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Review Article

# Pesticide Use in Cucumber Cultivation in Iran: A Systematic Review of Environmental and Health Impacts

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## Abstract

**Background:** Rapid population growth is putting pressure on agriculture to meet food demands with limited land and water. This has led to increased crop production and greater use of agrochemicals, especially pesticides. However, their impact on biodiversity, ecosystems, and human health—particularly in communities near agricultural areas—is a growing concern.

**Methods:** This systematic review followed three main steps: literature search, study selection, and data extraction. The searches were conducted in PubMed and Scopus using core keywords and synonyms. Relevant papers were screened by title, abstract, and full text. Also, VOSviewer software was used to visualize and assess bibliographic data.

**Results:** Pesticides have both acute (e.g., nausea, headaches, skin and eye irritation) and chronic effects (e.g., respiratory issues, memory disorders, depression, cancer, and infertility). Residues in crops, groundwater, and surface water pose risks to humans and ecosystems. Improper pesticide management, failure to follow pre-harvest interval (PHI), and inadequate washing or peeling can result in residues exceeding maximum residue limits (MRLs), threatening food safety. Proposed strategies to mitigate these risks include reducing pesticide use, improving spraying practices, training farmers, adopting sustainable methods like integrated pest management, and leveraging new technologies. Simple practices like washing, peeling, and low-temperature storage can also reduce residues.

**Conclusion:** Pesticide use should follow recommended guidelines. While transitioning to natural farming can reduce environmental and health impacts, social and cultural barriers limit its adoption in developing countries. Practical, context-specific solutions are urgently needed to reduce pesticide residues and ensure food safety.

**Keywords:** Behavioral intention, Sprayers, Pesticide residue, Food safety, Reducing residues, Pesticide handling, Cucumber

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## Introduction

Cucumber is one of the most popular vegetables consumed raw. In 2021, approximately 2.119 million tons were produced worldwide, marking an increase compared to 2020.[1,2] According to the Food and Agriculture Organization (FAO), Iran is the fourth-largest cucumber producer in the world, after China, Turkey, and Russia.[3] Cucumbers are nutritious and contain protein, calcium, phosphorus, iron, potassium, carotene, niacin, and vitamins B2, C, and E. They are beneficial for overall health.[4] Various pests and pathogens attack this plant, causing quantitative and qualitative damage.[5]

Modern agriculture has introduced innovative methods such as synthetic organic pesticides, which often contain organochlorine and organophosphorus compounds to enhance crop production.[6] Today, pesticides are an integral part of agricultural practices—they increase productivity, address nutritional challenges, and improve product quality. Also, they help reduce labor requirements in farming worldwide.[7,8] Without the use of pesticides, an estimated 78% of fruits, 54% of vegetables, and 32% of cereals would be lost to pests and diseases.[9] However, pesticide use also raises concerns about the increased demand for other agricultural inputs, including land, water, seeds, fuel, labor, and pest control products.[10,11] Pests and plant diseases not only threaten global food resources and economies but also directly affect the livelihoods of farmers, especially those who grow crops for local consumption or market sale.[12,13] While agriculture plays a critical role in ensuring global food security, it is also a significant contributor to environmental degradation and climate change.[14] Key agricultural pollutants include nitrogen-based fertilizers and pesticides, which are extensively used to maximize crop yields.[15,16] Alarmingly, only 1% to 4% of applied agrochemicals actually reach their intended targets, while the rest contribute to environmental issues such as soil compaction.[17,18] Between 2011 and 2020, pesticide use on fruits increased by 25 to 111%.[19] Farmers routinely apply a range of pesticides each year, which can account for up to 20% of total agricultural input costs.[20] Although banning pesticides would negatively impact food production, there is an urgent need to reduce and remove pesticide residues from food to ensure consumer safety.[21]

On the other hand, concerns about pesticide residues have prompted the World Health Organization (WHO) to propose a tolerable threshold level.[22,23] When pesticides are used according to the recommendations on product labels, they must not exceed the maximum residue limits (MRLs). Otherwise poisoning is unavoidable.[24] However, using pesticides over MRLs leads to plant burning and excessive concentrations of residues in agricultural products, air, water, and soil. So, potential safety issues cannot be ignored.[25,26] Due to the adverse effects, MRLs have been established to prevent health risks; however, the pre-harvest interval (PHI) is often not observed.[27] The duration of PHI varies for different products, pesticides, spraying conditions, and environments.[28] Washing is the first step in domestic and industrial-scale food processing to remove substances such as dust.[29] It has been reported that wash sanitizers are regulated by the US Food and Drug Administration (FDA) as food additives. Some organic acids and sodium carbonate, are generally recognized as safe (GRAS).[30] Several studies have been carried out to reduce pesticide residues in farm products (Table 1). In this context, researchers have described the effectiveness of home application as a helpful method to reduce residues.[31,32]

**Table 1.** Pests investigated at the time of cucumber crop planting in Iran

| Sampled | Genus Name | Location | Ref. |
|---|---|---|---|
| Greenhouse conditions | *Liriomyza* spp. | Kerman, Iran | 33 |
| Greenhouse conditions | *Liriomyza sativae* | Tabriz, Iran | 34 |
| Greenhouse conditions | *Liriomyza* | Kerman, Iran | 35 |
| Greenhouse condition | *Aphis gossypii* Glover | Tehran, Iran | 36 |
| Greenhouse condition | *Aphis gossypii* Glover | Lorestan, Iran | 37 |
| Greenhouse condition | *Aphis gossypii* Glover | Ardabil, Iran | 38 |
| Cucumber from field | *Bemisia tabaci* Gennadius | Ahvaz, Iran | 39 |
| Cucumber from field | Cucumber mosaic virus (CMV), Watermelon mosaic virus-2 (WMV-2) and Zucchini yellow mosaic virus (ZYMV) | Lorestan, Iran | 40 |

Pesticides are widely present in the environment, and human exposure to these toxic contaminants has increased significantly. As a result, monitoring and evaluating agricultural products—including cucumbers—during pre-harvest and packaging periods is essential to identify contamination sources and implement corrective measures. Several studies have reported that pesticide levels in cucumbers often exceed MRLs in many regions of Iran, including Mazandaran, Tehran, Tabriz, Hamedan, Kohgiluyeh and Boyer-Ahmad, Khuzestan, Isfahan, and Kerman. These findings are valuable for health professionals and provincial policymakers in developing targeted preventive strategies. They also help inform farmers and consumers about pesticide concentrations in cucumbers, encouraging the adoption of safer agricultural and consumption practices. Furthermore, health authorities should recognize the need for effective intervention programs to reduce pesticide exposure in cucumbers. This review summarizes the findings of studies on pesticide use in cucumber cultivation, with a particular focus on health and environmental impacts in Iran.

## Materials and Methods

This study focuses on pesticide use in Iran, with additional references from international research to provide broader context and highlight the global importance of the issue. The articles were identified through searches in PubMed, Google Scholar, and ScienceDirect using the keywords "pesticide residues," "maximum residue limit," and "cucumber." After identifying relevant studies, titles and abstracts were screened, followed by full-text reviews. Studies that assessed pesticide residues in cucumber fruit and examined the effects of pesticides on non-target organisms were included.

To analyze and visualize the bibliometric network, VOSviewer software was used (Figures 1 and 2). It helped identify major research themes and citation patterns related to pesticide use and its consequences. Inclusion criteria were based on the relevance of articles to the health and environmental impacts of pesticide exposure, particularly concerning non-target organisms—an area of longstanding global concern.

In total, 222 articles were selected, managed using EndNote software, and cited accordingly. The overarching objective of this study is to investigate the effects of pesticides on agricultural production and to address three specific aims:

1. To identify strategies that minimize the residual concentrations of pesticides in cucumber crops.
2. To evaluate strategies for the prudent use of pesticides.
3. To increase public awareness of the impacts of pesticides on neighboring residential areas.

The following criteria were considered for the inclusion and exclusion of studies:

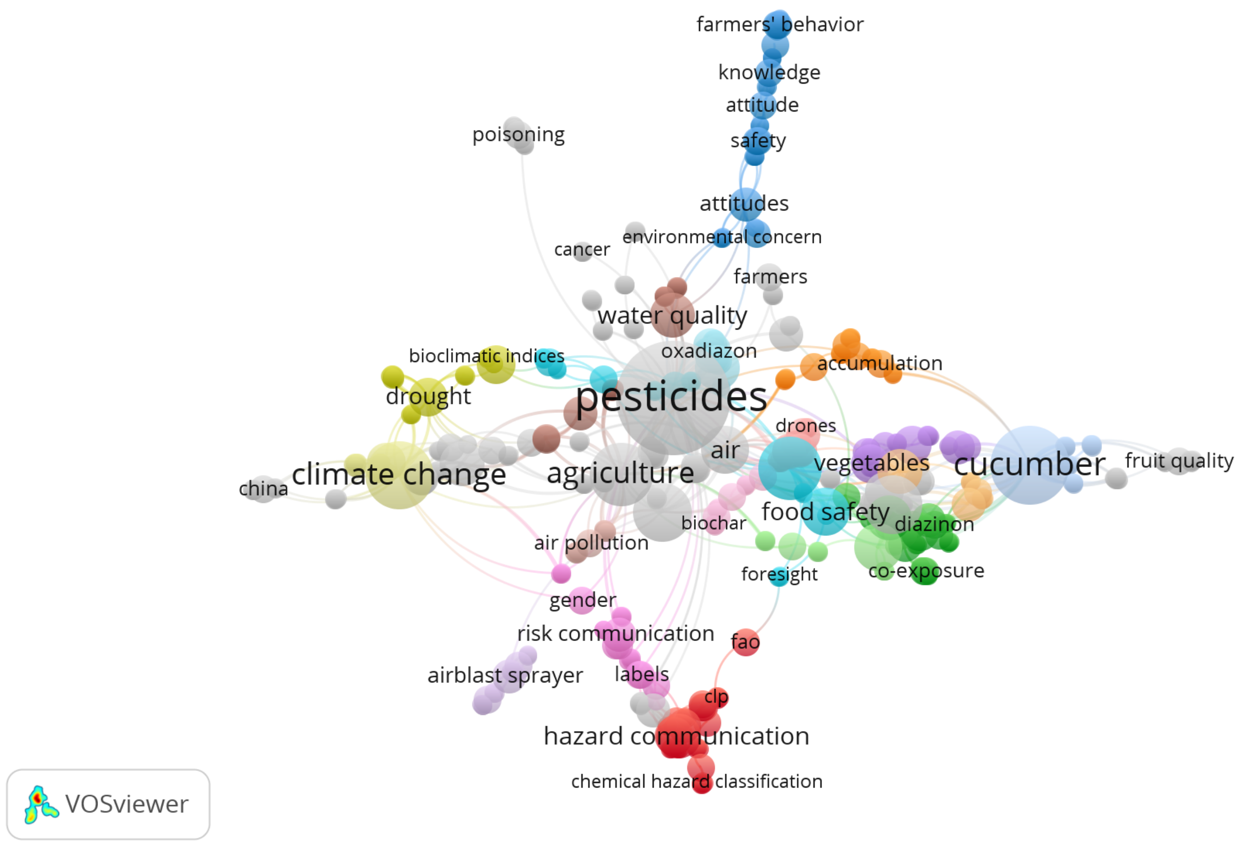


**Figure 1.** Network visualization of the keywords related to the pesticides

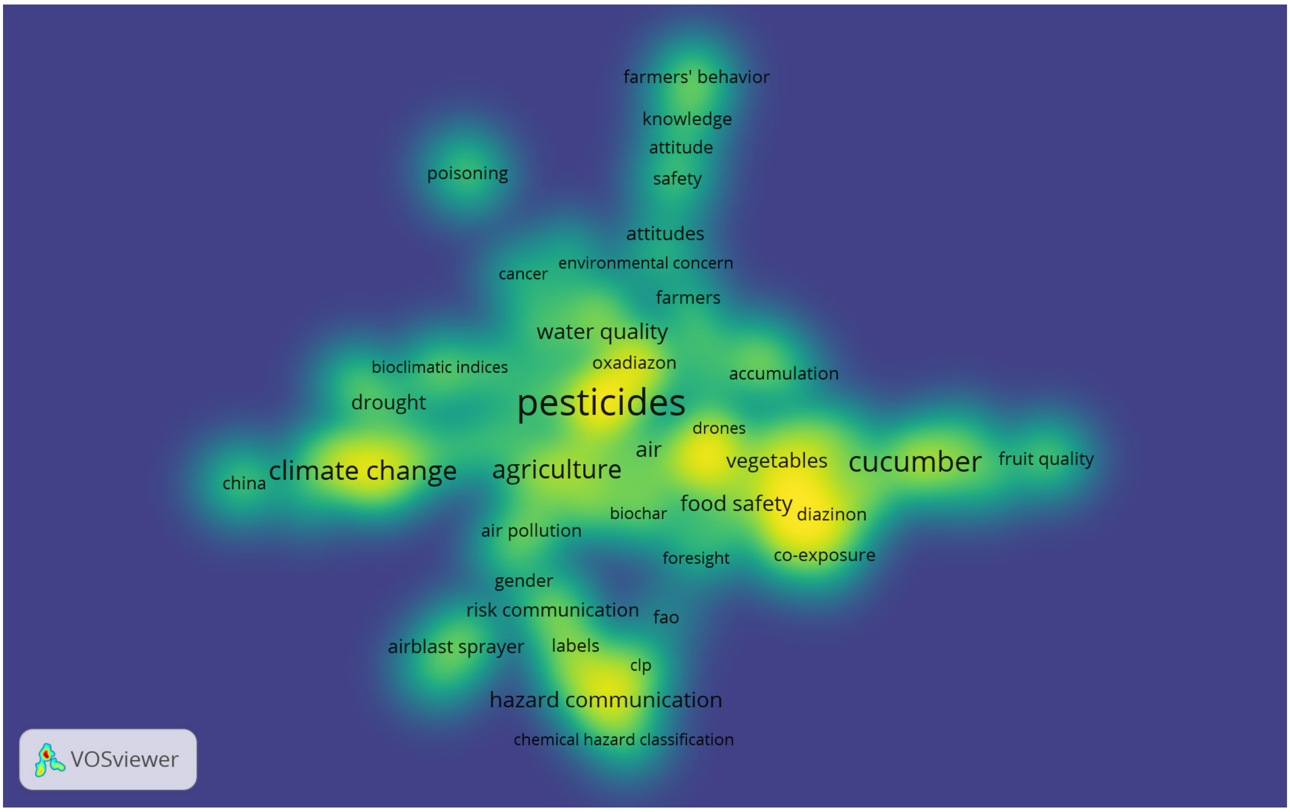


**Figure 2.** Density visualization of keywords related to the Pesticides

***Inclusion Criteria***

1. Studies that directly address pesticide use management strategies
2. Studies with a clear definition of cucumber fruit and pesticides used in this context
3. Field studies in farms and greenhouses

***Exclusion Criteria***

1. Lack of access to the main text of the articles
2. Incompleteness of the information data

## Consumer Awareness and Product Quality

Today's consumers want to know more than ever where their food comes from and how it was produced, especially in a food environment characterized by the convergence of agriculture, nutrition and sustainability.[41,42] For example, a new trend is marketing food with labels like 'clean' or 'free from.' Consumers use these to decide how much to buy a food.[43] In the past, people chose foods for their nutrients. These may help human health. However, consumer preferences have shifted toward simpler foods with fewer ingredients.[44] As awareness has increased, the focus has moved toward intrinsic product qualities.[45,46] Product quality is influenced by several factors, both pre- and post-harvest. At a basic level, genetic traits—particularly the crop variety—affect quality, while environmental conditions such as climate, soil, and water availability also play important roles. External features like size, color, shape, and pest-related damage are key quality indicators.[47] These are often the first aspects consumers assess and can dramatically affect their purchasing choices. Therefore, understanding and implementing proper post-harvest handling and treatment methods is essential to preserving product quality.

## Cucumber Pests

Cucumbers are generally grown commercially in Iran. These plants can be grown both in open fields and in greenhouses.[48] According to The US Environmental Protection Agency (EPA), pests are living organisms that are present where they should not be and cause harm to agricultural products, other organisms, and humans.[49,50] The whitefly (*Bemisia tabaci*) is another important pest of cucumber, causing great damage to the plant in two ways: by feeding directly on the plant and by transmitting plant viruses (Table 1).[51] Sohani et al found that *B. tabaci* can adapt well to high temperatures and that its range is expected to expand as global average temperatures rise due to climate change.[52] Razmjou et al reported that cucumber production in greenhouses and farms in Iran is currently struggling with challenges related to the aphid infestations, particularly by *A. gossypii.*[38] Since cucumbers are eaten raw and the time between two harvests is short, pest control with minimal use of chemical pesticides is crucial.[37,53] Therefore, environmentally friendly management methods are considered the best alternative for pest control in cucumber cultivation.

## Predicting the Impact of Climate Change on the Development of Pests

Several studies have been conducted to understand and quantify the impact of + 1.5 °C warming at global and regional scales.[54] For example, Liu et al assessed the changes with 1.5 and 2 °C warming targets at the global scale.[55] Ectothermic organisms, whose body temperature is directly dependent on ambient temperature, are likely to respond rapidly to such changes.[56] Such an increase in temperature is expected to alter pest pressure in agriculture. Because the distribution and survival, growth, development, and reproduction rates of insects are highly dependent on temperature.[57] Under warmer conditions, insects can cause more damage because their growth rates accelerate, leading to earlier emergence in spring and a higher number of generations per season as their life cycle is more compact.[58,59] Photoperiod length is an important factor in the seasonal synchronization of temperate insects, but their thermal requirements can vary at different times of the year. The interaction between photoperiod length and temperature determines phenology.[60] As many crop pests fall into this category (ectothermic organisms), it is important to consider projections of the effects of climate change on these organisms in future food security studies.[61] These projections also help estimate future pesticide usage trends and predict their potential effects on environmental health, including the development of pesticide resistance in target pests.[62]

## Pesticides Use

Globally, $12.4 \times 10^6$ $km^2$ of arable land is available for cultivation. The use of pesticides on agricultural land has increased by 96.6% worldwide from 1990 to 2021 ($3.54 \times 10^6$ tons). In addition, more than 800 different types of pesticides were used worldwide to achieve high crop yields on agricultural land.[63] Pesticides are classified based on the type of pests they target, including insecticides, acaricides, nematicides, fungicides, herbicides, rodenticides, molluscicides (snail control agents), and algaecides.[64] According to the FAO database, 140 countries have pesticide consumption patterns from 1993 to 2009. Among them, 10 countries (seven developing and three developed countries) use over 10 000 tons of pesticides annually.[65] Dehghani et al reported that farmers in Tehran and Isfahan provinces use 60 types of pesticides. These pesticides include organochlorines (10%), organophosphorus (28.4%), pyrethroids (10%), carbamates (10%), and others (41.6%). This year, the most used pesticide was organophosphorus. The least used was organochlorine.[66] Despite their known toxicity, organophosphorus pesticides (OPs) continue to be widely used.[67,68] Morteza et al stated that an average of 14,000 tons of pesticides were used annually in Iran between 2012 and 2014. Herbicides (43%) had the most significant volume. Insecticides and acaricides were next (37%), then fungicides (19%).[69] Like many countries, Iran relies on pesticides to control pests. About 30,000 tons of these chemicals are used in agriculture each year.[70]

Brazil is one of the leading consumers of pesticides in Latin America. The country uses more than 400 new pesticide products, nearly one-third of which contain active ingredients that are banned or restricted in the European Union (EU). Forecasts suggest that Brazil's agricultural production will continue to grow, which is expected to drive further increases in pesticide demand.[71] Similarly, Rahman et al reported that the rapid rise in pesticide use in Bangladesh raises serious concerns about its potential impacts on farmers' health and the environment.[72]

According to the Environmental Sustainability Index, Iran ranks 113th out of 146 countries. During 2018–2019, global pesticide use averaged around 2.69 kg/ha, while in Iran it reached 3.76 kg/ha (Table S1; Tables 2 and 3).[73] Although pesticides are widely used in Iran, accurate statistics on their total use are lacking due to a combination of imports and domestic production, which complicates reliable tracking.

### *Pesticides and Their Impacts on Greenhouse Farmers*

With limited agricultural land, greenhouses are vital to meet the growing food demand.[91] Greenhouses are the basis of protected cropping systems. They enable farming in poor soil, climate, and social conditions.[92,93] Greenhouse cultivation is a key vegetable production system. Pesticides are widely used to protect crops from weeds, diseases, and insects.[94] Organochlorine pesticides (OCPs) are a group of synthetic chemicals. They are widely used in greenhouses for pest and disease control in food production.[95] Due to their bio-accumulative,

**Table 2.** Identification of Pesticides in Cucumber Crop and Reduction Strategies

| Product type | MRLs | Effect of Some Procedures on Their Residues | The Best Practical Method | Region | Ref |
|---|---|---|---|---|---|
| Cucumbers grown in greenhouses | Ethion and Imidacloprid | Washing (with drinking water for 2 min. No detergent aid), peeling (with a kitchen knife dipped in acetone for a short time), and storing at 4 ˚C (refrigerator common temperature, for 24-48 h). | Peeling procedure also led to highest loss of 93.4 and 63.7% in ethion and imidacloprid residues, respectively. | Iran-Hamadan (2016) | 24 |
| Cucumbers grown in greenhouse | Metalaxyl | The effects of peeling and storage (at 3 ˚C for 4 days). | Processing factor values for peeling and storage were 0.50 and 0.93, respectively. | Iran- Varamin Agricultural Research Centre (2015) | 3 |
| Cucumbers grown in greenhouses | Dimethoate, Diazinon, and methyl parathion | Unwashed, washed, and peeled. | Mean reduction of pesticide residues in the peeled samples was in the range of 66.66 to 92.30%, respectively. | Iran-Tabriz (2024) | 74 |
| Cucumbers grown in greenhouses | Carbaryl and mancozeb | Effects of washing, peeling, storage, and fermentation. | Non-fermentative pickling in sodium chloride and acetic acid was the most effective way to reduce the mancozeb and carbaryl residues of the cucumbers. | Iran- Mazandaran. (2016) | 75 |
| Cucumbers grown in greenhouses | Carbaryl | Washing, peeling and refrigeration storage, at 4 ˚C for 2 days. | Peeling was the most effective way to reduce the carbaryl residues. | Iran- Mazandaran. (2010) | 76 |
| Cucumbers grown in greenhouses | Imidacloprid | Samples were collected at 1 h to 21 days after application and analyzed to determine the content and dissipation rate of Imidacloprid. | Residues of imidacloprid dissipated below the MRL of 1 mg kg-1 in 3 days. | Iran- Mazandaran. (2012) | 77 |
| Cucumbers grown in greenhouses | Ethion | Washing (with drinking water for 3 min), peeling, and storing at 4 ˚C (for 48 h). | Peeling procedure also led to highest loss of in ethion residues. | Iran- Mazandaran. (2010) | 78 |
| Cucumbers grown in greenhouses | Chlorpyrifos | Washing (with drinking water for 1 min), peeling, and storing at 4 ˚C (for 48 h). | Peeling was the most effective way to reduce residues in the cucumbers. | Iran- Mazandaran. (2019) | 79 |

**Table 3.** Identification of Pesticides Exceeding the MRL in Cucumber Product

| Product Type | Over Than MRLs | City | Ref |
|---|---|---|---|
| Cucumber samples were collected from three salad production plants | Dichlorvos and chlorpyrifos | Iran-Isfahan (2017) | 80 |
| Cucumber from greenhouse | Diazinon > thiacloprid > imidacloprid tebuconazole | Iran-Tehran (2022) | 81 |
| Cucumber from field | Diazinon | Iran-Khuzestan (2022) | 82 |
| Cucumber from field | Diazinon | Iran-Tehran (2019) | 83 |
| Cucumber from greenhouse | Diazinon- oxydemeton-methyl | Iran-Kerman (2014) | 84 |
| Cucumber from field | Diazinon | Iran- Kohgiloyeh and Boyerahmad (2012) | 85 |
| Cucumber from field | Malathion | Iran- Mazandaran (2017) | 86 |
| Shrub and nonshrub cucumbers | Benomyl and mancozeb | Iran- Mazandaran (2009) | 87 |
| Cucumber from field | Lindane | Iran- Mazandaran (2005) | 88 |
| Cucumber from both field and greenhouse | Benomyl, malathion and diazinon | Iran- Mazandaran (2023) | 89 |
| Samples were collected from Tehran Central Market fruits | Metalaxyl, Chlorpyrifos and Fenpropathrin | Iran-Tehran (2016) | 90 |

persistent, and toxic properties, many OCPs are on the Stockholm Convention's list of Persistent Organic Pollutants. Developed countries have banned their use since the 1970s.[96] However, researchers have detected their presence in recent human biological samples.[97,98] Ugalde-Resano et al reported that exposure to several OCPs may cause diabetes mellitus.[99] Gao et al reported that the average daily inhalation dose for humans exposed to six pesticides—imidacloprid, acetamiprid, prochloraz, triadimefon, hexaconazole, and tebuconazole—ranged from 1.2 to $2.1 \times 10^4$ pg/kg/d over a period of 1 to 35 days following application. These findings suggest the need for further research into the health risks associated with inhalation exposure to these pesticides, particularly in greenhouse environments.[100] Samiee et al investigated pesticide exposure and associated health risks in cucumber greenhouses.[101] During the mixing and loading phase, dermal exposure on the hands was measured at 1.15 mg for imidacloprid and 2.27 mg for dichlorvos. During spraying, total dermal exposure increased to 8.49 mg for imidacloprid and 16.21 mg for dichlorvos. The risk assessment revealed that the margin of safety for dichlorvos was less than 1, indicating a potential health risk to humans. These findings underscore the need for greater attention from policymakers to ensure safer pest management practices in greenhouse agriculture.

## Pesticides and Their Impacts on Field Farmers

Open farming refers to a form of agriculture in which crops are cultivated outdoors without protective structures. It typically relies on natural environmental conditions such as sunlight, rainfall, and wind, and employs various techniques to enhance crop growth and productivity.[102,103] Farmers overuse pesticides because they have higher expectations of future yields, which leads to increased inefficiency and remains unknown to farmers.[104] Health problems caused by pesticides reduce health capital while increasing inefficiency at the farm level.[105] Previous studies have shown that people who are directly exposed to pesticides, such as workers engaged in pesticide production or application, accumulate these compounds in harmful amounts in their bloodstream.[106] The acute health effects experienced by individuals working with pesticides have well been documented and can often be linked to specific classes of these chemicals.[107] Mirrezaei et al found that, after pesticide spraying by cucumber growers, the average plasma cholinesterase (ChE) level was 13 655.8 in the control group. In comparison, it was 8516.3 in the group without protective clothing and 11 639.3 in the group that used protective clothing.[108] In Iran, organophosphate pesticide (OPP) poisoning is one of the leading causes of death among farmers. The use of appropriate personal protective equipment is essential, as it helps reduce damage to the enzyme ChE. Fahed et al investigated the risks associated with 49 pesticides recommended by the Lebanese Ministry of Agriculture for cucumber cultivation. They found that 81.25% of these pesticides were teratogenic, and 31.25% were classified as carcinogenic and endocrine-disrupting.[109] A meta-analysis by Mohammad et al revealed a significant reduction in ChE activity in the blood of Iraqi agricultural workers previously exposed to pesticides. The study emphasized the need for a comprehensive national plan and strengthened regulations to promote the safer and more rational use of pesticides, along with ongoing monitoring, to mitigate potential health and environmental risks in Iraq.[110]

### *Policies or Regulatory Frameworks in Iran to Address Pesticide Overuse or Residue Limits*

In order to optimize the use of agrochemicals and promote the cultivation of healthy crops, the Ministry of Agricultural Jihad is obliged to design its promotion and incentive policy in such a way that priority is given to the production of healthy crops. According to Article 9 of the Implementing Regulation on the Control and Sanitary Supervision of Agrochemicals, all factories, workshops, clinics, enterprises and all individuals involved in the purchase or use of agrochemicals are required to properly dispose of empty containers in compliance with environmental regulations.[111,112] Any act considered a threat to public health—such as the contamination or distribution of unsafe drinking water, the unhygienic disposal of human and animal waste, the discharge of toxic substances into rivers, the dumping of garbage on the streets, the illegal slaughter of animals, or the unauthorized use of raw sewage and agricultural wastewater—is prohibited. Offenders may be sentenced to up to one year of imprisonment.[112]

## Pesticides' Impact on Neighboring Residential Areas

Assessing pesticide exposure is challenging, particularly in cases of environmental exposure, as people are often unaware of the pesticides used near their place of residence.[113,114] A study found measurable levels of pesticide a few hundred meters from application sites.[115] Due to pesticide application and drift, residential areas in farming communities may be important places of environmental exposure.[116,117] Ramirez Haberkon et al reported that over 90% of rural soils, including farms and roads, had at least one pesticide. This study provides preliminary evidence about pesticide residues in particulate matter ($PM_{10}$) released from rural soils under different land management practices. These results also confirm that $PM_{10}$ is a potential source of air pollution with pesticides.[118] Furthermore, Galimberti et al found that, on average, 13% of people may be exposed to pesticides due to living near treated crops. Among those exposed, 34% experienced low levels of exposure, 40% medium levels, and 25% high levels.[119] Pesticide exposure from the environment is usually low. However, many people may be at risk, including sensitive groups like children and the elderly.[120,121] The EPA reported that pesticides are linked to children's developmental disorders.[122] It is estimated that each year, over 320 000 infants worldwide are affected by neural tube defects (NTDs).[123] NTDs have a multifactorial etiology. Both genetic and environmental factors contribute to the observed phenotypes.[124,125] Rull et al stated that exposure to certain pesticides may raise the risk of NTDs.[126] These include amide, benzimidazole, methylcarbamate, and organophosphates. Asensio found that prenatal exposure to organophosphate and pyrethroid insecticides can harm fetal development, shorten gestational age, and alter anthropometric parameters at birth.[127] Abdollahdokht et al found that serum levels of beta-HCH, 4,4-DDE, and 4,4-DDT were significantly higher in a treatment group of 120 child farm workers compared to a control group of 53 non-farm children aged 6–11. The presence of illegal OCPs has been reported in southeastern Iran, where children are exposed to both OCPs and OPPs.[128] Elevated serum pesticide levels may lead to oxidative stress, which is associated with the development of various diseases.

## Impacts of Pesticide Residues in Drinking Water on Human Health

Pesticide residues in drinking water are one of the major sources of human exposure.[129,130] Some studies in Iran found OCPs in the hair of pregnant women and in the breast milk of women who ate fish weekly.[131,132] Long-term pesticides exposure, even in low doses, can harm human health. Pregnant women and children may suffer more from depression, endocrine and oxidative dysfunction, kidney disease, stress, immune and nervous system issues, and chromosomal changes.[133-136] Besides, it can damage human deoxyribonucleic acid (DNA).[137, 138]

### *Pesticide Residues in Surface Water*

Agriculture is a significant activity that harms water resources as a non-target ecosystem.[139] Point source pollution refers to any identifiable source that discharges pollutants directly into the environment.[140] According to Bagheri et al, pesticide use contributes significantly to point source pollution, adversely affecting soil and water quality, particularly in developing countries where pesticide use is widespread.[141] Common examples of point source pollution include discharges from wastewater treatment plants, industrial facilities, and combined sewer overflows.[142,143] Non-point source pollution occurs when pesticides move from agricultural fields to water resources through processes such as spray drift, surface runoff, leaching, and drainage flow.[144] The primary sources of non-point source pollution include residues from spray solutions after application, sprayer washing sites, washing effluents, and the improper disposal of expired pesticides.[145,146] These sources require greater attention. Additionally, washing contaminated fruits and vegetables contributes to pesticide-enriched wastewater.[147] Rivers are further polluted by industrial, agricultural, mining, and urban waste, all of which increase pesticide levels resulting from farming and landscaping activities.[148]

Fadaei et al found that two weeks after spraying, malathion and diazinon residues exceeded permissible limits at all sampling stations.[149] As a result, surface water often contains high levels of pesticides and other anthropogenic pollutants.[150,151] In response, various international bodies—such as the EU, USEPA, and WHO—have established maximum contaminant levels (MCLs) for pesticides in drinking water.[152] The EU imposes particularly strict limits: 0.1 μg/L for individual pesticide compounds and 0.5 μg/L for total pesticide concentrations in drinking water.[153,154] (Table S2). Several studies have shown that pesticides frequently enter surface waters at high rates, particularly during spring and summer when application is at its peak. Concentrations increase significantly during rainfall events.[155] Therefore, pesticides should not be applied before rain, as they may be washed away and fail to reach their intended targets.[156] Morales et al reported that nearby agricultural and urban activities can significantly affect water quality in small watersheds.[157] Kalantary et al[158] detected high concentrations of OPPs (ranging from 0.87 to 3.229 μg/L) in river water. OCP levels were generally low, except for 1,3-dichloropropene, which was present at 3.58 μg/L. In addition, Alachlor was detected at a relatively high concentration of 2.44 μg/L. The carcinogenic risk (CR) of Aldrin for children and adolescents was found to exceed safe levels.

### *Human Health Risk Model Uncertainty Bounds for Drinking Water*

Pesticide toxicity is usually measured using animal exposure tests to quantify the health effects of long-term use. The no-observed-adverse-effect level (NOEL) or the lowest observed effect level (LOEL) is often used to set the maximum safe pesticide level (equation 1).[152]

$$AD\frac{NOEL(\mathrm{NOEL})}{\mathrm{SF}} \tag{1}$$

Where, AD represents the animal dose (mg/kg/day) in which an effect is observed. Safety factor (SF) is often used as a SF. It accounts for different sensitivities in lab animals and test uncertainties across species. The MCLs of pesticides are then calculated based on the exposure scenario and AD, as Equation 2:

$$MCL\frac{(AD)(HW)(\mathrm{PF})}{(\mathrm{V})(\mathrm{SF})} \tag{2}$$

Where, HW is human weight (kg), V is water consumption (L/day). PF is a factor that shows what share of pesticide exposure comes from drinking water. V is the amount of water a person consumes daily. SF in the equation is a SF. It accounts for the different sensitivities of humans and lab animals.

### A Review of Pesticide Residues in Groundwater

Pesticide can travel far in the environment. It can reach untouched areas. Hosseini et al found that diazinon enters groundwater near farms through spraying. These pesticides can remain in the water for at least one month after the last spraying.[159] Shakerkhatibi et al reported that of 78 samples from 39 drinking water wells, the most frequently found pesticides were profenophos, malathion and diazinon. Their maximum concentrations were 0.542, 0.456 and 0.614 μg/L, respectively.[160] Tahmasebi et al investigated the content of toxins in the drinking water of Shiraz. They found chlorpyrifos and azinfos-methyl in groundwater at levels above EPA recommendations. The results also showed that malathion and trifluralin pose a significant CR to adults.[161] Jaipieam et al also found that organophosphate levels were higher in agricultural communities (0.085 and 0.418 μg/L in dry and wet seasons, respectively) than in non-agricultural communities (0.004 μg/L in both seasons). In agricultural communities, organophosphate consumption via contaminated water was 0.187 μg/day in the dry season and 0.919 μg/day in the wet. In non-agricultural communities, it was 0.008 μg/day.[162]

### Water Hardness Effect on Pesticide Performance

Water quality is the suitability of water for various uses. Many natural factors influence it.[163] Water quality parameters affect pesticide performance. They include hardness, pH, alkalinity, turbidity, and TDS.[164] Klokocar Smit et al found that raw water had higher pH, hardness, and $NO^{2-}$, $Fe^{2+}$, $Fe^{3+}$, $NH^{4+}$, $Ca^{2+}$, and organic matter than drinking tap water. This affected the spraying solutions' physical properties, tank mixability, and vegetable quality.[165] In most cases, water accounts for more than 99% of the spray mixture. It plays a crucial role in pesticide application and greatly influences control efficiency.[166] Daramola et al reported that the optimal temperature range for some weak-acid herbicide solutions is between 18 and 44 °C. However, their effectiveness decreases at lower (5 °C) or higher (56 °C) temperatures.[167] Similarly, Ranjbar et al evaluated the toxicity of three insecticides mixed with well, standard, and deionized water, incorporating Zero-7 and Arcane additives. The tested water samples had hardness levels of 1869 and 645 mg/L, respectively. In hard water, insecticide toxicity against Bemisia tabaci was greatly reduced, but the additives counteracted the antagonistic effects of hard water cations.[168] These findings emphasized that water turbidity and hardness can reduce pesticide efficacy. Therefore, purified water is recommended to minimize these issues and improve pesticide performance.

### Monitoring the Performance of Sprayers and Evaluating Chemical Control Operations

A better understanding of precision spray systems reveals a savings of 34 to 88% in spray solution volume compared to conventional systems.[169] In conventional spraying, significant pesticide loss occurs due to drift, influenced by several factors such as nozzle type, pressure, spray height, type of stock solution (systemic vs. contact),[170] and environmental conditions like wind direction and speed, temperature, and relative humidity.[171] For herbicides such as 2,4-D and dicamba, product labels specify the use of certain nozzle types and pressures to ensure proper spray quality and minimize drift.[172] Gholap et al demonstrated that mechanical devices, such as shields covering the spray boom or individual nozzles, can help reduce drift under windy conditions.[173] Gupta et al found that leaf surface density and the forward speed of the sprayer negatively affected droplet density.[174] In addition to the environmental pollution and pesticide loss, drift may also cause phytotoxic effects such as plant burns and increase residual toxin concentrations in crops.[175] High wind speeds can carry droplets away from the target area, depositing them on non-target surfaces. However, completely windless conditions are also undesirable due to the risk of temperature inversion, which can trap spray droplets in the air and cause them to settle unpredictably.[176]

### Mitigation Strategies

#### *Farmers' Knowledge and Attitude Toward Pesticides Use*

In many developing countries, farmers often lack the necessary training and equipment for the safe use of pesticides and proper disposal of pesticide waste.[177,178] Many farm owners employ low-literate migrant workers who receive no formal training, making them particularly vulnerable.[179] Hiring temporary or part-time farmers can increase agrochemical use in agriculture.[180] These workers lack a commitment to farming. Pirmoghani et al found that the improper use of pesticides was mainly related to the user's lack of awareness.[181] Bagheri et al also stated that 60% of greenhouse owners had a weak attitude toward using chemical pesticides.[182] Attitudes are shaped by a complex mix of beliefs, motivations, and past experiences.[183,184] Understanding farmers' knowledge about pesticides and the factors that influence it is crucial for preventing health issues and reducing pesticide-related poisonings.[185] However, to change their practices, it is necessary to recognize the factors that cause improper pesticide handling.[186] Behavioral models can help study what drives farmers' health and safety behaviors. A key model of preventive behavior is the theory of planned behavior (TPB).[187] The TPB includes three main constructs: (1) attitudes toward the behavior, (2) subjective norms, and (3) perceived behavioral control—all of which shape a person's intention to carry out a behavior.[188] Intention, in turn, strongly influences actual behavior.[189] In a study by Sandoghi et al, most farmers acknowledged that the use of pesticides and fertilizers poses risks to both human health and the environment. However, they often failed to comply with safety guidelines. This underscores the need to improve the knowledge and attitudes of cucumber greenhouse owners regarding fertilizer and pesticide management.[190]

### Pesticide Labels, Pictograms, and Farmers' Perceptions

Labels and pictograms of pesticide products are the first and most important source of information about the safe handling of them.[191,192] The labels are based on the global harmonized system of classification and labeling of chemical pesticides (GHS). They include some text and images on how to prepare and use a pesticide safely.[193] Pictograms are a series of warning graphics.

The FAO and the GIFAP designed them. They aim to help illiterate or undereducated people understand pesticide label safety information.[194,195] Many farmers in developing countries are too poor and uneducated to understand label information. These farmers usually prefer to get information from retailers, other farmers, or extension agents.[196,197] Jatto et al found that farmers preferred to obtain pesticide information from their peers due to the technical language and unclear imagery used on labels.[198] Bagheri et al stated that farmers had a poor understanding of pictograms. Education, extension courses, and attitude positively affected pictogram perception.[199] Perez et al reported a link between reading pesticide labels and high education and income.[200] Pesticide labels provide safe handling and use information for a product.[201] However, the effects of label information on pesticide use depend on its importance to farmers. It also depends on how they perceive it. This affects their safer behaviors, attitudes, and practices.[202] A lack of understanding of label information increases the risk of poisoning—not only for farmers themselves but also for consumers—and can result in environmental contamination and harm to non-target organisms.[203] Therefore, the current global system for classifying and labeling chemical pesticides must be improved to enhance its accessibility and effectiveness.[204]

### Strategies to Reduce Pesticide Residues in Drinking Water

Sustainable water supply has become a problem in many countries around the world. The water crisis is not limited to water scarcity. The decline in water quality due to pollution caused by human intervention is also one of the most important causes of this crisis.[205,206] Pesticides are one of the main sources of water pollution. Due to the increasing population growth and the increasing need for food, their use in agriculture has increased.[207] In recent years, many processes have been used to remove pesticides from water. These include chemical adsorption, ion exchange, electrolysis, filtration, biodegradation, and chemical oxidation.[208,209] However, low efficiency, secondary pollution, and high capital costs have been reported as further disadvantages of these technologies. Today, nanomaterials, like nanocomposites and bio-nanocomposites, are cost-effective and efficient catalysts. They have high specific surface areas, making them quick and effective. $TiO_2$ (photocatalyst) and $Fe_0$ can help remove pesticide contamination. When used alone or with oxidizing agents, they show promise. This opens up chances to explore other nanoparticles. Unlike $TiO_2$ and Fe0, metal oxides with different nanostructures quickly degrade OP pesticides. They do this by reacting fast and breaking the P–O bond through an SN2 mechanism.[210] In Iran, Rezaei et al found that the composite $ZnO@SiO_2@Fe_3O_4$/PMS/UV functions as a promising advanced oxidation process for the effective destruction of pesticides.[211] Similarly, Rahmanifar et al reported that chitosan-silver oxide nanoparticles act as high-capacity, eco-friendly, and biocompatible adsorbents suitable for water treatment.[212] Ranjbar Bandforuzi and Hadjmohammadi also stated that magnetic chitosan nanoparticles were very effective for the removal and determination of trace amounts of toxins in surface water, groundwater and wastewater samples collected from different regions of northern Iran.[213] Some pesticides require more attention and study. The best water treatment method for pesticide removal depends on the pesticide type and the treatment efficiency. So, it's important to identify priority compounds, the best refining technologies, and knowledge gaps. It is a key step in addressing this issue.

### Strategies to Reduce Pesticide Drift or Exposure in Residential Areas

Understanding pesticide exposure is crucial for protecting public health, informing regulations, and guiding environmental management strategies. The volatile nature of many pesticide compounds poses a significant risk for air pollution, particularly in large urban areas. Habran et al analyzed agricultural and demographic data in Wallonia, Belgium, and found that most residents live near agricultural zones. Their findings highlight the need for environmental pesticide control measures in areas where people and agricultural activities coexist.[214] Pesticides can enter the air through multiple pathways, including spray drift, evaporation from treated surfaces, and aerial application. The extent of drift is influenced by factors such as droplet size and wind speed. While small droplets ensure better coverage and contact with target surfaces, they are also more prone to drifting. Conversely, large droplets are more likely to detach from plant surfaces. Therefore, striking a balance in droplet size is critical—small enough for effectiveness, yet large enough to minimize drift. Reimer and Prokopy reported high adoption rates for basic drift-reduction technologies, such as low-drift spray nozzles (88%) and practices that increase spray droplet size (92%). However, adoption was low for more specialized equipment like band sprayers (13%). Farmers also faced challenges in identifying sensitive or high-risk drift zones. Promoting awareness through innovative and voluntary outreach methods in rural communities could improve drift prevention efforts.[215] Several environmental factors affect pesticide evaporation, including the time since application, surface area, ambient temperature, humidity, wind speed, and the vapor pressure of pesticide components. Timing is especially critical: early morning or evening applications are generally safer, as wind conditions are typically calmer. Wind tends to peak around noon, when ground temperatures are highest. During this time, thermal inversions—when cooler air is trapped near the ground under a layer of warmer air—can also exacerbate drift by limiting vertical air mixing. Sprayers must be aware of inversion conditions and avoid applying pesticides during such times. Wind speed is perhaps the most influential weather variable affecting pesticide drift. High wind speeds can cause droplets to drift far from the target area, particularly downwind, contaminating non-target surfaces. Natural and artificial barriers (e.g., trees, hedges, or fences) are highly effective at reducing pesticide drift. Research conducted in New Zealand and the Netherlands found that such barriers can reduce drift by up to 90%.[216]

### *Other Nonchemical Pest Control Methods*

#### *Agronomic Control*

Historically, agronomic control methods have been the best tool for farmers to prevent crop losses. Farmers around the world have long used agronomic control for pest management. They appreciate it for being eco-friendly and cost-effective.[217] Agronomic control includes a range of common farming practices that help reduce pest populations and protect crops from damage. Key methods include crop rotation, soil improvement, and soil solarization. Timely planting and harvesting are also important strategies. Furthermore, the application of pest-resistant crop varieties and certified seeds plays a significant role. Other techniques include allelopathy, intercropping or companion planting, and the use of decomposed manure. Organic and living mulches are also widely used.[218] Soil solarization and organic mulches—whether applied separately or in combination—are particularly effective and environmentally friendly for managing soil-borne pests such as insects, nematodes, and weeds. To enhance the effectiveness of agronomic controls, it's important to adapt these practices to the specific life cycle and behavior of the target pests.

#### *Biological Control*

Biological control involves the use of natural enemies to reduce pest populations, thereby helping to prevent or minimize economic losses. The most common biological control agents include parasitoids, predators, and pathogens. This method encompasses three primary strategies: introduction (localization), conservation, and augmentation (enhancement) of natural enemies. Biological control agents span a wide range of organisms, including vertebrates, annelids (such as flatworms and roundworms), arthropods (e.g., spiders, mites, and insects), and pathogens like viruses, bacteria, protozoa, fungi, and rickettsia. These agents play a crucial role in the natural regulation of insect and mite populations.[219] Biological control of weeds has been very successful worldwide. There are about 41 weed species that have been successfully controlled using insects and pathogens. Three weed species have also been controlled using native fungi as herbicides (mycoherbicides).[220, 221] In Australia, 12 insect species have been released to combat prickly pear (*Opuntia stricta*), with *Dactylopius* spp. and *Cactoblastis cactorum* demonstrating significant effectiveness. Over the past decade, Australia has launched 43 biological control agents—including arthropods and pathogens—across 19 projects to successfully manage invasive weeds.[222]

### *Future Research*

The results of this study indicate the presence of pesticides in cucumber samples harvested from cucumber supply farms and greenhouses in Iran. Therefore, necessary control and monitoring measures should be taken regarding the amount and method of pesticide consumption in the country. It is necessary to develop a training program for farmers and extension campaigns in order to use pesticides correctly, timely and within the permitted limits in the agricultural sector. Based on the outcomes of this study, the following areas are recommended for future research:

- Investigating farmers' knowledge and attitudes regarding the quality of water used on the performance of pesticides
- Providing strategies and solutions to improve and sustainable pest control methods, like agronomic and biological control.
- Studying the effects of extension educational programs on the reduction of pesticide use and improving farmers' health.
- Investigating strategies for using biological and environmentally friendly pesticides.
- Investigating methods to reduce pesticide use by farmers
- Investigating methods to optimum use of pesticides to minimize the health and the environmental impacts.

## Limitations

Like other review studies, the main limitation of this method is its reliance on a review of existing literature without field validation.

## Conclusion

The use of pesticides has become inevitable in modern agriculture, initially introduced to enhance crop yields and control pests. However, their adverse effects on human health and the environment have increasingly outweighed the benefits. Indiscriminate pesticide use poses significant risks, particularly to farming communities, which often face greater exposure during both dry and wet seasons. Pesticide compounds can enter the atmosphere through spray drift, evaporation, and erosion, and can also originate from surface waters and agricultural soils. These chemicals are primarily degraded by soil microorganisms, sunlight, and oxidants, while wind plays a key role in their dispersion. As a result, public concern has grown over the environmental persistence and health hazards of pesticide residues, especially through air exposure, which is closely linked to proximity to treated areas. To address these concerns, alternative pest control strategies such as integrated pest management offer sustainable solutions. Integrated pest management combines agronomic and biological methods, resistant crop varieties, physical and mechanical controls, and judicious pesticide use—reserving chemical intervention as a last resort. Additionally, modern technologies like biotechnology and nanotechnology can aid in developing pest-resistant crops or designing less harmful pesticides. Community development and agricultural extension programs are essential to educate and motivate farmers to adopt these innovative and eco-friendly practices. Furthermore, this study highlighted simple yet effective ways to reduce harmful pesticide residues in food. Proper processing, storage, washing, and peeling of raw produce significantly lower residue levels, depending on the type of food, pesticide, and processing method used. Thus, applying a combination of these techniques can substantially enhance food safety and protect public health.

## Authors' Contribution

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## Competing Interests

The authors declare that there is no conflict of interest concerning the publication of the study.

## Ethical Approval

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## Supplementary File

Supplementary file contains Tables S1-S2

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