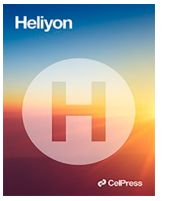
Heliyon 11 (2025) e41123

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Pesticide exposure and sleep disorder: A cross-sectional study among Thai farmers

Chudchawal Juntarawijit [a], Uraiwan Chaichanawirote [b], Nootchayong Yaowapanon [c], Kajohnsak Noppakun [d,e,*]

[a] Faculty of Agriculture, Natural Resources and Environment, Naresuan University, Phitsanulok, Thailand
[b] Faculty of Nursing, Naresuan University, Phitsanulok, Thailand
[c] McCormick Faculty of Nursing, Payap University, Chiang Mai, Thailand
[d] Department of Internal Medicine, Faculty of Medicine, Chiang Mai University, Chiang Mai, Thailand
[e] Pharmacoepidemiology and Statistics Research Center (PESRC), Faculty of Pharmacy, Chiang Mai University, Chiang Mai, Thailand

ARTICLE INFO

Keywords:
Sleep disorders
Sleep health
Pesticides
Insecticides
Herbicides
Fungicides

ABSTRACT

Pesticide exposure might be an important risk factor for sleep disorders, however current epidemiological evidence is limited. The main objective of this study was to determine the association between historical use of pesticides and sleep disorders. Data on the historical use of 38 individual pesticides of almost thirty thousand Thai farmers were collected using questionnaire method. This information was linked to medically diagnosed sleep disorders using a multivariable logistic regression. The study found a positive association of 19 individual pesticides (twelve insecticides, two herbicides, and five fungicides). Some associations demonstrated a dose-response pattern. Additionally, the study revealed that women are at a higher risk of sleep-related issues with pesticide exposure compared to males. These results not only substantiate existing literature but also unveil several new individual pesticides that may impact sleep health. Sleep health should receive more attention, as it can contribute to various diseases and significantly impact the overall well-being of individuals.

1. Introduction

Sleep health has become a global concern since sleep problems can affect both physical and mental health. Studies found sleep deficiency increased mortality [1] and various health complications, including hypertension [2], obesity and type 2 diabetes [3], cardiovascular diseases [4], mood disorders [5], and neurodegenerative disorder [6]. To be healthy, adults need a good sleep of 7–8 h each night. However, studies found many people in modern world, for instance in the United States, sleep less than 7 h per night [7]. Researchers identified various factors that affected sleep health, including gender, marital status, education level, socioeconomic status, genetics, alcohol consumption, cigarette smoking, stress, and emotional problems [8].

Recent research also found sleep health to be affected by environmental chemicals, e.g. particulate matter, second-hand smoke, dioxins, and lead [9,10]. In addition, solvents used in agricultural operations are also known to be neurotoxic and could cause depressive symptoms [11]. A recent study in Almeria reported a higher risk of insomnia among farmers who did not wear gloves or masks when using pesticides [12]. Results from a well-designed follow up study among mother-adolescent pairs found sleep health of

* Corresponding author. Department of Internal Medicine, Faculty of Medicine Chiang Mai University, Chiang Mai, 50300, Thailand.
E-mail address: kajohnsak.noppakun@cmu.ac.th (K. Noppakun).

https://doi.org/10.1016/j.heliyon.2024.e41123
Received 24 December 2023; Received in revised form 4 December 2024; Accepted 10 December 2024
Available online 13 December 2024

adolescents could be linked to pesticide exposure during pregnancy [13]. In an Agriculture Health Study in the US, a study found pesticide exposure to associate with dream-enacting behaviors or parasomnia [14]. This finding was consistent with a previous US study which reported pesticides used at home could be associated with insufficient sleep and trouble sleeping among adults, especially males [15]. A study from Uganda reported acute pesticide exposure to increase risk of sleep problems, sleep inadequacy and snoring [16]. In China, a study found greenhouse farmers with high cumulative pesticide exposure to have a short sleep duration, poor sleep quality, and difficulty sleeping [17].

For individual pesticide, a previous study found the association between carbofuran and sleep apnea [18]. Another study reported 3-PBA, a pyrethroid insecticide, to associate with insufficient sleep and trouble sleeping [13]. A recent study also found fungicide mancozeb and herbicide glyphosate to increase risk of sleep problems [16]. Pesticides influence the acetylcholine, gamma-aminobutyric acid (GABA), and serotonin pathways, which are critical for sleep regulation [19]. Disruption of these pathways may result in sleep disturbances by impairing the normal sleep-wake cycle. Many pesticides demonstrate endocrine-disrupting characteristics, potentially influencing sleep patterns. Exposure to endocrine-disrupting chemicals (EDCs), including specific herbicides and fungicides, may modify hormone levels (e.g., melatonin, cortisol) that play a direct role in regulating circadian rhythms and sleep patterns [20]. Research indicates that pesticides may stimulate the generation of reactive oxygen species (ROS) and inflammatory cytokines, potentially affecting brain regions involved in sleep regulation, including the hypothalamus [21].

Further research is necessary to examine the impact of pesticides on sleep health, especially regarding chronic exposure. Identifying additional individual pesticides as potential causative agents is also a crucial aspect that requires investigation. Furthermore, there is a need for more in-depth exploration of gender differences in this context. Thailand, characterized by heavy pesticide use and minimal protective measures, presents unique exposure circumstances that offer an opportunity to study the effects of pesticides. The objectives of this study were to determine the association between pesticide exposure and medically diagnosed sleep disorders among farmers in Thailand. Using a comprehensive cross-sectional design, the study explores the potential impact of various individual pesticides on sleep disorders. The findings serve as a basis for comparisons and contribute to the existing literature.

2. Methods

2.1. Study setting

The study collected information from farmers living in three provinces in the north of Thailand, namely Phitsanulok, Nakhon-Sawan, and Chiang Mai. The provinces are among the largest in terms of the agricultural area, population, and pesticide use, and represent the farmers from the north. Thai agriculture which accounts for about thirty percent of the workforce, depends heavily on pesticides to control of weeds, insects, and fungi [22]. As our previous research finding, most Thai farmers have poor knowledge, attitudes, and practices regarding pesticide use and, thus, were at a high risk of exposure and the toxic effects of pesticides [23].

2.2. Study design and participants

This cross-sectional study collected information from 27,334 farmers aged 20 years or more, who had work experience for at least 5 years. Detailed sampling schemes were presented in our previous study [24]. Briefly, about thirty thousand participants from the three selected provinces, ten thousand per province, were randomly selected using multistage sampling. The first, three districts were randomly selected from each province, and then, in each district, at least three sub-districts were further selected. In each sub-district, with the support of local hospitals and village health volunteers (VHVs), the study recruited at least 30 % of all farmer families. In each household, only one participant was selected.

2.3. Questionnaire and data collection

For data collection, VHVs visited the selected household and invited them to participate in the study. A face-to-face interview using online questionnaires was conducted after the participant agreed to join the study and signed the consent inform. The questionnaire was originally developed under the Agricultural Health Study in the USA and used in our previous study [24]. In addition to demographic data, participants supplied details on their historical pesticide use, specifying both the frequency and duration of exposure. These two sets of data were utilized to compute cumulative exposure (by multiplying frequency by duration) and determine the quartile day of exposure. Pesticide exposure was categorized into two groups for each pesticide: “exposed” and “not exposed”. Exposure was assessed based on the participant’s reported history of using a particular pesticide. The survey covered information on five categories of pesticides and a total of 38 individual pesticides. Each category was analyzed as an independent dichotomous variable. These consisted of seven organochlorine pesticides, eight organophosphates, four carbamates, three other insecticides, seven herbicides, and nine fungicides. These pesticides were chosen based on findings from previous studies that indicated a connection to sleep health and their common usage in Thailand.

For the outcome variable, participants were asked a yes-or-no question about whether a medical doctor had diagnosed them with a sleep disorder. The cases were later confirmed by the ICD-10 record from a local hospital. In this study, sleep disorder (F51) refers to a group of diseases including insomnia (F510), hypersomnia (F511), disorders of the sleep-wake cycle (F512), sleepwalking (F513), night terrors/sleep terrors (F514), nightmares (F515), and other sleep disorders (F518, F519). A local hospital staff member carried out this action.

To control information bias from the interview and data collection process, the VHVs were trained on how to use questionnaires

and to collect information. The interview normally took place in a house of a farmer or a public place, e.g., local hospital or temple. The interview session normally lasts about 40 min. The data was collected between October 2020 and February 2021.

2.4. Statistical analysis

Demographic information was analyzed using descriptive statistics and the association between pesticide exposure and sleep disorder was determined using multivariable logistic regression analysis control for the potential confounding factors. Each pesticide was included into the model as a dichotomous variable. The confounding factors included in the model were gender (male, female), age (20–29, 30–39, 40–49, 50–59, 60–69, 70 or more), marital status (married, single, divorce/widows/separated), education (not attend school, primary school, secondary school, college degree or higher), income per month (THB) (<5000, 5001–10000, 10001–30000, >30000), cigarette smoking (non-smoker, ex-smoker, smoker), and alcohol consumption (non-drinker or abstainer, ex-drinker, regular drinker).

The gender-stratify analysis was performed to compare the association among male and female group. The study also tried to control potential bias from using other pesticides by running two correlation matrices, one between types of pesticides and the other between individual pesticides. Those pesticides with a correlation coefficient 0.30 or more were included in the model as an adjusted variable. P-values of less than 0.05 or 95 % confidence intervals did not include 1 was statistically significant. All data analysis was performed using IBM SPSS Statistics (version 26) and OpenEpi online version 3.5.1.

2.5. Ethical considerations

The study was approved by the Ethical Committee of Naresuan University (COA No. 657/2019). All the study participants gave informed consent to participate in the study before the interview, and they were informed that they had the right to stop the interview at any time.

3. Results

Among 27,334 participants included in the data analysis, the distribution was as follows: NakhonSawan had 10,646 participants

Table 1
Demographic characteristics of sleep disorder and no sleep disorder groups.

	No sleep disorders (n = 27,282)		Sleep disorders (n = 52)		P-value[a]
	(n)	(%)	(n)	(%)	
Gender					0.33
Male	12,798	46.9	28	53.8	
Female	14,484	53.1	24	46.2	
Marital status					0.64
Married	20,845	76.4	37	71.2	
Single	2329	8.5	8	11.5	
Divorce/widows/separated	4108	15.1	9	17.3	
Age groups					0.01[a]
20-29	739	2.7	2	3.8	
30-39	2311	8.5	1	1.9	
40-49	5113	18.7	6	11.5	
50-59	8738	32.0	11	21.2	
60-69	7333	26.9	21	40.4	
≥70	3048	11.2	11	21.2	
Education					0.06
Not attend school	1796	6.6	8	15.4	
Primary school	19,618	71.9	35	87.3	
High school	5431	19.9	9	17.3	
College degree or higher	437	1.6	0	0	
Income per month (THB)					0.83
<5000	10,613	38.9	21	40.4	
5001-10000	13,648	50.0	27	51.9	
10001-30000	2742	10.1	4	7.7	
>30000	279	1.0	0	0	
Cigarette smoking					0.03[a]
Non-smoker	22,293	81.7	38	73.1	
Ex-smoker	1460	5.4	7	13.5	
Current smoker	3529	12.9	7	13.5	
Alcohol consumption					0.58
Non-drinker	19,785	72.5	36	69.2	
Ex-drinker	2089	7.7	6	11.5	
Regular drinker	5408	19.8	10	19.2	

[a] Pearson Chi-Square test, significant ($p < 0.05$).

(39.0 %), Phitsanulok had 9649 participants (35.3 %), and Chiang Mai had 7039 participants (25.7 %). The proportion of females was slightly higher than of the male group (Table 1). Most participants were married, aged 40–60 years old, finished primary school, and had monthly income of less than ten thousand THB (280 USD). Only about 13 % of them were regular cigarette smokers and 20 % alcohol drinkers. The female proportions in Nakhon Sawan, Phitsanulok, and Chiang Mai were 53.6 %, 56.9 %, and 47.1 %, respectively ($p < 0.001$). The proportions of participants aged 40–60 years were 45.5 %, 19.2 %, and 17.0 %, respectively ($p < 0.001$).

There were only 52 participants (28 male, 24 female) (0.2 % of 27,334 sample) with a confirmed sleep disorder (Table 1). The prevalence of sleep disorders in Nakhon Sawan, Phitsanulok, and Chiang Mai was recorded at 0 %, 0.3 %, and 0.4 %, respectively ($p < 0.001$). The case and the control group are similar in all demographic variables, except age distribution. Of the cases 62 % were aged sixty years or more while only 38 % of the control was in that group. It was also noticed that there was a higher proportion of the cases with low education and monthly income, but the difference was not statistically significant. For smoking, 27 % of the cases and 18 % of the control reported having ever smoked a cigarette (current smoker or ex-smoker).

For pesticide types, the study found no association between the historical use of any pesticides and sleep disorders (Table 2). For insecticides, a significant association was observed only among those with Q3 exposure (odds ratio 2.91, 95 % CI 1.14–7.44). For fungicides, a higher risk was found among those who reported ever using fungicides (odds ratio 2.75, 95 % CI 1.53–4.95) and the group with Q3 exposure (odds ratio 4.18, 95 % CI 1.39–12.59). An association was also observed among those who used molluscicides (odds ratio 2.33, 95 % CI 1.32–4.12).

For individual pesticides, significant associations were observed in 19 out of 38 individual pesticides. There were twelve insecticides, including three organochlorine insecticides (chlorpyrifos, chlordane, dichlorodiphenyl trichloroethane [DDT]), five organophosphates (ethyl p-nitrophenyl phenylphosphorothioate [EPN], folidol, methamidophos, mevinphos, profenofos), three carbamates (carbaryl, carbofuran, methomyl), and imidacloprid (Table 3). For gender-stratify analysis, a higher odds ratio was observed among the female group (Table 3). For instance, the odds ratio between fungicide and sleep disorder was 5.93 (95 % CI 2.20–16.03) in females but only 1.54 (95 % CI 0.72–3.30) in the male group. For chlorpyrifos, odds ratio among females was 5.53 (95 % CI 2.44–12.53) as compared to 3.21 (95 % CI 1.49–6.92) among males. These findings were consistent across all pesticide types.

The study also found significant ORs in two herbicides (diuron and paraquat) and five fungicides (benomyl, Bordeaux mixture, carbendazim, copper sulphate, metalaxyl) (Table 4). The association for some chemicals, e.g., chlorpyrifos, DDT, endosulfan, carbosulfan were in a dose-response pattern.

Given the widespread use of pesticide combinations in agricultural activities, the correlation among pesticide uses was examined. The correlation between pesticide use is detailed in Tables S1 and S2, and these findings were utilized for adjusted analyses in Model 2, which were given in Tables 2 and 3 We also examined the potential effects of specific combined pesticides (Table S3) and the effects associated with varying numbers of pesticide combinations (Table S4).

4. Discussion

This study investigated the prevalence and association of pesticides with sleep disorders among 27,334 Thai farmers. This study reported a prevalence of sleep disorders of 0.2 %, contrasting sharply with previous studies that found prevalence rates ranging from 20 % to 60 %, depending on the region and specific subtypes of sleep disorders [12,16]. Previous reports were from Europe and Africa. To our knowledge, this study represents the first report from Southeast Asia. The notable discrepancies in prevalence among studies arise from variations in the methodologies used to diagnose sleep disorders. This study employed self-reported sleep disorders validated by the ICD-10, whereas another study utilized a direct questionnaire to identify sleep disorders. This study is susceptible to recall bias resulting from self-reported outcomes. The study comprised over 27,000 participants, whereas other studies involved less than 400 participants. Given the substantial number of participants in our study, employing a direct questionnaire to identify sleep disorders is impractical.

This study revealed a significant connection between historical pesticide use and sleep disorders. Remarkably, this association persisted even after adjusting for demographic variations and potential confounding from exposure to other pesticides. The identified pesticides contributing to this association span various types, including insecticides, fungicides, and herbicides. Notably, within the subgroup exposed to insecticides, 12 out of 22 exhibited a significant association with sleep disorders, as outlined in Table 3. These chemicals belong to various groups of chemicals, including organochlorine, organophosphate, carbamate, pyrethroid, and neonicotinoid groups. Cholinesterase insecticides (organochlorine and carbamate) can inhibit acetylcholinesterase (AchE) and cause dysfunction of neurological system. Previous studies also found a higher sleep problem among those who exposed to organophosphate ester [25], carbamate insecticide as a group, and carbofuran [18]. In laboratory study, carbamate insecticides can affect melatonin functions on regulation of circadian rhythms, metabolism, mood, and other physiological function [26], sleeping [27]. Organochlorine are neurological toxic compounds, and some are also endocrine disruptors [28]. Exposure to organochlorine has been linked to several neurological symptoms, e.g., headache, nauseas, depression, tremor [29], Parkinson disease [30] and mental disorder symptoms [31]. Pyrethroid insecticides act as thyroid disruptors and can impact sleep health [32]. For example, 3-phenoxybenzoic acid (3-PBA) was identified as correlating with insufficient sleep and sleep difficulties [13]. Imidacloprid, a neonicotinoid insecticide, shares similarities with organophosphate and carbamates in its potential to affect the nervous system and disrupt normal hormone synthesis [33].

This study found several fungicides to associate with sleep disorders, including benomyl, carbendazim, metalaxyl, Bordeaux mixture, and copper sulphate. This novel finding is substantiated with limited support from the existing literature. Benomyl and its metabolite carbendazim displayed a robust association with sleep disorders (Table 3). Notably, their combination exposure exhibited a synergistic effect, doubling the odds ratio as shown in Table S3. Both compounds have demonstrated testicular effects, and a separate study found a link between benomyl exposure and Parkinson disease [34]. Metalaxyl, a systemic fungicide that belong to the phenyl

Table 2
The association (OR) between types of pesticide and sleep disorders.

Pesticide use	No sleep disorders, n (%)			Sleep disorder, n (%)			OR (95 % CI)			
	Male (n = 12,798)	Female (n = 14.484)	Total (n = 27,282)	Male (n = 28)	Female (n = 24)	Total (n = 52)	**Model 1**[a]	**Model 2**[b]	**Male**	**Female**
Any pesticides	11,949 (93.4)	12,941 (89.3)	24,890 (91.2)	25 (89.3)	22 (91.7)	47 (90.4)	0.95 (0.37–2.40)	–	0.61 (0.18–2.05)	1.47 (0.34–6.34)
Insecticides	10,518 (82.2)	10,786 (74.5)	21,304 (78.1)	24 (85.7)	21 (87.5)	45 (86.5)	1.88 (0.84–4.20)	1.15 (0.43–3.07)	1.45 (0.50–4.24)	2.47 (0.73–8.35)
Herbicides	11,180 (87.4)	11,813 (81.6)	22,993 (84.3)	23 (82.1)	22 (91.7)	45 (86.5)	1.25 (0.56–2.79)	0.91 (0.37–2.21)	0.74 (0.28–1.97)	2.62 (0.61–11.20)
Fungicides	6200 (48.5)	5755 (39.7)	11,955 (43.8)	16 (57.1)	19 (79.2)	35 (67.3)	**2.75 (1.53–4.95)**	**2.41 (1.20–4.84)**	1.25 (0.52–3.11)	**6.05 (1.81–20.27)**
Rodenticides	2616 (20.4)	2456 (17.0)	5072 (18.6)	7 (25.0)	7 (29.2)	14 (26.9)	1.57 (0.84–2.91)	0.85 (0.42–1.73)	1.34 (0.57–3.19)	1.89 (0.78–4.62)
Molluscicides	3089 (24.1)	2979 (20.6)	6068 (22.2)	11 (39.3)	10 (41.7)	21 (40.4)	**2.33 (1.32–4.12)**	1.81 (0.93–3.55)	2.09 (0.83–5.29)	1.62 (0.61–4.29)

c Gender-stratify analysis, using data from Model 1.

[a] Multivariable logistic regression adjusted for demographic variables: gender (male, female), age (20–29, 30–39, 40–49, 50–59, 60–69, 70 or more), marital status (married, single, divorce/widows/separated), education (not attend school, primary school, secondary school, college degree or higher), income per month (THB) (<5000; 5001–10,000; 10,001–30,000; >30,000), cigarette smoking (non-smoker, ex-smoker, smoker), and alcohol consumption (non-drinker (or abstainer), ex-drinker, regular drinker).

[b] Adjusted for demographic variables and using other pesticides (See Table S2).

Table 3
The associations between individual pesticides and sleep disorders.

Pesticide exposure	No sleep disorders, n (%)			Sleep disorders, n (%)			OR (95 % CI)			
	Male (n = 12,798)	Female (n = 14.484)	Total (n = 27,282)	Male (n = 28)	Female (n = 24)	Total (n = 52)	Model 1[a]	Model 2[b]	Male[c]	Female[c]
Organochlorine insecticide (7)										
Aldrin	78 (0.6)	60 (0.41)	138 (0.6)	0	2 (8.3)	2 (3.8)	**8.28 (1.94–35.28)**	4.04 (0.68–23.85)	–	**21.16 (4.56–98.16)**
Chlorpyrifos	2697 (21.1)	2619 (18.1)	5316 (19.6)	12 (42.9)	13 (54.2)	25 (48.1)	**4.12 (2.36–7.17)**	NA[d]	**3.21 (1.49–6.92)**	**5.53 (2.44–12.53)**
Chlordane	190 (1.5)	176 (1.2)	366 (1.3)	1 (3.6)	5 (20.8)	6 (11.5)	**9.37 (3.95–22.26)**	NA	2.36 (0.32–17.65)	**20.58 (7.43–57.02)**
Dieldrin	124 (1.0)	114 (0.8)	238 (0.9)	0	3 (12.5)	3 (5.8)	**7.51 (2.29–24.63)**	4.17 (0.71–24.35)	–	**17.93 (5.08–63.26)**
Dichlorodiphenyl trichloroethane (DDT)	574 (4.5)	605 (4.2)	1179 (4.3)	4 (14.3)	6 (25.0)	10 (19.2)	**5.01 (2.48–10.11)**	NA	**3.51 (1.20–10.31)**	**7.12 (2.78–18.23)**
Endosulfan	1882 (14.7)	1785 (12.3)	3667 (13.4)	3 (10.7)	5 (20.8)	8 (15.4)	1.14 (0.53–2.47)	NA	0.73 (0.22–2.45)	1.85 (0.68–5.07)
Heptachlor	1413 (11.0)	1824 (12.6)	3237 (12.0)	1 (3.6)	3 (12.5)	4 (7.7)	0.62 (0.22–1.72)	NA	0.30 (0.04–2.22)	1.03 (0.31–3.48)
Organophosphate insecticides (8)										
Dicrotophos	270 (2.1)	263 (1.8)	533(1.9)	1 (3.6)	2 (8.3)	3(5.8)	3.13 (0.96–10.15)	NA	1.78 (0.24–13.27)	**4.65 (1.06–20.46)**
Dichlorvos	253 (2.0)	196 (1.4)	449 (1.6)	0	2 (8.3)	2 (3.8)	2.41 (0.56–10.27)	NA	–	**6.35 (1.35–29.93)**
Ethyl p-nitrophenyl phenylphosphorothioate (EPN)	357 (2.8)	331 (2.3)	688 (2.5)	2 (7.1)	3 (12.5)	5 (9.6)	**4.00 (1.57–10.16)**	NA	2.86 (0.67–12.28)	**5.87 (1.71–20.14)**
Folidol/parathion	1515 (11.8)	1556 (10.7)	3071 (11.3)	8 (28.6)	9 (37.5)	17 (32.7)	**3.75 (2.08–6.79)**	NA	**3.06 (1.32–7.07)**	**4.70 (2.02–10.89)**
Methamidophos	559 (4.4)	494 (3.4)	1053 (3.9)	2 (7.1)	3 (12.5)	5 (9.6)	**2.61 (1.03–6.65)**	NA	1.72 (0.40–7.36)	**4.06 (1.19–13.83)**
Mevinphos	166 (1.3)	152 (1.1)	318 (1.2)	0	3 (12.5)	3 (5.8)	**5.28 (1.62–17.21)**	**3.96 (1.01–15.61)**	–	**12.21 (3.48–42.79)**
Monocrotophos	277 (2.2)	301 (2.1)	578 (2.1)	0	3 (12.5)	3 (5.8)	3.02 (0.93–9.77)	1.58 (0.35–7.16)	–	**6.71 (1.96–23.06)**
Profenofos	269 (2.1)	286 (2.0)	555 (2.0)	1 (3.6)	3 (12.5)	4 (7.7)	**4.27 (1.52–12.00)**	3.21 (0.98–10.46)	1.85 (0.25–13.84)	**7.30 (2.11–25.30)**
Carbamate insecticides (4)										
Carbaryl	942 (7.4)	895 (6.2)	1837 (6.7)	4 (14.3)	7 (29.2)	11 (21.2)	**3.58 (1.82–7.03)**	NA	2.03 (0.70–5.93)	**6.07 (2.48–14.86)**
Carbofuran	1356 (10.6)	1375 (9.5)	2731 (10.0)	3 (10.7)	7 (29.2)	10 (19.2)	**2.02 (0.99–4.10)**	NA	0.98 (0.29–3.33)	**3.52 (1.41–8.75)**
Carbosulfan	1478 (11.6)	1438 (9.9)	2916 (10.7)	3 (10.7)	6 (25.0)	9 (17.3)	1.77 (0.86–3.66)	1.67 (0.77–3.63)	0.96 (0.29–3.19)	**3.02 (1.19–7.71)**
Methomyl	1102 (8.6)	1028 (7.1)	2130 (7.8)	8 (28.6)	7 (29.2)	15 (28.8)	**4.50 (2.43–8.32)**	NA	**4.15 (1.79–9.64)**	**4.51 (1.80–11.30)**
Pyrethroids insecticides										
Permethrin	1324 (10.4)	1436 (9.9)	2760 (10.1)	2 (7.1)	5 (20.8)	7 (13.5)	1.46 (0.66–3.26)	NA	0.74 (0.17–3.14)	2.43 (0.89–6.59)
Other insecticides										

(*continued on next page*)

Table 3 (*continued*)

Pesticide exposure	No sleep disorders, n (%)			Sleep disorders, n (%)			OR (95 % CI)			
	Male (n = 12,798)	Female (n = 14.484)	Total (n = 27,282)	Male (n = 28)	Female (n = 24)	Total (n = 52)	Model 1[a]	Model 2[b]	Male[c]	Female[c]
Abamectin	6675 (52.2)	6876 (47.5)	13,551 (49.7)	13 (46.4)	17 (70.8)	30 (57.7)	1.44 (0.82–2.50)	NA	0.84 (0.40–1.79)	**2.88 (1.18–7.00)**
Imidacloprid	573 (4.5)	479 (3.3)	1052 (3.9)	3 (10.7)	2 (8.3)	5 (9.6)	**2.66 (1.05–6.77)**	NA	2.78 (0.83–9.37)	2.44 (0.56–10.69)
Herbicide (8)										
2,4-dichlorophenoxyacetic acid (2,4-D)	5129 (41.1)	5582 (38.5)	10,711 (39.3)	14 (50.0)	11 (45.8)	25 (48.1)	1.47 (0.85–2.54)	NA	1.58 (0.75–3.36)	1.44 (0.64–3.26)
Alachlor	972 (7.6)	1011 (7.0)	1983 (7.3)	5 (17.9)	3 (12.5)	8 (15.4)	**2.39 (1.12–5.10)**	1.86 (0.73–4.76)	**2.81 (1.06–7.46)**	1.91 (0.57–6.46)
Acetochlor	319 (2.5)	293 (2.0)	612 (2.2)	2 (7.1)	2 (8.3)	4 (7.7)	**3.49 (1.25–9.78)**	2.07 (0.52–8.29)	2.93 (0.69–12.48)	3.76 (0.85–16.61)
Ametryn	375 (2.9)	356 (2.5)	731 (2.7)	1 (3.6)	2 (8.3)	3 (5.8)	2.21 (0.68–7.16)	NA	1.23 (0.17–9.14)	3.32 (0.75–14.65)
Butachlor	2340 (18.3)	2250 (15.5)	4590 (16.8)	6 (21.4)	7 (29.2)	13 (25.0)	1.77 (0.94–3.35)	NA	1.36 (0.54–3.39)	2.36 (0.96–5.81)
Diuron	257 (2.0)	236 (1.6)	493 (1.8)	5 (17.9)	2 (8.3)	7 (13.5)	**7.95 (3.53–17.91)**	NA	**10.30 (3.83–27.71)**	**4.48 (1.00–20.15)**
Glyphosate	9067 (70.1)	9869 (68.2)	18,936 (69.4)	25 (89.3)	20 (83.3)	45 (86.5)	**2.85 (1.28–6.35)**	2.07 (0.83–5.18)	**3.39 (1.02–11.29)**	2.49 (0.84–7.34)
Paraquat	6465 (50.5)	6991 (48.3)	13,456 (49.3)	17 (60.7)	19 (79.2)	36 (69.2)	**2.29 (1.27–4.15)**	NA	1.46 (0.68–3.14)	**4.27 (1.58–11.54)**
Fungicide (9)										
Benomyl	187 (1.5)	157 (1.1)	344 (1.3)	2 (7.1)	2 (8.3)	4 (7.7)	**6.18 (2.19–17.42)**	NA	**5.22 (1.21–22.56)**	**6.93 (1.56–30.85)**
Carbendazim	2344 (18.3)	2027 (14.0)	4371 (16.0)	10 (35.7)	11 (45.8)	21 (40.4)	**3.64 (2.08–6.38)**	NA	**2.57 (1.18–5.62)**	**5.51 (2.44–12.46)**
Bordeaux mixture	95 (0.7)	74 (0.5)	169 (0.6)	0	2 (8.3)	2 (3.8)	**6.33 (1.51–28.51)**	NA	–	**17.41 (3.78–80.24)**
Copper sulphate	714 (5.6)	706 (4.9)	1420 (5.2)	5 (17.9)	5 (20.8)	10 (19.2)	**4.25 (2.10–8.60)**	**3.57 (1.68–7.60)**	**4.13 (1.53–11.16)**	**3.22 (1.02–10.14)**
Mancozeb	1005 (7.9)	925 (6.4)	1930 (7.1)	1 (3.6)	2 (8.3)	3 (5.8)	0.82 (0.25–2.65)	NA	0.45 (0.06–3.34)	1.25 (0.29–5.43)
Maneb	549 (4.3)	576 (4.0)	1125 (4.1)	0	3 (12.5)	3 (5.8)	1.44 (0.45–4.67)	NA	–	3.18 (0.92–10.96)
Metalaxyl	954 (7.5)	974 (6.7)	1928 (7.1)	6 (21.4)	6 (25.0)	12 (23.1)	**3.99 (2.07–7.67)**	**4.77 (2.41–9.42)**	**4.41 (1.72–11.29)**	**4.96 (1.82–13.57)**
Propineb	575 (4.5)	552 (3.8)	1127 (4.1)	0	2 (8.3)	2 (3.8)	1.00 (0.24–4.12)	NA	–	2.36 (0.55–10.19)
Thiophanate	246 (1.9)	227 (1.6)	473 (1.7)	0	2 (8.3)	2 (3.8)	2.46 (0.59–10.21)	NA	–	**5.47 (1.24–24.15)**

[a] Unconditional multivariable logistic regression adjusted for demographic variables: gender (male, female), age (20–29, 30–39, 40–49, 50–59, 60–69, 70 or more), marital status (married, single, divorce/widows/separated), education (not attend school, primary school, secondary school, college degree or higher), income per month (THB) (<5000; 5001–10,000; 10,001–30,000; >30,000), cigarette smoking (never smoked, ex-smoker, regular smoker), and alcohol consumption (never drink, ex-drinker, regular drinker).

[b] Adjusted for demographic variables and use of other pesticides (See Table S2).

[c] Gender-stratify analysis, using data from Model 1.

[d] NA = not applicable.

Table 4
Dose-response relationship of some pesticides and sleep disorders.

Pesticide exposure	No sleep disorders	Sleep disorders	OR (95 % CI)[a]
Fungicides			
Q4 (442.6–9030.0 days)	2514 (9.2)	12 (23.1)	2.80 (0.89–8.83)
Q3 (116.1–442.5 days)	2731 (10.0)	16 (30.8)	**4.18 (1.39–12.59)**
Q2 (50.8–116.0 days)	3539 (13.0)	3 (5.8)	0.63 (0.14–2.84)
Q1 (1.2–50.7 days)	3171 (11.6)	4 (7.7)	1.00
P for trend			0.70
Chlorpyrifos			
Q4 (245.1–9030.0 days)	1050 (3.8)	15 (28.8)	**5.19 (1.46–18.46)**
Q3 (105.1–245.0 days)	1377 (5.0)	4 (7.7)	1.49 (0.33–6.76)
Q2 (37.6–105.0 days)	1417 (5.2)	3 (5.8)	1.01 (0.20–5.05)
Q1 (1.2–37.5 days)	1472 (5.48)	3 (5.8)	1.00
P for trend			**<0.01**
Abamectin			
Q4 (245.1–9030.0 days)	3342 (12.2)	15 (28.8)	**11.55 (1.51–88.26)**
Q3 (105.1–245.0 days)	3429 (12.6)	3 (5.8)	2.97 (0.31–28.61)
Q2 (37.6–105.0 days)	3384 (12.4)	11 (21.2)	**10.74 (1.38–83.41)**
Q1 (1.2–37.5 days)	3397 (12.5)	1 (1.9)	1.00
P for trend			0.38

[a] OR adjusted for gender (male, female), age (20–29, 30–39, 40–49, 50–59, 60–69, 70 or more), marital status (married, single, divorce/widows/separated), education (not attend school, primary school, secondary school, college degree or higher), income per month (THB) ((<5000; 5001–10,000; 10,001–30,000; >30,000), cigarette smoking (never smoked, ex-smoker, regular smoker), and alcohol consumption (never drink, ex-drinker, regular drinker), and use of other pesticides.

amide, is a well-known hazard for the liver, kidneys, and lungs. An animal study also showed that the herbicide affects brain and reduces acetylcholinesterase enzyme, just like organophosphate and carbamate pesticides [35]. However, epidemiology studies from the US, matalaxyl did not have a positive association with sleep apnea [18]. Copper sulphate and Bordeaux mixture are natural minerals deemed harmless at low doses, and there is no supporting literature indicating any impact on sleep effects [36]. Mancozeb is identified as an endocrine disruptor, and prior research reported a positive effect on sleep problems [16]. However, in this study, a significant association was not found in exposure events with either mancozeb or maneb (Table 3) or a combination of the two (Table S3). This discrepancy might be explained by the small number of cases, as the results of this study were based on only three cases of sleep disorders in the analysis. Future investigations on this issue are certainly warranted.

The dose-response relationship between pesticide exposure, particularly fungicides, and sleep disorders may not be apparent, as indicated by a non-significant odds ratio for the highest exposure category of fungicides. This probably indicates the impact of various factors. The limited number of participants in the highest category may diminish statistical power, leading to broader confidence intervals. Additionally, the adverse effects of pesticides may reach a plateau at higher exposure levels due to survivor bias, where individuals with the highest exposure may have died and thus are not included in the study, or due to behavioral adaptations, such as health-seeking behaviors or the use of protective equipment. The relationship between pesticide exposure and sleep disorders is thought to be either linear or curvilinear in nature. The scientific rationale does not support a cubic relationship, as increased exposure is anticipated to result in greater or plateau effects on sleep disorders. Consequently, we decided that advanced analyses, such as restricted cubic spline regression, would not provide a better explanation of the dose-response relationship between pesticides and sleep disorders.

The study also noted an association between sleep disorders and exposure to certain individual herbicides, particularly paraquat and diuron. This finding is relatively novel, lacking comparisons with extensive epidemiological studies. However, evidence from laboratory studies and related research supports this discovery. Specifically, this study found that exposure to either paraquat or glyphosate significantly increased the risk of sleep disorders (Table 3), and a combination exposure almost doubled the risk (Table S3). A previous study [16] identified a significant association between last-week exposure to glyphosate and sleep problems. In animal studies, researchers found that paraquat increases oxidative stress, a condition that can decrease the length of the sleep-wake cycle and disrupt sleep consolidation [37]. In addition, a study also identified paraquat exposure as increasing the risk of Parkinson disease, indicating effects on the brain and nervous system [38]. For diuron, a urea derivative herbicide, an animal test found it behave like EDCs and can reduce AChE [39]. 2,4-dichlorophenoxyacetic acid (2,4-D) is also EDCs, and the study found an elevated risk but not statistically significant. Alachlor and butachlor are of low toxicity but in a poisoning case report found that the ingestion of the herbicides increases the depression of the central nervous system [40]. Scientists believe that chloroacetanilides, a group of herbicides which commonly includes alachlor, butachlor, metolachlor, and pretilachlor, have acute effects like organophosphate toxicity [41]. Ametryn, of the triazine family, is EDCs. Although, toxicological data is scarce, animal study found it has estrogenic and anti-androgenic properties which can affect the testes and reproduction [42]. More research is needed to verify the association between herbicides and sleep disorders and to elucidate the mechanisms through which they cause these effects.

The study also aimed to explore gender effects on sleep disorders, given the inconsistency in existing literature. A study from Uganda found a higher risk of sleep disorders among female [16]. This finding was supported by a similar investigation on sleep health among greenhouse farmers in China [17]. However, at least two studies from the US reported a higher risk of sleep problems among males [13,18,25]. A recent study on the effect of organophosphate esters metabolites also found a higher risk for sleep problems among

males [25]. In this study, a higher ORs were observed in female groups for almost all pesticides, except copper sulphate, glyphosate, diuron, imidacloprid (Table 3). For instance, the odds ratio of carbofuran was 2.02 (95 % CI 0.99–4.10) in the combined group, 0.98 (95 % CI 0.29–3.33) in males, and 3.52 (95 % CI 1.41–8.75) in females. This discrepancy might be explained by the fact that sleep health depends on various factors, and through different mechanisms, certain types of pesticides might selectively have more effects on specific groups of people. For pesticides affecting hormones, the menstrual cycle, stress, and depression, women may be at a greater risk compared to men [43].

The differences in patient characteristics, specifically age and gender distributions, as well as the prevalence of sleep disorders across the three provinces–Phitsanulok, NakhonSawan, and Chiang Mai–highlight the complex relationship between pesticide exposure and sleep health. Sleep disorder prevalence varies by province, possibly due to variances in age and gender distribution. The prevalence of sleep disorders varied considerably throughout the three provinces. This may indicate variations in the intensity of pesticide exposure, the types of pesticides employed, agricultural practices, and societal conditions. The availability of healthcare resources and diagnostic techniques may vary by province, influencing the likelihood of discovering sleep problems. Chiang Mai exhibits greater urbanization, potentially leading to better diagnostic facilities and more health awareness compared to other provinces. Analyzing regional variations provides useful insights for developing targeted public health interventions and policies, such as pesticide management guidelines and preventive measures tailored to specific locations.

This study has several limitations. Firstly, we did not collect data on body mass index and other potential risk factors related to sleep disorders such as ambient pollution, cooking fumes, chronic diseases, stress, genetic factors, and other psychological issues [10]. These factors could impact sleep health and introduce bias to the results. Secondly, the study may be susceptible to information bias, as data on pesticide exposure were solely collected through questionnaire methods without laboratory measurements. However, it is important to note that this bias would likely impact both the study and control groups and may only attenuate the observed association. The questionnaire method has been widely used in epidemiological studies of pesticide exposure, especially for chronic exposure [24]. To address potential recall bias during data collection on past pesticide use, particularly when farmers may not remember or know the names of the pesticides they used, a precautionary measure was implemented. To mitigate this issue, all names of pesticides, including chemical names, common names, or commercial/trade names, were explicitly read to participants during the interviews. Thirdly, a key drawback of this study is its cross-sectional design, which limits the capacity to infer causality. Our findings indicate associations between pesticide exposure and sleep disorders; however, we are unable to ascertain the temporal sequence of exposure relative to the onset of sleep disorders. Longitudinal studies are necessary to confirm causality and further explore these associations over time. Fourthly, stresses could serve as both a mediator and a confounder, potentially intensifying the effects of pesticide exposure on sleep disorders. This study did not include data on specific psychological stresses or mental health conditions, which are recognized to affect sleep quality and may confound the relationship between pesticide exposure and sleep disorders. Lastly, it is important to interpret the results with caution, considering the potential for false positives due to multiple comparisons.

A notable strength of this study lies in its collection of exposure information for various pesticides, coupled with the use of medically diagnosed diseases confirmed by ICD-10, which is considered more accurate than relying on self-reported outcomes. The results provide valuable insights into the effects on sleep health in a developing country like Thailand, where pesticides are extensively used with minimal exposure prevention. This study serves as a robust comparison group for results from studies conducted in other parts of the world. The impact of pesticides on sleep health deserves increased attention, considering that sleep deficits might be an underlying cause of various health problems and compromise the overall well-being of individuals. This significance is heightened by the widespread use of pesticides as chemicals.

In conclusion, the study contributes support to existing literature regarding the potential effects of pesticides on sleep disorders. It confirms the effects of insecticides and suggests potential effects of fungicides and herbicides. Furthermore, the study adds valuable information on gender-related effects. Future research endeavors should aim to confirm these results and identify additional individual pesticides that may contribute to sleep disorders—an underrecognized global public health challenge in the modern world.

CRediT authorship contribution statement

Chudchawal Juntarawijit: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Uraiwan Chaichanawirote:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Nootchayong Yaowapanon:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Kajohnsak Noppakun:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethical declarations

This study was reviewed and approved by the Ethics Board of Naresuan University, with the approval number: COA No. 657/2019, dated November 29, 2019. Written informed consent was obtained from each participant prior to the interview process.

Data availability statement

This study does not cover data posting in public databases. Data are available upon reasonable request up for up to 24 months after study publication to the corresponding author, Kajohnsak Noppakun (kajohnsak.noppakun@cmu.ac.th), subject upon approval from

the Ethics Board of Naresuan University.

Funding

This work was supported by a grant from Thailand Science Research and Innovation (grant no. R2563B009).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We express our gratitude to the study participants for providing valuable information and extend our appreciation to the village health volunteers and local hospital staff for their dedicated efforts in data collection and support. Special thanks to Mr. Kevin Mark Roebl of Naresuan University Writing Clinic for English editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e41123.

References

[1] C. Hublin, M. Partinen, M. Koskenvuo, J. Kaprio, Sleep and mortality: a population-based 22-year follow-up study, Sleep 30 (2007) 1245–1253.
[2] M. Grandner, J.M. Mullington, S.D. Hashmi, N.S. Redeker, N.F. Watson, T.I. Morgenthaler, Sleep duration and hypertension: analysis of > 700,000 adults by age and sex, J. Clin. Sleep Med. 14 (2018) 1031–1039.
[3] S. Reutrakul, E. Van Cauter, Sleep influences on obesity, insulin resistance, and risk of type 2 diabetes, Metabolism 84 (2018) 56–66.
[4] D.J. Gottlieb, V.K. Somers, N.M. Punjabi, J.W. Winkelman, Restless legs syndrome and cardiovascular disease: a research roadmap, Sleep Med. 31 (2017) 10–17.
[5] L.M. Lyall, C.A. Wyse, N. Graham, A. Ferguson, D.M. Lyall, B. Cullen, C.A. Celis Morales, S.M. Biello, D. Mackay, J. Ward, R.J. Strawbridge, J.M.R. Gill, M.E. S. Bailey, J.P. Pell, D.J. Smith, Association of disrupted circadian rhythmicity with mood disorders, subjective wellbeing, and cognitive function: a cross-sectional study of 91 105 participants from the UK Biobank, Lancet Psychiatr. 5 (2018) 507–514.
[6] J.A. Pillai, J.B. Leverenz, Sleep and neurodegeneration: a critical appraisal, Chest 151 (2017) 1375–1386.
[7] P. Consensus Conference, N.F. Watson, M.S. Badr, G. Belenky, D.L. Bliwise, O.M. Buxton, D. Buysse, D.F. Dinges, J. Gangwisch, M.A. Grandner, C. Kushida, R. K. Malhotra, J.L. Martin, S.R. Patel, S.F. Quan, E. Tasali, O. Non-Participating, M. Twery, J.B. Croft, E. Maher, S. American Academy of Sleep Medicine, J. A. Barrett, S.M. Thomas, J.L. Heald, Recommended amount of sleep for a healthy adult: a joint consensus statement of the American academy of sleep medicine and sleep research society, J. Clin. Sleep Med. 11 (2015) 591–592.
[8] V.K. Chattu, S.K. Chattu, D. Burman, D.W. Spence, S.R. Pandi-Perumal, The interlinked rising epidemic of insufficient sleep and diabetes mellitus, Healthcare (Basel) 7 (2019).
[9] J. Liu, T. Wu, Q. Liu, S. Wu, J.C. Chen, Air pollution exposure and adverse sleep health across the life course: a systematic review, Environ. Pollut. 262 (2020) 114263.
[10] R. Pan, Y. Zhang, Z. Xu, W. Yi, F. Zhao, J. Song, Q. Sun, P. Du, J. Fang, J. Cheng, Y. Liu, C. Chen, Y. Lu, T. Li, H. Su, X. Shi, Exposure to fine particulate matter constituents and cognitive function performance, potential mediation by sleep quality: a multicenter study among Chinese adults aged 40-89 years, Environ. Int. 170 (2022) 107566.
[11] M. Siegel, S.E. Starks, W.T. Sanderson, F. Kamel, J.A. Hoppin, F. Gerr, Organic solvent exposure and depressive symptoms among licensed pesticide applicators in the Agricultural Health Study, Int. Arch. Occup. Environ. Health 90 (2017) 849–857.
[12] R. Zheng, J. Garcia-Gonzalez, R. Romero-Del Rey, A. Lopez-Villen, R. Garcia-Alvarez, R. Fadul-Calderon, M. Requena-Mullor, R. Alarcon-Rodriguez, Occupational exposure to pesticides as a risk factor for sleep disorders, Int. J. Environ. Res. Publ. Health 20 (2023).
[13] A.N. Zamora, D.J. Watkins, K.E. Peterson, M.M. Tellez-Rojo, H. Hu, J.D. Meeker, A. Cantoral, A. Mercado-Garcia, E.C. Jansen, Prenatal maternal pesticide exposure in relation to sleep health of offspring during adolescence, Environ. Res. 204 (2022) 111977.
[14] Y. Yuan, S. Shrestha, Z. Luo, C. Li, B.L. Plassman, C.G. Parks, J.N. Hofmann, L.E. Beane Freeman, D.P. Sandler, H. Chen, High pesticide exposure events and dream-enacting behaviors among US farmers, Mov. Disord. 37 (2022) 962–971.
[15] A.N. Zamora, D.J. Watkins, K.E. Peterson, E.C. Jansen, Association between pesticide exposure and sleep health among a representative sample of US adults: evidence from NHANES 2009-2014, BMC Publ. Health 21 (2021) 2199.
[16] S. Fuhrimann, I. van den Brenk, A. Atuhaire, R. Mubeezi, P. Staudacher, A. Huss, H. Kromhout, Recent pesticide exposure affects sleep: a cross-sectional study among smallholder farmers in Uganda, Environ. Int. 158 (2022) 106878.
[17] J. Li, Y. Hao, D. Tian, S. He, X. Sun, H. Yang, Relationship between cumulative exposure to pesticides and sleep disorders among greenhouse vegetable farmers, BMC Publ. Health 19 (2019) 373.
[18] B.O. Baumert, M.U. Carnes, J.A. Hoppin, C.L. Jackson, D.P. Sandler, L.B. Freeman, P.K. Henneberger, D.M. Umbach, S. Shrestha, S. Long, S.J. London, Sleep apnea and pesticide exposure in a study of US farmers, Sleep Health 4 (2018) 20–26.
[19] D.M. Soderlund, J.M. Clark, L.P. Sheets, L.S. Mullin, V.J. Piccirillo, D. Sargent, J.T. Stevens, M.L. Weiner, Mechanisms of pyrethroid neurotoxicity: implications for cumulative risk assessment, Toxicology 171 (2002) 3–59.
[20] W. Mnif, A.I. Hassine, A. Bouaziz, A. Bartegi, O. Thomas, B. Roig, Effect of endocrine disruptor pesticides: a review, Int. J. Environ. Res. Publ. Health 8 (2011) 2265–2303.
[21] B.D. Banerjee, V. Seth, A. Bhattacharya, S.T. Pasha, A.K. Chakraborty, Biochemical effects of some pesticides on lipid peroxidation and free-radical scavengers, Toxicol. Lett. 107 (1999) 33–47.
[22] W. Laohaudomchok, N. Nankongnab, S. Siriruttanapruk, P. Klaimala, W. Lianchamroon, P. Ousap, M. Jatiket, P. Kajitvichyanukul, N. Kitana, W. Siriwong, T. Hemachudhah, J. Satayavivad, M. Robson, L. Jaacks, D.B. Barr, P. Kongtip, S. Woskie, Pesticide use in Thailand: current situation, health risks, and gaps in research and policy, Hum. Ecol. Risk Assess. 27 (2021) 1147–1169.

[23] T. Kangkhetkron, C. Juntarawijit, Factors influencing practice of pesticide use and acute health symptoms among farmers in Nakhon sawan, Thailand, Int. J. Environ. Res. Publ. Health 18 (2021).
[24] K. Noppakun, C. Juntarawijit, Association between pesticide exposure and obesity: a cross-sectional study of 20,295 farmers in Thailand, F1000Res 10 (2021) 445.
[25] X. Kang, J. Li, J. Luo, D. Zhang, Associations between organophosphate esters metabolites and sleep disorder and trouble sleeping in adults: a machine-learning approach, Environ. Sci. Pollut. Res. Int. 29 (2022) 67287–67300.
[26] M. Popovska-Gorevski, M.L. Dubocovich, R.V. Rajnarayanan, Carbamate insecticides target human melatonin receptors, Chem. Res. Toxicol. 30 (2017) 574–582.
[27] G.C. Glatfelter, A.J. Jones, R.V. Rajnarayanan, M.L. Dubocovich, Pharmacological actions of carbamate insecticides at mammalian melatonin receptors, J. Pharmacol. Exp. Therapeut. 376 (2021) 306–321.
[28] E.N. Tzanetou, H. Karasali, A comprehensive review of organochlorine pesticide monitoring in agricultural soils: the silent threat of a conventional agricultural past, Agriculture (2022).
[29] D.A. Wallace, J.P. Gallagher, S.R. Peterson, S. Ndiaye-Gueye, K. Fox, S. Redline, D.A. Johnson, Is exposure to chemical pollutants associated with sleep outcomes? A systematic review, Sleep Med. Rev. 70 (2023) 101805.
[30] A. Elbaz, J. Clavel, P.J. Rathouz, F. Moisan, J.P. Galanaud, B. Delemotte, A. Alperovitch, C. Tzourio, Professional exposure to pesticides and Parkinson disease, Ann. Neurol. 66 (2009) 494–504.
[31] P. Ong-Artborirak, W. Boonchieng, Y. Juntarawijit, C. Juntarawijit, Potential effects on mental health status associated with occupational exposure to pesticides among Thai farmers, Int. J. Environ. Res. Publ. Health 19 (2022).
[32] M. Leemans, S. Couderq, B. Demeneix, J.B. Fini, Pesticides with potential thyroid hormone-disrupting effects: a review of recent data, Front. Endocrinol. 10 (2019) 743.
[33] L.J. Ramirez-Cando, M.S. Guzman-Vallejos, L.G. Aguayo, F.D. Vera-Erazo, S.J. Ballaz, Neurocytotoxicity of imidacloprid- and acetamiprid-based comercial insecticides over the differentiation of SH-SY5Y neuroblastoma cells, Heliyon 9 (2023) e15840.
[34] M. Kara, E. Oztas, R. Ramazanogullari, D. Kouretas, C. Nepka, A.M. Tsatsakis, A.S. Veskoukis, Benomyl, a benzimidazole fungicide, induces oxidative stress and apoptosis in neural cells, Toxicol Rep 7 (2020) 501–509.
[35] S.A. Mohamed, H.M. Ahmed, S.D. Aly, A.I. Ahmed, Pathological and Biochemical Assessment of the Fungicide (Metalaxyl) on Rats, Egypt, vol. 24, J. Comp. Path & Clinic Path, 2011, pp. 136–154.
[36] M. Tavares-Dias, Toxic, physiological, histomorphological, growth performance and antiparasitic effects of copper sulphate in fish aquaculture, Aquaculture 535 (2021) 736350.
[37] K. Koh, J.M. Evans, J.C. Hendricks, A. Sehgal, A Drosophila model for age-associated changes in sleep:wake cycles, Proc. Natl. Acad. Sci. U. S. A. 103 (2006) 13843–13847.
[38] C. Vaccari, R. El Dib, J.L.V. de Camargo, Paraquat and Parkinson's disease: a systematic review protocol according to the OHAT approach for hazard identification, Syst. Rev. 6 (2017) 98.
[39] Y. El-Nahhal, R. Lubbad, M.R. Al-Agha, Toxicity evaluation of chlorpyrifos and diuron below maximum residue limits in rabbits, Toxicol. Environ. Health Sci. 12 (2020) 177–190.
[40] Y.C. Lo, C.C. Yang, J.F. Deng, Acute alachlor and butachlor herbicide poisoning, Clin. Toxicol. 46 (2008) 716–721.
[41] O. Shilpakar, B. Karki, B. Rajbhandari, Pretilachlor poisoning: a rare case of a herbicide masquerading as organophosphate toxicity, Clin Case Rep 8 (2020) 3507–3509.
[42] T.A. Dantas, G. Cancian, D.N. Neodini, D.R. Mano, C. Capucho, F.S. Predes, R.B. Pulz, A.A. Pigoso, H. Dolder, G.D. Severi-Aguiar, Leydig cell number and sperm production decrease induced by chronic ametryn exposure: a negative impact on animal reproductive health, Environ. Sci. Pollut. Res. Int. 22 (2015) 8526–8535.
[43] S. Nowakowski, J. Meers, E. Heimbach, Sleep and women's health, Sleep Med Res 4 (2013) 1–22.