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METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS PART IV: PESTICIDES MANUFACTURING

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METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS

PART IV: PESTICIDES MANUFACTURING

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Abstract

This paper is part of a series detailing new methodologies for estimating key components of agrifood systems emissions, with a view to disseminate the information in FAOSTAT. It describes methods for estimating greenhouse gas (GHG) emissions associated with historic and current pesticide manufacturing, as part of an overall aim to inform countries of the environmental impacts of agrifood systems and the possible options to reduce them. Based on the proposed methodology, we built a new database of the annual carbon footprint from energy used in pesticides manufacturing, on a country basis and with global coverage, for the period 1990–2020. Global GHG emissions from pesticide manufacturing peaked in 2017 at approximately 71 megatonnes of carbon dioxide equivalent (Mt CO_2eq), and average emissions intensities decreased from 0.085 kg CO_2eq per megajoule (MJ) to 0.073 kg CO_2eq/MJ from 1990 to 2020.

Our efforts help to better characterize agrifood systems and the role they can play in achieving the Sustainable Development Goals (SDGs). In particular, they align well with SDG 12 to ensure "sustainable consumption and production patterns'', specifically Target 12.2, "achieve the sustainable management and efficient use of natural resources" and Indicator 12.2.1, which monitors the "material footprint, material footprint per capita, and material footprint per GDP" of different products.

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1 Introduction

Agrifood systems generate about one-third of greenhouse gas (GHG) emissions from human activity and their emissions can be classified into three main categories: i) farm gate; ii) land use change; and iii) pre- and post-production (Tubiello *et al.*, 2021a). While statistics of GHG emissions generated within the farm gate and from land use change are well characterized globally with country details and over sufficiently long time series (FAO, 2021a), methods and data for estimating emissions beyond the farm gate are generally lacking (Clark *et al.*, 2020). These include methods to estimate emissions from energy demand in several critical pre- and post-production processes, such as in pesticide manufacturing, food processing activities, retail facilities and household consumption (Flammini *et al* 2022; Karl and Tubiello, 2021a; Karl and Tubiello 2021b, Tubiello *et al*. 2022, Rosenzweig *et al*., 2021). This work builds on work by Tubiello *et al.* (2021a), which laid the foundations for the development of an independent database in FAOSTAT, with a view to disseminate country-level statistics on GHG emissions from agrifood systems, with annual updates and global coverage.

The work presented contributes to linking statistics on agrifood systems, as typically reported by countries to FAO, to those reported under the United Nations Framework Convention on Climate Change (UNFCCC). Relevant FAO classifications are specifically linked to those of the Intergovernmental Panel on Climate Change (IPCC) and as used by countries when reporting to the UNFCCC. This mapping approach enables countries to better employ the information in their national GHG inventories in order to design effective mitigation strategies for their agrifood systems (Tubiello *et al.*, 2021a; Rosenzweig *et al.*, 2021).

2 Pesticides manufacturing in context

2.1 Pesticide definitions

Pesticides are a key input into the majority of global agricultural systems (Hedlund *et al.*, 2020). The main categories of pesticide covered herein are insecticides, herbicides, fungicides and bactericides. Together these represent over 90 percent of global agriculture pesticide use (FAOSTAT, 2022a). Fungicides and bactericides are substances that either destroy or inhibit the growth of fungal or bacterial pathogens. Since they serve a similar function, they are grouped together in FAOSTAT. Insecticides are substances used to kill or repel insects, and also include substances that kill or repel mites, snails, slugs and nematodes. Herbicides are substances that kill or inhibit the growth of plants, including but not limited to defoliants and desiccants.

2.2 Trends in pesticide usage

About 2.7 million tonnes of pesticide active ingredients were deployed by agriculture in 2020, an increase of 58 percent from 1990 (FAO, 2022a). Herbicide usage has grown the fastest among the three groups, increasing by 115 percent from 1990 to 2020. It represents more than half of all pesticide use by weight of active ingredient (FAO, 2022a). The share of fungicides and bactericides of total pesticide use has remained constant at roughly 25 percent, while the share of insecticides fell from 26 percent in 1990 to 18 percent in 2020 (FAO, 2022a).

2.3 Energy use in pesticides manufacturing

The production of pesticides requires significant energy inputs, with attendant GHG emissions when demand is met by fossil fuels. The production of pesticides relies on three energy-intensive processes:

1) inherent energy is used in the manufacture of the chemical and is retained in the chemical structure of the pesticide’s active ingredient;

2) process energy used in the manufacturing process (e.g. for heating, cooling and pressurizing), and

3) indirect energy used for the formulation of pesticide mixtures.

Barber (2004) used data from Pimentel (1980), filtering for formulations still on the market, to estimate that, on average, herbicides require roughly 430 megajoules per kilogram of active ingredient (MJ/kg a.i.) produced, while fungicides and insecticides require approximately 210 MJ/kg a.i. and 310 MJ/kg a.i., respectively. Lillywhite (2007) did not present data for aggregated herbicides but estimated that insecticides and fungicides require 214 MJ/kg a.i. and 168 MJ/kg a.i. in their production, similar to the averages presented by Green (1987). These estimates consider all three energy processes highlighted above.

The mix of energy sources used in the pesticide production process is specific for each active ingredient, although some differences exist across products. For instance, the relative contribution of electricity to total production energy (which includes inherent and process energy) hovers around 30–35 percent for most products (Audsley *et al.*, 2009). Country-specific data on the energy mix for electricity generation were considered (see section 3.3). The relative contribution of other energy sources, such as naphtha, coke, fuel oil and natural gas, however varies widely by product, active ingredient, and by locally specific energy system factors (Audsley *et al.*, 2009).

3 Pesticides methodology overview

GHG emissions from pesticides manufacturing consist of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emitted during the energy-intensive processes outlined in section 2.3.

Emissions from pesticides can be estimated at the country level, using this basic formula:

$$\textit{Emissions} = P_{i,c} * E_{s,c} * EF_{s,i}$$

where:

Emissions **= CO_2 equivalent (kilotonnes CO_2eq)**

P **=** Weight of active ingredient manufactured in country *i*, per pesticide category *c* (tonnes a.i.)

E **=** Energy source *s*, used to manufacture pesticide *c* (Terajoule tonnes a.i.$^{-1}$)

EF **=** Emission factor for energy source *s*, in country *i* (kilotonnes CO_2eq Terajoule^{-1})

3.1 Activity data

Activity data for pesticide manufacturing are drawn from the newly updated FAOSTAT *Pesticide Use* and *Pesticide Trade* domains (FAOSTAT 2022a, 2022b). For each category, the sum of export and agricultural quantities used, less those embedded in imports, was used as a proxy for how much pesticide was manufactured by each pesticide group. All data are year and country-specific. Where negative values are estimated through this equation – for example, where imports exceed the sum of exports and agricultural use – the values are estimated at 0. In other words, in such cases it is assumed that the country does not manufacture pesticides in that specific pesticide category at significant levels.

The *Pesticide Use* domain already disseminates estimates of agricultural use of pesticides across pesticide categories in units of weight of active ingredient. However, data from the *Pesticide Trade* domain express export and import quantities in terms of weight of formulated product. The following conversion factors were used to convert data from formulated product into active ingredient weights, as per the country notes in the *Pesticide Use* domain (FAOSTAT, 2022a):

- Insecticides: 0.31
- Herbicides: 0.34
- Fungicides: 0.60
- Bactericides: 0.60

3.2 Energy data

As mentioned in section 2.3, a range of estimates have been published on the average energy intensity of pesticide manufacturing per pesticide category. For the manufacture of insecticides, fungicides and bactericides, this study uses the average energy intensity estimates of Barber (2004) and Lillywhite (2007), as quoted in Audsley *et al*. (2009). Since Lillywhite (2007) did not provide estimates for herbicides as a category, those from Barber (2004), repeated in Saunders and Barber (2007), were used. The energy intensity factors used in this study are presented in Table 1.

Table 1. Average energy intensity of pesticide active ingredient by pesticide category

Pesticide Category	Terajoules/tonne active ingredient
Insecticides	0.262
Herbicides	0.430
Fungicides and Bactericides	0.189

Source: Authors' own elaboration.

The shares of energy carriers used in pesticide manufacturing were taken from Audsley *et al*. (2009) and are summarized in Table 2.

Table 2. Average mix of energy sources used in pesticide manufacture, by pesticide category (percent)

	Naphtha	Natural gas	Coke	Fuel oil	Electricity	Total
Insecticides	18.2	15.8	1.7	30.3	33.9	100
Herbicides	27.1	16.0	0.1	25.0	31.9	100
Fungicides and Bactericides	22.9	19.8	1.2	22.7	33.5	100

Source: Authors' own elaboration.

The share of energy use required in the pesticide manufacturing process attributable to different energy sources was then applied to the total energy requirements to estimate the amount of energy utilized for each source, for each pesticide category, in a given country and year.

3.3 Emissions factors

As done for energy use components in agrifood systems as presented in Tubiello *et al*. (2021b), emission factors to estimate GHG emitted per unit of fossil fuel combusted to meet end-use energy demands were taken from default values for *stationary combustion in manufacturing industries and construction* as used by IPCC (2006). Grid emissions factors for electricity production were taken from the International Energy Agency (IEA) emissions factors dataset (IEA, 2021).

The emissions data were then converted from methane and nitrous oxide to CO_2 equivalents using global warming potentials (GWP) as defined in the IPCC Fifth Assessment Report (AR5). As used in the CO_2eq (AR5) calculations:

- The GWP for CH_4 was 28 (100-year time horizon global warming potential) when used to convert kt CH_4 to kt CO_2eq.
- The GWP for N_2O was 265 when used to convert kt N_2O to kt CO_2eq.

4 Validation

There is a dearth of studies on GHG emissions from pesticide manufacturing at the country level or providing a global coverage. Nevertheless, a few global estimates exist for CO_2eq from pesticide manufacturing. For example, Williams *et al.* (2006) estimated that the average global carbon intensity of pesticide manufacturing was 0.069 kg CO_2eq per MJ of energy used in pesticide manufacture, as quoted in Audsley *et al*. (2009). Using this methodology herein, global emissions intensities are reported as kg CO_2eq per MJ of energy demand in pesticide manufacture from 1990 to 2020 (Table 3).

Table 3. Global CO_2eq emissions, energy use, and average emissions intensities from pesticide manufacture

Year	GHG emissions (Mt CO_2eq)	Energy demand (PJ)	Average emissions intensity (kg CO_2eq/MJ)
2000	56.9	671	0.085
2001	57.9	680	0.085
2002	57.9	686	0.084
2003	59.7	712	0.084
2004	64.0	759	0.084
2005	66.4	800	0.083
2006	65.3	796	0.082
2007	66.8	843	0.079
2008	68.2	865	0.079
2009	63.1	821	0.077
2010	69.2	895	0.077
2011	72.0	929	0.078
2012	73.7	950	0.078
2013	71.2	931	0.076
2014	72.2	947	0.076
2015	70.9	937	0.076
2016	71.6	954	0.075
2017	71.2	958	0.074
2018	68.0	923	0.074
2019	67.0	915	0.073
2020	67.2	921	0.073

Source: Authors' own elaboration.

The range of emissions intensities are consistently slightly higher than the estimates derived by Williams *et al.* (2006). However, in this methodology, estimates cover both direct (primary) and indirect energy use, whereas Williams *et al.* (2006) covered only primary energy use, as explained in Audsley *et al.* (2009). Therefore, it is reasonable that the estimates employed throughout this methodology yield slightly higher emissions intensities.

Bellarby *et al.* (2008) used energy use and emissions factors from Lal *et al.* (2004) to estimate that between 3 and 140 Mt CO_2eq were emitted globally in 2003 from pesticide production. The methodology in this paper estimates that approximately 60 Mt CO_2eq were emitted globally in 2003, which is in the middle of the range provided. The Lal *et al.* (2004) figures are presented as emissions intensities (expressed in kg CO_2eq/kg a.i.), which are defined by the year-specific emissions factors relevant at the time.

At the country level, Liang *et al.* (2021) used emissions factors from Zhang *et al.* (2016) and statistical modelling to estimate that 4–6 Mt CO_2eq were likely emitted annually from pesticide production in China between 1990 and 2016. The broad range of estimates stretched, at the high end, to around 35 Mt CO_2eq of emissions in 2010. The methodology presented herein estimates an average of about 10.5 Mt CO_2eq per year for China over that time frame. While higher than the modelled mean estimate, the country-level data determined through this methodology for China – one of the highest emitting countries, behind only the United States of America – is comfortably within the range presented in the study.

5 Uncertainties

Uncertainties when estimating GHG emissions are due to uncertainties in emission factors and activity data. They may be related to, among others, natural variability, partitioning fractions, lack of spatial or temporal coverage, spatial aggregation or modelling errors. More detailed information on uncertainties associated with applying the IPCC Guidelines can be found in the IPCC report *Good practice guidance and uncertainty management in national greenhouse gas inventories* (IPCC, 2006). In the case of industrial manufacturing, more detailed information is available in the IPCC Guidelines (IPCC, 2019).

6 Areas for advancement

One opportunity for future refinement of assessing energy input and GHG emission data from pesticide manufacturing is to rely on product-specific emissions factors rather than average emissions factors derived from groups of pesticides. Furthermore, the energy mix of each country's pesticide production processes are likely to vary significantly by country, whereas this study applies global mean estimates for the mix of naphtha, natural gas, coke, fuel oil and electricity used to produce pesticides (for each pesticide category). While the emissions factors applied for electricity use in this study are indeed both year-specific and country-specific, and electricity is the most significant form of energy across the pesticide production process, electricity use still only accounts for around 40 percent of total energy use on average. This methodology also assumes fixed energy efficiency coefficients over time, which is unlikely to capture advancements in process efficiency in the latter part of the time series. However, not all energy used in pesticide manufacturing is subject to gains in efficiency. For example, the amount of energy that is required to formulate the chemical structure of a pesticide's active ingredient, and which is ultimately embedded in the pesticide, is fixed over time.

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