaches. Mango cultivation shows the highest human health impact scores of 0.07 DALY/ha mainly caused by Propineb, while rice cultivation with a dry direct-seeded system shows the highest ecotoxicity impact scores of 3934 PDF m³ day/ha mainly caused by Oxadiazon. Pesticides-related total damage costs across nine food crops cultivated in Thailand amounted to 7.2 billion THB/crop-year, with mango cultivation contributing 70% to total human health damage costs, and rice cultivation contributing 98% to total ecotoxicity damage costs. Mango and rice cultivation were chosen to demonstrate how damage costs from pesticide use correlate with the annual net incomes from the respective crop production systems. Total external costs due to the toxicity impacts from pesticide use in mango and rice cultivation are, respectively, 36% and 20% of the annual net income.

More detailed statistics on the pesticide used in the field throughout the crop calendar are required to monitor and assess related toxic impacts and to evaluate relevant national pesticide policies. Pesticides that were identified in our study as predominant contributors to impacting human health and/or ecosystem quality should be prioritized for substitution with less toxic agents or practices. Such alternatives are in an ideal case not just less toxic but are within any carrying capacities for toxicity in humans and in ecosystems to achieve overall sustainability (Fantke and Illner 2019; Kosnik et al. 2022). Our study constitutes a valuable starting point to achieve this goal by identifying possible pesticide candidates for substitution, as input for policy improvement and recommendations toward better decision making regarding sustainable pesticide use.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-022-02094-1>.

Acknowledgements Financial support by the Thailand Science Research and Innovation (TSRI), National Research Council of Thailand (NRCT), and the National Science and Technology Development Agency (NSTDA) under the Royal Golden Jubilee Ph.D. program (Grant No. PHD/0050/2561) are gratefully acknowledged. This research was also supported by NSTDA through the Research Chair

Grant 2559 (RD&E Fund: FDA-CO-2559-3268-TH), Mahidol University (MU-Talents on Research), and by the SPRINT project funded by the European Commission through Horizon 2020 (grant agreement no. 862568).

Author contribution Phatchari Mankong: conceptualization, methodology, investigation, formal analysis, writing—original draft and revision. Peter Fantke: methodology, formal analysis, writing—review and editing. Tanapon Phenrat: supervision. Jitti Mungkalasiri: supervision, writing—review and editing. Shabbir H. Gheewala: conceptualization, methodology, supervision, writing—review and editing. Trakarn Prapasongsa: conceptualization, methodology, supervision, writing—review and editing.

Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interest The authors declare no conflict of interest.

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