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A shared socio-economic pathway based framework for characterising future emissions of chemicals to the natural environment

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ABSTRACT

Chemicals are used in all aspects of our lives and are either intentionally or unintentionally released into the natural environment, leading to chemical pollution which negatively effects biodiversity and ecosystem and human health. The world is going through socio-economic, climate and technological changes that will affect chemical emissions to the natural environment but the extent of these affects is unknown. Scenarios of future chemical emissions are therefore needed to inform research and policy decisions to protect the health of humans and ecosystems into the future. In this article, we present a framework, based on Shared Socio-economics Pathways (SSPs) in combination with Representative concentration pathways (RCPs), to develop future chemical environmental emissions scenarios for single molecules or groups of chemicals sharing similar features. The framework has 4 steps: 1) determination of the characteristics of the scenario; 2) review and prioritisation of socio-economics and climate drivers; 3) development of scenarios; and 4) consistency checks. The framework is demonstrated for antidepressant and insecticide emissions into European freshwater-systems in 2050. Output narratives provide multiple pathways of chemical emissions in the future and can be used by researchers, regulators, politicians, governments, and the private sector to develop mitigation and adaptation strategies to chemical pollution issue.

1. Introduction

Chemicals are used in all aspects of our lives including as pesticides in agriculture, pharmaceuticals for health care, preservatives for processed food, personal care products for hygiene and well-being, and flame-retardants for textiles (CEFIC, 2021). During production, usage, and disposal, chemicals are released into the environment either intentionally e.g. via the application of agrichemicals to crops or unintentionally e.g. via urban run-off or from wastewater effluent when chemicals are not effectively removed by wastewater treatment plants (WWTP) (Burns et al., 2018; Domercq et al., 2018). The negative effects of chemicals in the environment

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are well documented including: depletion of the ozone layer by compounds used as refrigerants; feminisation of fish by endocrine disrupting chemicals; selection of antimicrobial resistance by antibiotics; accumulation of heavy metals in fish tissues; and biomagnification of brominated compounds through food chains resulting in human exposure via the diet (Aslam et al., 2018; Baldigo et al., 2006; Dong et al., 2014; Roy et al., 2018; Thompson & Darwish, 2019; Zhang et al., 2018). The effects of chemical pollutants could alter in the future as a result of societal changes in response to global megatrends such as climate change and urbanisation (Balbus et al., 2013; Hader et al., 2022; Redshaw et al., 2013). However, the extent of changes in emissions, which will drive the effects, is currently unclear.

Chemical consumption has doubled in volume in the last decades (United Nations Environment, 2019). This increased usage has resulted in a range of benefits. For example, advances in the development of medicines, technology and health care have drastically modified the world. The number of people suffering from hunger, poverty and disease has reached unprecedented low levels and, for the wealthiest countries, living standards have never been higher (United Nations Development Programme, 2019). However, societal changes happen rapidly and affect consumption and emissions of chemicals (Bunke et al., 2019) so in the future the use of chemicals will likely increase further.

For example, despite increased human development, the prescriptions and consumption of antidepressants are continuously increasing in developed countries and are expected to be exacerbated by natural disasters in the future (Exeter et al., 2009; Gualano et al., 2014; Olié et al., 2002; Redshaw et al., 2013; To et al., 2021). Pesticides have experienced a rapid shift in usage in the last 60 years. Pesticides use has increased by 15–20-fold since the 60 s to increase food production and respond to global food demand (Oldenkamp et al., 2019). Because they are very toxic chemicals which may affect human health and the environment, pesticides frequently receive negative media coverage in some public debate (Le Monde, 2022; Newsbeat, 2022; Rani et al., 2021). However the pressure to meet food demands for the 9 billion inhabitants predicted by 2050 (Finger, 2021; Popp et al., 2013) will mean that pesticide could continue to increase. Changes in consumption will lead to changes in emissions, exposure and risks to the natural environment. For instance, the risk posed by antibiotic ciprofloxacin to aquatic species has increased by 10–20 fold worldwide in twenty years because of increasing exposure (Oldenkamp et al., 2019). Future societal changes will therefore affect the number, the quantity and the diversity of chemicals and subsequently chemical risks in different ways.

Few societal changes have been studied to determine their impact on chemical emissions. Advanced technologies for wastewater treatment can decrease the load of chemicals released in water bodies (Fairbairn et al., 2018; Yaman et al., 2017); legislation and regulation can limit the number of compounds available on the market (van Dijk et al., 2020); chemical engineering can create genetically modified crops (GMO) that reduce the number and volume of fertilisers and pesticides used by farmers (Klümper and Qaim, 2014). At the same time, new chemicals designed to satisfy specific needs can also be more persistent and more dangerous for the environment (e.g. perfluorooctanoic acid); GMO crops can promote resistant pests that will require stronger and potentially more toxic pesticides (Van Acker et al., 2017). The societal changes (including socio-economic factors such as human development, urbanization, demographics change, inequalities, international agreements, economic growth, diets, etc) have not been studied altogether to estimate their potentials effects on chemical emissions for the future. Potentially important trends in future environmental emissions may be missed if all aspects of societal changes are not considered. This also means that mitigation and adaptation strategies to deal with future chemical pollution are based on incomplete evidence.

One approach to inform the research and management of chemical emissions in the future under global change is to use scenarios. Scenarios explore multiple alternative futures with the aim of evaluating strategies to respond to any potential adverse changes (Jones et al., 2015). A very influential set of recent scenarios are the representative concentration pathways -RCPs- (van Vuuren et al., 2011) and the shared socio-economic pathways -SSPs- (O'Neill et al., 2017), developed by the global climate change research community. The SSPs describe five contrasting socio-economics pathways with their abilities to adapt and mitigate to global change challenges. They are based on six categories: demographics, human development, economy and lifestyle, policies and institutions, technology and environment and natural resources. Each category is further detailed with SSP elements like, among others, population growth, fertility and urbanisation for demographics or education, health investment and equity for human development. For each SSP storyline, a socio-economic situation is described with variation of SSP elements (e.g. health investment is high under SSP1 and low under SSP3). They are meant to be used as baselines for climate change and sustainable development research. SSPs are made to serve the global climate change community, but they are also designed to be extended to multiple sectors and scales and improve consistency with all global change-related research. Different sectors and geographic scales, including land-use management in central Asia, European agriculture or more recently the United Kingdom, have downscaled scenarios based on the SSPs to explore the impacts of future climate conditions (Mitter et al., 2020; Nunez et al., 2020; Pedde et al., 2021). Scenario development and scenario extensions are a relatively recent area of research, but the number of scenario studies has increased rapidly in recent years. An article looking at achievements of the climate change scenario framework reported 1400 articles that used and/or developed scenarios based on SSPs since 2010 (O'Neill et al., 2020). Nevertheless, such scenarios have not yet been developed for emissions to the environment from the chemical sector.

Ideally, global SSP scenarios would be extended to all the chemicals within the chemical sector. The research community focusing on chemical emissions in the future could then work under the same storylines and extend those scenarios to more specific research questions if needed. To do so, key drivers and relevant scale for all chemicals must be defined. This is not possible as key drivers and relevant scale vary between and among groups of chemicals. A single set of narratives cannot adequately cover all chemicals because of the diversity of chemicals' physical and chemical properties, environmental behaviour, human usage and future needs for society.

To be able to study chemicals in the future, here, we present a framework, based on the socio-economic and climate scenarios (combined SSP-RCPs), for the development of scenarios for emissions of single chemicals or groups of similar chemicals to the natural environment in the future. 'Chemicals', being a heterogeneous group, do not have the same drivers of emissions and relevant study scales for all classes. A 'simple' extension of SSPs cannot, therefore be made, the thematic focus of scenarios developed must be for single chemicals or groups of similar chemicals. We therefore illustrate the approach for antidepressant and insecticide emissions in Europe in the 2050 s

Antidepressants and insecticides were chosen for multiple reasons. Their usage is reported to come from different drivers in the literature. On one hand, antidepressant usage is driven by sociodemographic drivers like education, social cohesion, inequalities and/or culture (Gomez-Lumbreras et al., 2019; Henriksson & Isacsson, 2006; Hiilamo, 2014; Lewer et al., 2015; Park et al., 2018). On the other hand, usage of insecticides can be driven by cultural practices (e.g. type of crops, crops rotation, conventional vs. non-conventional practices), regulations, technology development but also by consequences of climate change like increase temperature or increase rainfall (Bloomfield et al., 2006; Brookes & Barfoot, 2018; Meissle et al., 2010; Rhodes & McCarl, 2020; Wan et al., 2018). Consumption has consistently increased in the last 50 years and is expected to continue. However, looking at SSPs storylines, the changes in antidepressants and insecticides' emissions in the future are uncertain. Global changes that are projected to occur over the next 30 years could have an effect on antidepressant and insecticide consumption and, therefore, on emissions into the environment. These future emissions must be understood in order to assess future risk and mitigate their impacts.

Here we propose a four-step framework, inspired by the approach developed by Mitter et al. (2019) for the European agricultural sector, and apply it to antidepressants and pesticides to demonstrate the framework's utility as a tool to gain a better understanding of future chemical emissions and the way that societal change influences this future.

2. Methods

a group of eight scientists with expertise in scenario developments, in environmental sciences, in chemistry and in toxicology gathered to develop the following four-step framework to characterise chemical emissions in the future under the SSPs. The framework proposed is inspired by the methodology developed by Mitter et al. (2019) to European SSPs to Agricultural European SSPs and follow standard methodologies for scenario development (O'Brien, 2004; Priess & Hauck, 2014; Rose & Star, 2013; Rounsevell & Metzger, 2010).

2.1. Step 1: Define key characteristics of scenarios

The first step focuses on the determination of key characteristics of the scenarios required. This is an essential step to have a clear understanding of the specifications and boundaries of the scenarios, as well as to answer "why", "for whom" and "how" are those scenarios being developed. The following questions should be addressed:

- **What is the goal and purpose of the scenario**? the goal and purpose of the scenarios must be determined: Why are the scenarios needed? What are the questions we want to answer with the output from the scenarios?
- **Which chemical or group of chemicals is being investigated?** The chemical or group of chemicals for which the scenarios are to be applied should be defined. Multiple chemicals/molecules could be considered as one group of chemicals for scenario development if molecules have the same dynamics in the society, environmental behaviours and fates within the temporal and spatial scale chosen further in step 1. If a group of chemicals is to be considered, similarities in production, usage, consumption and environmental behaviours are mandatory. Here, we want to avoid selecting multiple chemicals that would be impacted by socio-economic drivers in different ways, making the development of a scenario storyline for all chemicals included impossible.
- **Which environmental matrices are being considered?** Do the scenarios focus on air, water, or soil compartments? We recommend to only select one matrix as chemicals can behave differently in different environmental compartments.
- **What temporal scale is required?** Are the scenarios focusing on future of chemicals in 2030, 2050, 2100 etc?
- **What geographical scale is required?** Are the scenarios focusing on a city, a country or a continent? Urban environments? Urban environments in developed countries? A small geographical scale involves an easier understanding of the dynamics of the system, but literature can be limited on the system in question. Moreover large scale SSPs might be more difficult to extend because they are not specific enough for smaller scale systems. A large geographic scale has more chances to have available SSPs (e.g. Europe, United Kingdom), but the system might be more difficult to understand and to apply to a chemical or group of chemicals. Determination of temporal and spatial scale are necessary to define the system boundary in which scenario will be develop and should be primary determined by the goal and purposes of the scenarios.
- **How many and which SSPs need to be explored?** There are multiple SSPs that are available in the literature: global SSPs, European SSPs, water-sector SSPs, drought characteristics in China SSPs to cite a few (Graham et al., 2018; Kok et al., 2019; Riahi et al., 2017; Su et al., 2021). Depending on the characteristics of the scenarios wanted, the most relevant and logical SSPs should be selected for use. The number of scenarios can range from a minimum of two scenarios to five (all SSP scenarios). A single scenario should not be developed by itself, as it should be comparable to another.
- **Which climate projections should be explored?** The use of many chemicals will be affected by weather conditions such as temperature, moisture content and flood events. For the system of interest, therefore, projections of future weather patterns associated with the selected SSPs should be obtained to provide a foundation for identifying any climate-driven changes in chemical use during Step 2.
- **Who is the target audience**? The targeted audience can be climate change scientists, social scientists, regulators, industries, public, etc. The format of the scenarios and the level of detail should be relevant to the knowledge and needs of the targeted audience.

– **What will be the form of the scenario**? How will the scenario look: an infographic? a set of storylines? a table with increasing and decreasing chemicals trends? Output scenarios can have any format, but must be relevant to the scenario's goal, purpose and targeted audience.

2.2. *Step 2: Review and prioritisation of the potential impacts of changes in socio-economic and climate on chemical emissions*

In step 2, a combination of literature searching and expert elicitation is used to develop an evidence-base on how chemical emissions could change in the future. This analysis considers: a) the socio-economic changes expected for the selected SSPs from Step 1; and b) the effects of projected changes in weather patterns on chemical use. The findings from the systematic review are then used in an expert consultation exercise to select the most important future changes for chemical emissions which are then used as a basis for the emission scenario development in Step 3.

These drivers can be related to socio-economics elements (similar as SSP elements in O'Neil et al., 2017) or climate change elements (e.g. natural disasters, temperature). The idea here is to understand how the thematic focus is influenced in a society and to develop a list of drivers by conducting a systematic review. We recommend using the elements of the SSPs to extend chosen to extend in step 1.

To do the systematic review, we recommend using the elements of the SSPs initially chosen in step 1 to extend as specific search terms. The driver(s) and findings should be extracted from the articles. We found that the search terms "association", "impact", "influence", "effect" and "connection" might extend search results to a large number of relevant articles when looking for dynamic/ interactions between drivers and the thematic focus. Direct (e.g. leakage from production site; release from road runoff) and indirect drivers (e.g. consumption; outbreaks of diseases) should be considered in the systematic review.

For some chemicals, climate change driven effects will need to be considered alongside socio-economic driven effects. For example, use of UV-filter molecules in sunscreens might be expected to increase due to projected increases in hot and dry weather. Increased pest disease pressures resulting from changes in climate could alter the use of insecticides, herbicides and fungicides. As climate change has multiple possible future outlooks, selection of climate change scenario is needed. Representative Concentration Pathways (RCPs) provide estimations of plausible future changes in greenhouse gas emissions, that translate into a different range of temperature and precipitation outputs. We recommend using RCPs for climate change integration as SSPs and RCPs can be combined in a scenario matrix architecture (van Vuuren et al., 2017). These 'integrated scenarios' help to understand the combined effect of socio-economic change and climate change. Relevant RCPs and related climate change impacts should be chosen and integrated in the same way as SSPs in the scenarios.

Because not all aspects of a society have been researched with respect to chemicals, relevant literature is limited. To enrich the comprehension of the thematic focus dynamic in a society and the list of drivers of the SSPs to extend and the thematic focus should be analysed one by one. The elicitation of experts' judgement is encouraged. This allows the inclusion of multiple perspectives and opinions on the thematic focus in a society. Expert judgements can be solicitated in multiple ways (e.g. personal interview, group interviews, development of fuzzy cognitive map, survey) depending on cost and logistical limitations. If an SSP element is considered relevant to the thematic focus by scenario developers and/or experts, then it should be added to the list of drivers.

When the systematic review is done, prioritisation or determination of key drivers is recommended. Drivers (direct and indirect) do not have the same importance to the thematic focus. Two methodologies are recommended here:

– Scenario developers can conduct a qualitative synthesis based on literature review and, if applicable, experts' input to determine which drivers are key drivers for scenario development. A criterion could be 'a driver that influences the consumption of chemical "x" is more relevant than a driver influencing the production of "x"'.
– Experts' judgements can also be solicitated to define key drivers using the same methodologies as mentioned before. A survey to experts with specific questions (e.g. Do you consider this driver to have a high, medium or low influence on the thematic focus?) could be used to identify key drivers. Experts' time involvement is then limited, and experts are free to complete the survey on their own time.

2.3. *Step 3: develop chemicals emissions scenarios*

This step of the framework is focused on the development of scenarios. We recommend doing it in two parts. The first part is to focus on each key driver and each scenario at a time. The second part is to gather all the effects of drivers, consider the drivers' direct and indirect impacts on the thematic focus and propose an overall effect on the thematic focus.

For the first part, each key driver is studied individually. For each key driver, an impact on the thematic focus must be defined following 3 steps:

A. Gather outputs from the literature review and experts' judgements from step 2 for the chosen driver
B. Identify how the driver is said to change/be in the SSP to extend in step 1 (e.g. in SSP1, the world population increases until 2100)
C. Propose an impact of the driver on the chemical or group of chemicals. The impact could be qualitative (e.g. increase/decrease) or semi-quantitative (e.g. small/medium/high increase). The proposed-impact should be consistent with the findings from literature review and with how the driver is said to change/be in the SSPs. The reasoning should be rational. The following statements should be verified:
    1. The driver's proposed-impact is consistent with the findings on how the driver impacts the thematic focus in the literature review

2. The driver's proposed-impact is consistent with the literature review and with how the driver is said to change in the SSPs to extend
3. The proposed-impact can be explicate by rational thinking

For the second part, drivers direct or indirect impact on the thematic focus must be explained. For example: "*Changing population size does not have a direct impact on the emissions of chemical X in the environment, however changing population size impact consumption of chemical of X. Increase consumption of X is found to be positively correlated to emissions of X in the environment. Therefore for the development of our scenario we consider population size to be an indirect driver positively correlated to emissions of chemical X in the environment*" When all driver's impacts on the thematic focus are explicit, an overall effect can be proposed and presented in the format chosen on step 1.

2.4. Step 4: consistency checks

This last step aims to check consistency and to assure quality control of the developed scenarios. For this step, the scenario products developed are checked for consistency with the systematic review and with the SSPs. Consistency with the systematic review consists of verifying that a driver's dynamic in the environment and in the society are the same across the literature and scenario developed. For consistency with the SSPs, driver's evolution must be similar across SSPs chosen to extend in step 1 and in scenario developed (e.g. if population side increase in SSP1 chosen to extend, population side must decrease in the scenario developed). Conducting these consistency checks multiple times is essential for quality control of the scenario development process (Priess & Hauck, 2014). When time and financial resources permit, we recommend to conduct consistency checks with experts (Ernst et al., 2018; Mitter et al., 2019). Consistency checks can also be done by scenario developers by repeating and verifying step 3 multiple times.

2.5. Uncertainties

There are uncertainties when scenarios are developed. Uncertainties can arise around lack of system understanding of the thematic focus, on the thematic focus within a society and on the study of the future that is fully unknown.

In step 2, uncertainties can arise around lack of understanding on how chemicals behave in the environment or a society. This could be due to lack of data availability or literature on the chemical in question but also on the dynamics of a society. or general.

In step 3 of our framework, the SSPs' storyline and other products must be interpretated for the development of chemical emissions scenarios (e.g. population growth increases strongly). Vagueness and ambiguity of scenario terminologies make interpretations of SSPs different between researchers. Techniques to address these uncertainties can be to increase the number of scenarios to develop, to perform sensitivity analysis or to solicit experts (Gao et al., 2016; Rounsevell et al., 2021). The advantage of involving experts is to build consensus on uncertainties, but also to discuss and obtain diverse expertise on the chemical focus, allowing an improved understanding. Uncertainties should not deter the development of scenarios but should be considered in output scenario interpretations. (Fig. 1).

3. Results

The framework is illustrated for two case studies: antidepressants and insecticides emissions in European freshwater systems in 2050. The methodology followed is the same as the one presented previously except that exploratory reviews were conducted instead of systematic reviews. Moreover uncertainties on scenario developed were not investigated. The reasons are that fully developed scenarios for antidepressants or insecticides would require individual articles with more extensive reviews and engagement with experts. This does not impact the aim of this section which is to illustrate how the proposed framework can be applied.

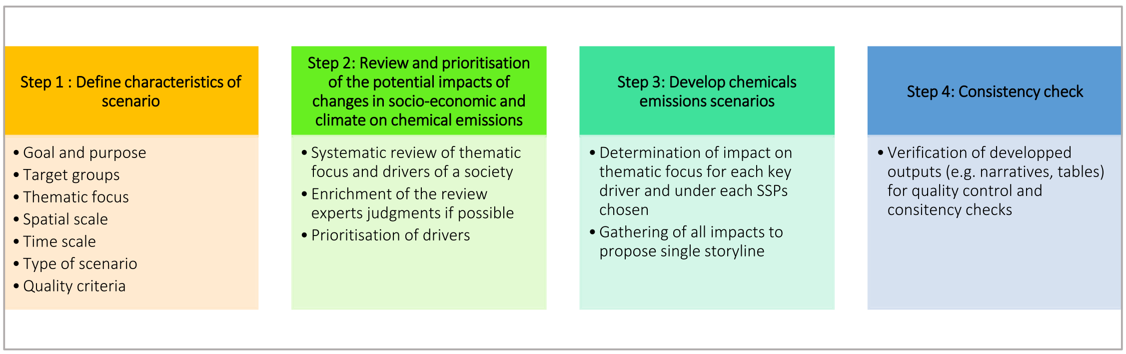

Fig. 1. Framework proposal to extend SSPs storylines to single chemicals emissions or group of chemical sharing similar features.

Table 1
Exploratory review or antidepressants with socio-economics and climate drivers.

Category	Driver (s) studied in article	Article's findings	Source
Demographics	Age	*Antidepressant use increased for non-elderly adults age 18–64 and the elderly age 65 and older but not for children under 17 between 1997 with 2002 for U. S. Civilian Noninstitutionalized Population.*	Stagnitti (2005)
Demographics	Gender	*Increase in the use of antidepressants by both males and females between 1997 and 2002 for U.S. Civilian Noninstitutionalized Population*	Stagnitti (2005)
Demographics	Gender	*Association between the use of antidepressants and mental health did not vary substantially between men and women.*	Van der Heyden et al. (2009)
Demographics	Gender	*From 2009–2010 through 2017–2018, the percentage of adults who used antidepressants increased among women, but not men.*	Brody and Gu (2015)
Demographics	Migration	*Immigrants with depression initiate antidepressants more often than the Finnish-born population, but they also discontinue them earlier.*	Kieseppä et al. (2022)
Demographics	Urbanisation	*Higher rates of antidepressant use among patients living in urban compared with rural communities.*	Leventhal Perek, Thomas, Gaver, Matalon, and Yeshua (2019)
Human development	Social cohesion	*Beliefs that mentally ill people are 'dangerous' were associated with higher use. Individual beliefs such as they will 'never recover' or 'have themselves to blame' associated less regular use of antidepressants.*	Lewer et al. (2015)
Human development	Social cohesion	*Belief in the harmfulness of antidepressants is associated with a general lack of exposure to depression, leading to an underestimation of its seriousness and of the necessity for intervention.*	Jorm, Christensen, and Griffiths (2005)
Human development	Social cohesion	*Drug use as a treatment in people with a psychiatric disorder can be interpreted from different points of view according to cultural characteristics that could play a decisive role in people's opinion, physicians and patients, regarding these diseases and in their decision regarding the use of antidepressants.*	Gomez-Lumbreras et al. (2019)
Human development	Social cohesion	*Antidepressant consumption increased drastically between 2000 and 2011, from 8.18 to 36.12 DDD per 1000 inhabitants per day because of less stigmatized by public opinion of mental health diseases.*	Gualano et al. (2014)
Human development	Education	*No differences in the consumption of antidepressants have been found between the North and South of Europe.*	Gomez-Lumbreras et al. (2019)
Human development	Education	*Antidepressant use was higher among non-Hispanic white (16.6 %) adults compared with non-Hispanic black (7.8 %), Hispanic (6.5 %), and non-Hispanic Asian (2.8 %) adults.*	Brody and Gu (2015)
Human development	Education	*Antidepressant use increased for white non-Hispanics, other non-Hispanic and did not change significantly for black non-Hispanics or Hispanics between 1997 with 2002 for U.S. Civilian Noninstitutionalized Population.*	Stagnitti (2005)
Human development	Education	*A trend towards a greater prescription of antidepressants and fewer suicides after an educational programme on depression.*	Henriksson and Isacsson (2006)
Human development	Access to healthcare	*Increases for both insured and uninsured persons between 1997 with 2002 for U.S. Civilian Noninstitutionalized Population.*	Stagnitti (2005)
Human development	Access to healthcare	*Higher healthcare access associated with regular use of antidepressants.*	Lewer et al. (2015)
Human development	Socio-economic status; Access to health	*Healthcare and educational workers in Denmark are at increased risk of depression and that this risk is partly mediated by the high emotional demands of the work.*	Madsen, Diderichsen, Burr, and Rugulies (2010)
Exceptional event	Exceptional event	*Antidepressant prescribing in general practice substantially increased, whereas the number of people in contact with adult mental health services, and the number of referrals to those services decreased in the UK in 2021 (COVID) compared to 2015.*	Armitage (2021)
Exceptional event	Exceptional event	*Since March 2020, the number of patients reimbursed weekly for antidepressants has increased compared to the period from January 2015 to February 2020 (COVID).*	Levaillant et al. (2021)
Economics and lifestyle	Economy	*Consumption of antidepressants increases in Greece since the economics crisis.*	Madianos, Alexiou, Patelakis, and Economou (2014)
Economics and lifestyle	Economy	*The unemployed and the employed with job insecurity not only have worse mental health and, consequently, a higher need for care, but also report a higher use of mental health care and antidepressants.*	Buffel, Dereuddre, and Bracke (2015)
Climate change	Extreme event - Flooding	*There was an increase of 0.59 % (95 % CI 0.24–0.94) prescriptions in the postflood year among practices located within 1 km of a flood over and above the change observed in the furthest distance band. The increase was greater in more deprived areas.*	Milojevic, Armstrong, and Wilkinson (2017)
Climate change	Extreme event - Flooding	*With a relative risk (RR) of 1.54 (95 % CI, 1.39–1.62) corresponding to an estimate of 409 new deliveries of psychotropic drugs during the three weeks following the storm, this study confirms the importance of the psychological impact of Xynthia. This impact is seen on all three classes of psychotropic drugs studied. The impact is greater for tranquilizers (RR of 1.78; 95 % CI, 1.59–1.89) than for hypnotics (RR of 1.53; 95 % CI, 1.31–1.67) and antidepressants (RR of 1.26; 95 % CI, 1.06–1.40). The RR was higher for females than for males.*	Motreff et al. (2013)

(*continued on next page*)

Table 1 (*continued*)

Category	Driver (s) studied in article	Article's findings	Source
Climate change	Extreme event - Heatwaves	*While only incremental increases in morbidity and mortality above previous findings occurred in 2008, health impacts of the 2009 heatwave stand out. These findings send a signal that the intense and long 2009 heatwave may have exceeded the capacity of the population to cope.*	Nitschke et al. (2011)
Climate change	Extreme event - Wildfires	*The results show an increased rate of PTSD, depression, and generalized anxiety at several times of follow-up post-wildfire, from the subacute phase, to years after. An increased rate of mental health disorders post-wildfire has been found in both the adult and pediatric population, with a number of associated risk factors, the most significant being characteristics of the wildfire trauma itself.*	To et al. (2021)
Climate change	Global change	*Mental health impacts represent both direct (*i.e. *heat stress, exposure to extreme weather events) and indirect (i.e. economic loss, threats to health and well-being, displacement and forced migration, collective violence and civil conflict, and alienation from a degraded and potentially uninhabitable environment) consequences of acute, subacute and long lasting climate-related events.*	Palinkas and Wong (2020)
Multiples	Age; Gender	*Antidepressants use is higher in women than in men, and increases progressively with age in both sexes.*	Gomez-Lumbreras et al. (2019)
Multiples	Age; Gender	*Antidepressant use increased with age, overall and in both sexes—use was highest among women aged 60 and over (24.3 %). During 2015–2018, 13.2 % of adults aged 18 and over used antidepressant medications in the past 30 days. Use was higher among women than men.*	Brody and Gu (2015)
Multiples	Age; Education	*Disbelief in the medical model of depression and family shame reduced willingness to use mental health counseling and antidepressants in older population in Korea.*	Park et al. (2018)
Multiples	Urbanisation; Environment	*Antidepressant medication has strong associations with neighborhood conditions including socioeconomic satisfaction and the seasonality of particulate matter under 2.5 μm in the air.*	Lee, Kim, and Ham (2022)
Multiples	Urbanisation; Education	*Lower rate of antidepressant use was found in urban and rural Arab-majority communities.*	Leventhal Perek et al. (2019)
Multiples	Urbanisation; Age	*Associations of neighbourhood socioeconomic and physical characteristics with older people's antidepressant use were small and inconsistent.*	Tarkiainen et al. (2021)
Multiples	Age; Socio-economics status	*Antidepressant medication use was higher for adults with at least some college education compared with those with a high school education or less.*	Brody and Gu (2015)
Multiples	Gender; Education	*In men, antidepressant treatment was less common among low educational groups than among high educational groups'. 'In women, socio-economic position was not associated with antidepressant use.*	Kivimäki et al. (2007)
Multiples	Gender; Socio-Economics Status	*Use of antidepressants was significantly associated with female gender, higher socioeconomic status, and unemployment in Rio Grande do Sul State in Brazil in 2006.*	Garcias et al. (2008)
Multiples	Socio-economic status; access to health	*Socioeconomically disadvantaged respondents reported greater antidepressant use than those who were not classified as disadvantaged. These findings suggest Australia's universal health-care system does promote equitable health care across the population.*	Butterworth, Olesen, and Leach (2013)
Multiples	Age; Gender; Inequalities	*More young adult females used antidepressants in municipalities where relative poverty had increased. Fewer elderly females used antidepressants in municipalities where the Gini index (calculating distance between the richest and the poorest) increased. More young adults used antidepressants in municipalities where the number of those not being educated or trained had increased.*	Hiilamo (2014)
Multiples	Age; Gender; Social cohesion	*An increase in the number of persons over 65 years of age living alone was positively associated with an increase in the use of antidepressants among elderly females.*	Hiilamo (2014)
Multiples	Age; Gender; Education	*In this elder sample, taking into account depressive symptom severity and other confounds, antidepressant use is nearly half as likely among men and African Americans.*	Grunebaum, Oquendo, and Manly (2008)

3.1. Antidepressants emissions at European scale for 2050 (Eur-Ant-SSPs)

Antidepressants are regularly detected in European fresh water monitoring campaigns, mostly in urban environments where consumption is high and waste water treatment does not effectively remove this type of molecule (Metcalfe et al., 2016; Wilkinson et al., 2022). Traces of antidepressants in the aquatic environments threaten aquatic ecosystems by altering swimming and cryptic behaviours of invertebrates and behaviour and the development and reproduction of aquatic vertebrates (Sehonova et al., 2018). Global changes that are projected to occur in the next 30 years will likely affect antidepressant consumption and therefore, emissions into the environment. These future emissions must be understood in order to assess future risk and mitigate their impacts. Here, we develop antidepressant emissions scenarios under global change.

3.2. Step 1: Define characteristics of scenarios of Eur-Ant-SSPS

The characteristics of the chemical emissions scenario wanted were developed:

- **What is the goal and purpose of the scenario?** Extend European SSPs (Kok et al., 2019) to antidepressant emissions to envision multiple scenarios of antidepressant emissions in 2050
- **Which chemical or group of chemicals is being investigated?** Within the EU market, antidepressants currently available, antidepressants currently developed but not registered yet and future antidepressants molecules developed under the green chemistry framework by Ganesh et al. (2021)
- **Which environmental matrices are being considered?** European freshwater aquatic systems
- **What spatial scale is required?** Europe
- **What temporal scale is required?** 2050
- **How many and which SSPs needs to be explored?** European SSP1 (Eur-SSP1), SSP4 and SSP5 (Kok et al., 2019). Eur-SSP1 is selected to study antidepressant emissions in a sustainable society with less resource-intensive lifestyles, high human investment and high social cohesion. Eur-SSP4 and Eur-SSP5 are selected to study antidepressant emissions in nuanced societies with high inequalities in human development and some environmental considerations in Eur-SSP4, and intensive lifestyle with high human investment and high environmental considerations for Eur-SSP5.
- **Which climate projections should be explored?** Climate change impacts human mental health in multiple ways in the literature. Increased temperature could lead to more aggressive behaviour and extreme events to stress-related psychiatric disorders (Padhy et al., 2015). The consumption of antidepressants among practices located within 1 km of a flood areas increased compared to further distance lands (Milojevic et al., 2017). Climate change-related declining/changing societies affect mental health with more psychiatric disorders (e.g. ecoanxiety, post-traumatic events stress, depression, survivor guilt) (Cianconi et al., 2020; Hayes et al., 2018; Palinkas & Wong, 2020). The impacts of climate change is therefore considered for antidepressants emissions scenarios. Climate change is considered and integrated with RCP 4.5, 6 and 8.5 combined with Eur-SSP1, Eur-SSP4 and Eur-SSP5 respectively.
- **Who is the targeted audience?** Scientists from the climate change research community like eco-toxicologists, chemists and social scientists working at European scales.
- **What will be the form of the scenario?** Tables with antidepressants trends for each key driver and qualitative storylines assessing the overall effects of the set of drivers for each scenario.

Table 2
Eur-Ant-SSP1, Eur-Ant-SSP4 and Eur-Ant-SSP5 antidepressant emissions scenarios for Europe for the year 2050 for each key drivers defined.

SSPs drivers	SSPs sub-drivers	Eur-SSP1[1] and other SSPs	Eur-Ant-SSP1	Eur-SSP4[1] and other SSPs	Eur-Ant-SSP4	Eur-SSP5[1] and other SSPs	Eur-Ant-SSP5
Demographics	*Population Growth*	Relatively low growth [2]	↗	Low growth [2]	↗	Relatively low growth [2]	↗
Economy and lifestyle	*Inequalities*	Reduced across and within countries [2]	↘	High, especially within countries [2]	↗	Strongly reduced, especially across countries [2]	↘
Environment and natural ressources	*Urbanization*	High and well-managed [2]	↘	Medium with mixed urbanisation type across and within cities [2]	↗	High with a better management over time [2]	↗
Human development	*Economy*	Gradual (with hiccups at the beginning) [1]	↘	High [1]	↗	High [1]	↗
	Social participation	High for rich OECD countries [2]	↘	Low for rich OECD countries [2]	↗	High for rich OECD countries [1]	↘
	Social cohesion	High [1]	↘	Low [1]	↗	High [3]	↘
	Healthcare investment	High [3]	↗	High for elites, medium for lower class [3]	↗	High [3]	↗
	Healthcare access	High [2]	↗	Medium [2]	↗	High [2]	↗
	Education	High [1]	↘	High for elites, medium for lower class [1]	↗	High [1]	↘
Technology	*Development*	High, but no pervasive [1]	↘	High in some areas; low in labour intensive areas [1]	↘	Strong and crucial [1]	↘
Climate Change	Extreme events	RCP-4.5–6: droughts and floods increase [3]	↗	RCP6: droughts and floods increase [3]	↗	RCP-8.5: droughts and floods increase [3]	↗

1 Kok, K., Pedde, S., Gramberger, M. et al., (2019) New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. Reg Environ Change 19, 643–65.
[2] Brian C. O'Neill, Elmar Kriegler, Kristie L. Ebi, et al., (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, Volume 42, 169–180.
[3] Tabari, H., Hosseinzadehtalaei, P., Thiery, W., & Willems, P. (2021). Amplified Drought and Flood Risk Under Future Socioeconomic and Climatic Change. Earth's Future*, 9(10), e2021EF002295*

3.3. Step 2: Review and prioritisation of the potential impacts of changes in socio-economic and climate on chemical emissions

An exploratory review was conducting using the Scopus search engine. The search terms “antidepressant” in combination with Eur-SSPs drivers’ elements. 51 articles were identified. Further targeted searching was conducted when cited literature yielded relevant peer-reviewed articles. Articles were kept if they confirmed the following statements: 1) the article focuses on change in trends in antidepressants use/consumption; 2) the change in antidepressants trends is related to a socio-economics, technological or climate change; 3) the article does not focus on people with medical pre-conditions; and 4) the article focused on Europe, a country in Europe or a society similar in socio-economic development as Europe. In total, 23 relevant articles were kept. Articles covered primally drivers related to demographics and human development change. The driver(s) studied and their impacts on antidepressant were extracted from each article and presented in Table 1.

To prioritise drivers, nine experts on chemical emissions from academia were solicited. Based on the exploratory review provided and their expertise, experts were asked to assign a priority (high, low or uncertain) for all SSPs elements of Kok et al. (2019) and climate change drivers. If 70 % of experts defined a driver as “high” priority, the driver was considered key and selected for scenario development. For antidepressants emissions, 11 key drivers were identified: population growth, inequalities, urbanization, economy, social participation, social cohesion, healthcare access, healthcare investment, education, technology development and extreme droughts and floodings events (see Table S1). Those drivers were studied exclusively in step 3 to develop emissions scenarios.

3.3.1. Step 3: Develop chemicals emissions scenarios

Prioritised drivers of antidepressants emissions in European aquatic freshwater systems selected in step 2 were studied individually. An emissions trend (increasing, decreasing or both) was proposed for each prioritized driver. Each driver’s individual future trend is presented in section 3.1 and in Table 2, and output scenario storylines are presented in the section 3.2. Note that because of time and financial restrictions and because these scenarios storylines were mostly developed to illustrate the framework, step 3 was developed using desk-based research conducted by the authors.

3.3.2. Step 3.1 Antidepressants emissions trends by priority drivers in Eur-Ant-SSPs

The 11 prioritised drivers were studied one at a time based on results from the exploratory review, historical data and storylines from Eur-SSPs (Kok et al., 2019). If a key driver has no specific indication in Eur-SSPs (e.g. “Inequalities”), storylines provided in global SSPs for Rich-OECD countries (high-income countries – GNI per capita above $13 205 – according to the World Bank) was used (O’Neill et al., 2017; WBD, 2022). When considered relevant and useful for the general understanding of antidepressant emissions in a society, effects of key drivers were extended to mental health or depression by desk-based research.

3.4. Population growth

The total European population was 738 million in 2010. European population growth is estimated to increase in SSP1 (up to 769 million) and SSP5 (847 million) and to decrease in SSP4 (716 million). Based on historical data, we concluded that antidepressants emissions is positively correlated to population growth, therefore antidepressants emissions increase in Eur-Ant-SSP1 and Eur-Ant-SSP5 and decreases in Eur-Ant-SSP4.

3.5. Inequalities

In Global SSPs, inequalities were found to be “reduced across and within countries” in SSP1, “high, especially within countries” in SSP4 and “strongly reduced, especially across countries” in SSP5. Correlations between inequalities and antidepressants or mental health can be difficult to interpret as inequalities can cover poverty, unequal career opportunities or unequal access to education among others. The consensus though is that higher inequalities is correlated to low mental health (Murali & Oyebode, 2004; Yu, 2018) and indirectly to antidepressant consumption. We concluded that in Eur-Ant-SSP1 and Eur-Ant-SSP5, because inequalities decrease, antidepressants emissions decrease. In Eur-Ant-SSP4, we concluded that antidepressants increase.

3.6. Urbanisation

Urbanisation is high and well-managed in global SSP1, medium with mixed type of urbanisation across and within cities in SSP4 and high and better managed over time in SSP5. Dynamic between urbanisation and antidepressants or/or mental health is unclear from the literature. Some articles showed that antidepressant use was higher in urban environments (Leventhal Perek et al., 2019). Another study found that rural individuals are at increased risk to suffer from depression than people living in urban environments (Wang et al., 2019). The type and quality of urbanisation also influences mental health (Triguero-Mas et al., 2015; Wheeler et al., 2015). For Eur-Ant-SSP1 and Eur-Ant-SSP5, because urbanisation increases with environmental considerations and desire for better management, we concluded that antidepressants emissions decrease. In Eur-Ant-SSP4, because of the infrastructure inequalities and the lack of consideration for the environment, we concluded that antidepressants emissions increase.

3.7. Economy

Economy development in Eur-SSPs increases gradually in SSP1 and is defined as a “high economy” in SSP4 and SSP5. Exploratory review showed that high economy in terms of high employment and job security is correlated with less antidepressant consumption compared to unemployed or employed with no job security (Buffel et al., 2015). For Eur-Ant-SSP1, we interpreted that gradual economy in a human-based society with high and security employments result in a decrease in antidepressant emissions. For Eur-Ant-SSP4, economic competition and low consideration for human well-being was translated as employment but with insecurity. We concluded antidepressant increases for Eur-Ant-SSP4, but also in Eur-Ant-SSP5 where we concluded that competition surpasses human consideration.

3.8. Social participation and social cohesion

Social participation is high in SSP1 and SSP5 and low in SSP4. Similar projections were determined for social cohesion in European SSPs. High social cohesion (e.g. playing sport, social encounters) is associated with lower depressive symptoms and better mental health (Almedom, 2005; Wang et al., 2019). Exploratory review also showed that society divergence and malicious regards to the mental health issue discourage individuals to take antidepressants (Jorm et al., 2005; Lewer et al., 2015; Park et al., 2018). While impacts of social participation was not directly studied with respect to antidepressants, we considered that social participation and social cohesion are positively related. We concluded that antidepressants emissions decrease in Eur-Ant-SSP1 and Eur-Ant-SSP5 and increase in Eur-Ant-SSP4 based on social participation and social cohesion.

3.9. Healthcare investment and healthcare access

In Eur-SSPs, human health investment and access is high for SSP1 and SSP5 and high for elites and medium for lower class for SSP4. In the literature, access and investment in healthcare was positively associated with antidepressant use and better mental health outcomes (Chisholm, 2015; McGorry & Purcell, 2007). We therefore concluded that antidepressants emissions increase in all Eur-Ant-SSPs.

3.10. Education

In Eur-SSP1 and Eur-SSP5, education is high. In Eur-SSP4, the number of highly educated people decreases. Articles found in the exploratory review showed that antidepressant consumption were less for highly educated groups. Education in terms of culture was also found to be an influencing factor (Brody & Gu, 2015; Kivimäki et al., 2007). "Open-minded" environments with less judgement and more cohesion were found to encourage individuals to seek help and accept antidepressant treatment (Gomez-Lumbreras et al., 2019). High numbers of educated and, indirectly, high support for human development was translated into antidepressant emissions decreasing in Eur-Ant-SSP1 and Eur-Ant-SSP5 and, inversely, increasing in Eur-Ant-SSP4.

3.11. Technology development

Technology development is "high, but not persuasive" in Eur-SSP1, "High in some areas; low in labour intensive areas" in Eur-SSP4 and "strong and crucial" in Eur-SSP5. For antidepressants emissions, technology development could cover improved wastewater treatment technology or shift in antidepressants chemistry design (Ganesh et al., 2021). Green chemistry encourages the development of less toxic molecule, for instance less persistent or less bio-accumulative (Kümmerer, 2007). We concluded that because of high investments in technology development in Eur-SSP1, Eur-SSP4 and Eur-SSP5, antidepressants emissions decrease for all Eur-Ant-SSPs.

3.12. Extreme droughts and floodings events

Droughts and floodings are increasing in Europe RCP 4.5, RCP6 and RCP 8.5 (Tabari et al., 2021). The exploratory review showed correlations between extreme weather events and mental health (Nitschke et al., 2011; To et al., 2021). Number of antidepressants prescriptions increases after floodings events. (Milojevic et al., 2017; Motreff et al., 2013). We concluded that antidepressants emissions increase under all RCPs considered.

3.13. Eur-Ant-SSP1, Eur-Ant-SSP4 and Eur-Ant-SSP5 storylines

Before developing the Eur-Ant-SSPs, the authors considered the interactions between direct and indirect drivers of antidepressants on a society. While scenario development focuses on emissions, the antidepressants exploratory review focussed only on indirect drivers related to consumption and usage. The development of the scenario narratives was conducted in accordance with the following assumptions:

1. Key drivers including population growth, inequalities, economy, social participation, social cohesion, healthcare investment, healthcare access and education are indirect drivers of antidepressants emissions. These drivers are related to related to consumption and usage of antidepressants.
2. Consumption of antidepressants impact antidepressants loads in wastewater and sewage treatment facilities. These wastewater and sewage treatment facilities can remove/decrease antidepressants emissions release in the natural environment.

Table 3
Exploratory review of insecticides and socio-economics drivers.

Category	Driver (s) studied in article	Article's findings	Source
Demography	Urbanisation	*Higher concentrations occurred in the central Pearl River Delta (China) with more urbanization level than that in the Pearl River Delta's surrounding areas. Relatively higher concentrations of legacy organochlorine pesticides and current-use insecticides were found in the residency land than in other land-use types, which may be attributed to land-use change under rapid urbanization.*	Wei et al. (2015)
Demography	Urbanisation	*Wash-off potential of urban use insecticides on concrete surfaces.*	Jiang et al. (2010)
Environment & natural resources	Environment	*Presence of a border crop of soybeans and neighboring crops (maize, eggplant and Chinese cabbage), both without weed control, increased invertebrate predator abundance, decreased the abundance of pests and dependence on insecticides, and increased grain yield and economic profits.*	Wan et al. (2018)
Environment & natural resources	Land-use	*Since the use of pesticides can negatively impact the population of farmland birds via direct poisoning or, indirectly, by affecting food availability (seeds and insects) and habitat for breeding and foraging, practices that support integrated pest management and that minimise pesticide applications can potentially reduce those negative impacts*	Chiron et al. (2014); Stanton et al. (2018)
Environment & natural resources	Land-use	*At the field level, agricultural intensification, reflected by increasing chemical inputs and field areas and decreasing crop diversity, leads to increased yield, whereas at the farm level, the spread of cropped areas results in a loss and fragmentation of natural and semi-natural habitats.*	Doxa et al. (2012); OECD (2019)
Human development	Food Demand	*Pesticides increased by 15–20-fold since the 60 s to increase food production and respond to world food demand.*	Oerke (2006)
Human development	Education	*For underdeveloped countries like Pakistan a comprehensive and well planned program targeting on alternative pest control method and use of biological agents along with insecticides need to be initiated that can reduce the total dependency on chemicals.*	Id and Afsheen (2021)
Human development	Education	*Farmers' inadequate knowledge of pesticides, the influence of pesticide retailers and lack of access to non-synthetic methods of pest control are positively associated with pesticide overuse, while the propensity to overuse decreases with higher levels of education.*	Jallow, Awadh, Albaho, Devi, and Thomas (2017)
Human development	Consumption and Diets	*Vegetarian and vegan diets with an increased amount of organic foods may further improve upon the toxicity potential by removing conventionally-produced products and removing pesticides.*	Martin and Brandão (2017)
Human development	Consumption and Diets	*Assessment suggests that on average the complete life cycle environmental impact of nonvegetarian meals may be roughly a factor 1.5–2 higher than the effect of vegetarian meals in which meat has been replaced by vegetable protein. Although on average vegetarian diets may well have an environmental advantage, exceptions may also occur. Long-distance air transport, deep-freezing, and some horticultural practices may lead to environmental burdens for vegetarian foods exceeding those for locally produced organic meat.*	Reijnders and Soret (2003)
Human development	Consumption and Diets	*Using a quadrant analysis, a recommended diet was identified with a 38 % lower pesticide toxicity footprint. This was achieved mainly through a reduction in the discretionary food intake and by limiting the choice of fresh fruits. As the latter contradicts dietary recommendations to eat a variety of fruits of different types and colors, we concluded that dietary change may not be the best approach to lowering the environmental impacts of pesticides in the food system. Instead, targeted action in the horticultural industry may be more effective.*	Ridoutt, Baird, Navarro, and Hendrie (2021)
Economy	Economic Model	*Our analysis shows that a 1 % increase in crop output per hectare is associated with a 1.8 % increase in pesticide use per hectare but that the growth in intensity of pesticide use levels off as countries reach a higher level of economic development. However, very few high income countries have managed to significantly reduce the level of intensity of their pesticide use, because decreases in insecticide use at higher income levels are largely offset by increases in herbicide and fungicide use*	Schreinemachers & Tipraqsa (2012)
Technology	Technology Development	*While improved seeds increase pesticide, herbicide and fungicide use, mixed cropping and row planting generally reduce these practices. Moreover, mixed cropping moderately increases expected harvest while improved seeds and row planting have the reverse effect*	Onjewu et al. (2022)
Technology	Technology Development	*Adoption of GM insect resistant and herbicide tolerant technology has reduced pesticide spraying by 671.4 million kg (8.2 %) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops.*	Brookes and Barfoot, (2018)
Technology	Technology Development	*We also report increasing applied toxicity to aquatic invertebrates and pollinators in genetically modified (GM) corn and to terrestrial plants in herbicide-tolerant soybeans since approximately 2010.*	Schulz et al. (2021)
Climate change	Flooding event	*There was an increase of 0.59 % (95 % CI 0.24–0.94) prescriptions in the postflood year among practices located within 1 km of a flood over and above*	Milojevic et al. (2017)

(continued on next page)

Table 3 (*continued*)

Category	Driver (s) studied in article	Article's findings	Source
		the change observed in the furthest distance band. The increase was greater in more deprived areas.	
Climate change	Flooding event	*With a relative risk (RR) of 1.54 (95 % CI, 1.39–1.62) corresponding to an estimate of 409 new deliveries of psychotropic drugs during the three weeks following the storm, this study confirms the importance of the psychological impact of Xynthia. This impact is seen on all three classes of psychotropic drugs studied. The impact is greater for tranquilizers (RR of 1.78; 95 % CI, 1.59–1.89) than for hypnotics (RR of 1.53; 95 % CI, 1.31–1.67) and antidepressants (RR of 1.26; 95 % CI, 1.06–1.40). The RR was higher for females than for males.*	Motreff et al. (2013)
Climate change	Heatwaves	*While only incremental increases in morbidity and mortality above previous findings occurred in 2008, health impacts of the 2009 heatwave stand out. These findings send a signal that the intense and long 2009 heatwave may have exceeded the capacity of the population to cope.*	Nitschke et al. (2011)
Climate change	Wildfires	*The results show an increased rate of PTSD, depression, and generalized anxiety at several times of follow-up post-wildfire, from the subacute phase, to years after. An increased rate of mental health disorders post-wildfire has been found in both the adult and pediatric population, with a number of associated risk factors, the most significant being characteristics of the wildfire trauma itself.*	To et al. (2021)
Multiples	Land-use; public policy	*Our results indicate that the direct impacts of agricultural land use changes on pesticide use in France have varied depending on the time period considered, reflecting the influence of public regulations, notably the compulsory set-aside policy in force during the 1990 s, and market conditions, particularly the context of high prices for cereal grains at the end of the 2000 s. Over the six years from 2008 to 2013, this index is roughly constant, indicating that the 17 % increase in French pesticide use in 2013 compared to 2008 (as assessed from annual pesticide sales) cannot be even partially attributed to agricultural land use changes*	Urruty et al. (2016)
Multiples	Land-use; Economy	*Our analysis affirms that organic farming has large positive effects on biodiversity compared with conventional farming, but that the effect size varies with the organism group and crop studied, and is greater in landscapes with higher land-use intensity. Decisions about where to site organic farms to maximize biodiversity will, however, depend on the costs as well as the potential benefits.*	Tuck et al. (2014)
Multiples	Land-use; Consumption and diets	*This investigation showed that compliance with healthy eating guidelines leads to lower energy demand and a decrease in greenhouse gas emissions, largely due to a decrease in livestock numbers. Furthermore, arable land and grassland no longer needed for animal feed production becomes redundant and can possibly be used for the production of raw materials for renewable energy.*	Fazeni and Steinmüller (2011)
Multiples	Climate change; Economics	*Increases in rainfall increases average per acre pesticide usage costs for corn, cotton, potatoes, soybeans, and wheat. Hotter weather increases pesticide costs for corn, cotton, potatoes, and soybeans but decreases the cost for wheat.*	Chen and McCarl (2001)
Multiples	Climate change; Economics	*Climate factors influence fungicide, herbicide, and insecticide expenditures and that this influence is heterogeneous, varying in nature across crops and pesticide categories.*	Rhodes and McCarl (2020)
Multiples	Climate change; Regulation	*In the absence of green house gases emission and pesticide externality regulations, climate change would not only increase agricultural production in the USbut also raise pesticide use and the external environmental and human health costs.*	Shakhramanyan at al. (2013)
Multiples	Climate change; Land-use	*In the long-term, indirect impacts, such as land-use change driven by changes in climate, may have a more significant effect on pesticides in surface and groundwaters than the direct impacts of climate change on pesticide fate and transport.*	Bloomfield et al. (2006)
Multiples	Regulations; Public opinion; Urbanisation	*Denmark, Sweden, the Netherlands and Germany have, or have had, a strong public and political interest for reducing the use of herbicides to control weeds in urban amenity areas and also have very strict regulations. The UK is currently undergoing a period of increasing awareness and strengthening regulation, while Latvia and Finland do not have specific regulations for weed control in urban amenity areas or on hard surfaces.*	Kristoffersen et al. (2008)

3. Capacities of wastewater and sewage treatment are related to technology development. Cities connectiveness of water systems is related to urbanisation. Technology development and urbanisation are therefore considered direct drivers of emissions.
4. If there is no change in technological development, then an increase in antidepressants consumption would increase antidepressants emissions in the natural environment. Similarly, if there is no change in technological development, an increase in consumption would lead to an increase in emissions.

3.13.1. Eur-Ant-SSP1

In 2050 in Europe, social and environmental awareness shift the European societies towards human and environment development and sustainable management of resources like water. Despite easy access to antidepressants due to healthcare investment, consumption of antidepressants is reduced because of a supportive society with high social participation and cohesion, high investment in education, and low inequality between individuals. Urbanisation and technologies increase in line with human and environmental desires for the more sustainable- and human- friendly societies. Because of the decrease in antidepressant consumption and investment in technological development, **antidepressant emissions in freshwater systems decrease.**

3.13.2. Eur-Ant-SSP4

In 2050 in Europe, despite a strong economy and high technological development permitting stable economic outcomes and a low unemployment rate, the consumption of antidepressants is high because of generally poor human well-being. Antidepressant usage is triggered by low human consideration in the society. The poorer population are more likely to take antidepressants because of high inequality in the society and low investment in education, making access to higher social status and good quality of life more difficult. Investment in wastewater technology does not counterbalance the high consumption of antidepressants. Consumption of antidepressants is exacerbated by increasing extreme climate weather events. **Emissions of antidepressants increase in freshwater systems** because of low human consideration in the societies.

3.13.3. Eur-Ant-SSP5

In 2050 the European societies shift toward economic and human development. Economy is boosted by innovation and technological development ensuring low labour-intensive work and a low unemployment rate. There is high social cohesion and participation between individuals, and education is accessible to all. Healthcare investments make antidepressants widely available but increasing human well-being and economic stability reduce the number of antidepressant consumers. Antidepressant consumption is, however, important for individuals who do not fit to the intensive society lifestyle based on performance and for individuals concerned about natural resources. Technology development is strongly based on fossil-fuel resources, provoking anxiety and stress for the portion of the population concerned about natural resources and extreme climate events. Overall, **antidepressants emissions decreased in freshwater systems** because of high human well-being consideration in societies and innovation in wastewater technologies.

3.13.4. Step 4. Consistency check

Eur-Ant-SSPs outputs scenarios narratives as well as the results represented in Table 2 were repeated and verified to ensure consistency with results from the exploratory review and with Eur-SSPs storylines by the authors. When consistency was considered satisfactory, the output narratives scenarios were considered fully developed.

3.14. Insecticides emissions at European scale for 2050 (Eur-Ins-SSPs)

Insecticides are used in agricultural production for pest control and for minimizing risk of crop loss. They are regularly detected in surface water through runoff or groundwater contamination, exposing and affecting surrounding non-target organisms (Kreutzweiser et al., 2007). Usage of insecticides is predicted to be correlated to agricultural practices and climate change (Delcour et al., 2015; Kattwinkel et al., 2011; Rhodes & McCarl, 2020). Global changes that are projected to occur over the next 30 years could have an effect on insecticide usage and, therefore, on emissions into the environment. Table 3.

3.14.1. Step 1: Define characteristics of scenarios

- **What is the goal and purpose of the scenario?** To extend European Agriculture SSPs (Mitter et al., 2020) to insecticide emissions coming from agricultural fields in order to envision multiple scenarios of insecticide emissions in European freshwater systems in 2050.
- **Which chemical or group of chemicals is being investigated?** Within the EU market, insecticides currently available, insecticides currently developed but not registered yet and future insecticides molecules developed under the green chemistry framework by Ganesh et al. (2021)
- **Which environmental matrices are being considered?** European freshwater aquatic systems in rural areas
- **Spatial scale:** Europe
- **Temporal scale:** 2050
- **How many and which SSPs need to be explored?** European Agriculture SSP1 (Eur-Agri-SSP1), SSP4 and SSP5 will be extended to insecticide emissions (Mitter et al., 2020). Eur-Agro-SSP1 was selected to study insecticide emissions in a sustainable society with rapid technological development. Eur-Agri-SSP4 was chosen because of inequalities between urban and rural populations and because policies supporting economic development that predominantly benefit the largest industrial companies. Last, Eur-Agri-SSP5 was selected to represent a liberal society with high investment in technology by private actors. Public environmental awareness is low and public financial support for farmers is low.
- **Which climate projections should be explored?** Climatic events such as increase rainfall, temperature or pest pressure were found to be correlated to incesctices usage in the literature (Chen & McCarl, 2001; Grünig et al., 2020; Rhodes & McCarl, 2020). Climate change is considered and integrated with RCP 4.5, 6 and 8.5 combined with Eur-Agri-SSP1, Eur-Agri-SSP4 and Eur-Agri-SSP5 respectively.

– **Targeted audience:** scientists from the climate change research community with eco-toxicologists, chemists and social scientists working at European scales
– **Type of scenarios:** tables with emissions trends for each key driver with qualitative storylines assessing the overall effects of the set of drivers for each scenario.

3.14.2. Step 2: Review and prioritisation of the potential impacts of changes in socio-economic and climate on chemical emissions

An exploratory review was conducted in order to define dynamic between SSP drivers listed in Mitter et al. (2020) and insecticides. Articles were kept if they confirmed the following statements: 1) the article focuses on change in trends in insecticides use/-consumption; 2) the change in insecticides usage trends is related to a socio-economic, technological or climate change; 3) the article focused on Europe, a country in Europe or a society similar in socio-economic development as Europe. Twenty-five articles were reviewed and major findings are in Table 4.

Using the same methodology applied for the determination of key drivers for antidepressant emissions, ten experts on chemical emissions in academia were solicited to determine key drivers of insecticide emissions. Ten key drivers were considered as high priority by at least 70 % of our expert panel: population growth, education, consumption and diet, land-use, policy orientation, technology development (including agricultural practices) and temperature, rainfall, extreme events and pest pressure regarding climate change (see Table S2). These drivers were studied exclusively in step 3 to develop insecticides emissions scenarios.

3.14.3. Step 3: Develop chemical emissions scenarios

An emissions trend (increasing, decreasing or both) was proposed for each prioritized driver. Each driver's individual future trend is presented in section 3.1 and Table 4, and output scenario storylines are presented section 3.2. As mentioned for Eur-Ant-SSPs, step 3 was developed by desk-based research conducted by the authors.

3.14.3.1. Step 3.1. Insecticides emissions trends by priority drivers in Eur-Ins-SSPs. Prioritised drivers of insecticide emissions selected in step 2 were studied individually using Eur-Agri-SSPs (Mitter et al., 2020).

Table 4
Eur-Ins-SSP1, Eur-Ins-SSP4 and Eur-Ins-SSP5 insecticides emissions scenarios for Europe for the year 2050 for each key drivers defined.

SSPs drivers	SSPs sub-drivers	Eur-SSP1[1] or Global SSP1[2]	Ins-Eur-SSP1	Eur-SSP4[1] or Global SSP4[2]	Ins-Eur-SSP4	Eur-SSP5[1] or Global SSP5[2]	Ins-Eur-SSP5
Demographics	*Population Growth*	Relatively low growth [2]	↗	Low growth [2]	↗	Relatively low growth [2]	↗
Human Devlopment	Education	High [1]	↘	High for elites, medium for lower class [1]	↗	High [1]	↘
Economy and Lifestyle	Consumption and diet	Low growth in material consumption, low-meat diets, first in high income countries [2]	↘	Elites: High consumption life, Rest: low consumption, low mobility [2]	↗	Materialism, status consumption, meat-rich diets [2]	↘
Environment and Natural Resources	Land-use	Strong regulations to avoid environmental trade-offs [2]	↘	Highgly regulated in High income countries[2]	↗	Medium regulations lead to slow decline in rate of deforestation [2]	↗
Policies and Institutions	Policy orientation	Towards sustainable development [2]	↘	Toward the benefit of political and business elite [2]	↗	Toward development, free market, human capital [2]	↗
Technology	Technology development and agricultural practices	Improvement in agriculture productivity; rapid diffusion of best practices [2]	↘	Ag productivity high for large scale industries, low for small scale industries [2]	↗	Highly managed, resource-intensive; rapid increase in ag productivity [2]	↗
Climate Change	Temperature	RCP-4.5–6: Temperature increases [3]	↗	RCP- 6: Temperature increases [3]	↗	RCP-8.5: Temperature increases [3]	↗
	Rainfall	RCP-4.5–6: Rainfalls increase [3]	↗	RCP- 6: Rainfalls increase [3]	↗	RCP-8.5: Rainfalls increase [3]	↗
	Extreme events	RCP-4.5–6: Droughts and floods increase [3]	↗	RCP- 6: Droughts and floods increase [3]	↗	RCP-8.5: Droughts and floods increase [3]	↗
	Pest pressure	RCP-4.5–6: Rising pest pressure[4]	↗	RCP-6: Rising pest pressure[4]	↗	RCP-8.5: Rising pest pressure[4]	↗

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3.15. Population growth

European population size is stable in Eur-Agri-SSP1 and Eur-Agr-SSP4 but increase in Eur-Agri-SSP5. Insecticides usage since the 60 s increase to increase food production and answer to the food demand (Oerke, 2006). We considered that increase population is positively correlated with food demand. Therefore, we concluded that insecticides emissions are stable in Eur-Ins-SSP1 and Eur-Ins-SSP4 and increase in Eur-Ins-SSP5.

3.16. Education

In Eur-Agri-SSP1 and Eur-Agri-SSP5, education investment increases. For Eur-Agri-SSP4, education investment stays stable. Despite being conducted in countries outside Europe, the exploratory review showed low education for farmers and food producers was associated with over-consumption of pesticides (Jallow et al., 2017). We considered that similar effects would occur in European countries. We concluded that insecticides emissions decrease in Eur-Ins-SSP1 and Eur-Ins-SSP5 and stays stable in Eur-Ins-SSP4.

3.17. Consumption and diet

In Eur-Agri-SSP1, demand for meat and feed decrease. For Eur-Agri-SSP4 and Eur-Agri-SSP5, demand for meat and feed stay stable. One article in the exploratory review showed vegan or vegetarian diets decreases pesticides usage (Fazeni & Steinmüller, 2011; Martin & Brandão, 2017; Reijnders & Soret, 2003). There are many uncertainties between diet consumption and insecticide usage though. A decrease in meat demand means a shift towards vegetable and fruit crops. Meat production is usually associated with high antibiotic treatments while vegetables and food crops are associated with high pesticide treatment including insecticides (Ridoutt et al., 2021). Our interpretations of European Agriculture SSPs and the exploratory review was that in Eur-Ins-SSP1 less demand for food and feed led to less insecticide usages and emissions. For Eur-Ins-SSP4 and Eur-Ins-SSP5, insecticides emissions stay stable because the food demand stay stable.

3.18. Policy orientation

Relative importance of agri-food policy increases in Eur-Agri-SSP1, stabilises in Eur-Agri-SSP4 and decreases in Eur-Agri-SSP5. Regarding these policies, the socio-environmental focus increased in Eur-SSP1 and stabilizes in Eur-Agri-SSP4 and Eur-Agri-SSP5. For Eur-Ins-SSP1, we concluded that utilisation of insecticides is regulated and limited, therefore emissions decreases. In Eur-Ins-SSP4, the stabilise agri-food policies and socio-environmental focus was translated as no or limited actions are taken for the regulations of insecticides probably due to a lack of interest in environmental topics in the society. Therefore emissions increase in Eur-Ins-SSP4. Similarly, in Eur-Ins-SSP5, the decrease of agri-food policies means a free-market with no chemical regulations. Insecticide emissions increase.

3.19. Land-use

Multiple aspects of land-use are covered in Eur-Agri-SSPs: land productivity, resources depletion and resources use efficiency. In all scenarios considered here, land productivity increases. In Eur-Agri-SSP1, resources use efficiency increase and resources depletion decrease. In Eur-Agri-SSP4, resources use efficiency and resources depletion increase. In Eur-SSP5, resources use efficiency stabilize and resource depletion increase. In our exploratory review, land use and pest management can reduce pesticides usage but is usually correlated to public policies and economic investments (Tuck et al., 2014; Urruty et al., 2016). We interpreted that in Eur-Ins-SSP1, insecticides emissions decrease because of conscious and well managed land and water resources, leading to increase food productivity. Reversely, in Eur-Ins-SSP4 and Eur-Ins-SSP5, insecticides emissions increase to increase food productivity while resources are mismanaged and resources depletion increase.

3.20. Technology Development and agricultural practices

In Eur-Agri-SSP1 and SSP5, speed of agricultural technology development increases alongside an increase technology uptake in agriculture and an increase technology acceptance by producers and consumers. In Eur-Agr-SSP4, the difference is that technology acceptance by producers and consumers stabilizes. Technology development like GMO was said to reduces pesticides and insecticides utilisation in one while another article stated the opposite in the exploratory review (Brookes & Barfoot, 2018; Schulz et al., 2021). For Eur-Ins-SSP1, the general interest in social and environmental topics in the society makes that the increasing technology development aims at the reducing chemicals emissions. For Eur-Ins-SSP5, increasing investments in technical infrastructures for technology developments and technological innovations brings agricultural practices that do not require insecticides usage (e.g. indoors farming; connected farms). Therefore insecticides emissions decreases. For Eur-Ins-SSP4, we concluded that insecticides emissions increase because technology development benefits large, industrialized farms that do not have an interest in chemicals usage, but mostly focuses on low-emissions technology and nitrogen efficiency (Mitter et al., 2020).

3.21. Rainfall, temperature, extreme events and pest pressure

In the RCPs 4.5, 6 and 8.5, the climate events of temperature, rainfall, *pest pressure* and extreme events are increasing (Tabari et al., 2021). Articles found in the exploratory review showed climatic events have a significant effects on pesticides expenses dependent to type of crops. Increase temperature, rainfall and extreme events led increase pesticides costs for most of the crops (Chen & McCarl, 2001). The magnitude will depend on the type of crops, the sub-category of the pesticides and, for few cases, are location-specific (Rhodes & McCarl, 2020). Therefore we concluded that for most crops, increase temperature, rainfall, pest pressure and extreme climatic events led to increase insecticides emissions. Insecticides emissions increase in all Eur-Ins-SSPs.

3.21.1. Step 3.2. Eur-Ins-SSPs storylines

Before developing the Eur-Ins-SSPs, the authors considered the interactions between direct and indirect drivers of insecticides on a society. While scenario development focuses on emissions, the exploratory review focused mostly on indirect drivers related to consumption and usage. The development of the scenario narratives was conducted in accordance with the following assumptions:

– Socio-economics drivers (population growth, education, consumption and diet, land-use, policy orientation and technology development) are indirect drivers of insecticides emissions as they impact consumption and usage. Climate drivers (temperature, rainfall, extreme events and pest pressure) can have direct and indirect impacts on insecticides emissions.
– Because agriculture fields are open-systems and because there is no treatment of agriculture effluent, we consider that an increase in insecticides consumption/usage causes an increase of insecticides emissions in the surrounding environment.

3.21.2. Eur-Ins-SSP1

In Europe in 2050, social and environmental awareness encourages the usage of insecticides to be largely reduced. Consumers are educated on environmental problems and prefer buying products that do not require pesticides or insecticides. Farmers are encouraged financially and by new technologies to shift towards no or low pesticides and insecticides farming. Climate change does increase pest pressure but adaptation strategies are developed to avoid insecticide usage. **Insecticide emissions in freshwater systems decrease**.

3.21.3. Eur-Ins-SSP4

In Europe in 2050, agricultural policies are developed by the wealthy upper class. The larger portion of the population is not represented in public institutions. Policies and regulations are developed for the advantage of large, industrialized companies. Environmental issues like insecticide usage are considered low importance topics compared to social inequalities happening in the society. The large majority of individuals in the society is unaware of environmental problems related to insecticides. Climate change increases pest pressure and usage of insecticides is the only adaptation strategy available. **Insecticide emissions in freshwater systems increase.**

3.21.4. Eur-Ins-SSP5

In Europe in 2050, individuals are educated on environmental issues but technology is believed to be the solution to these issues. Investments in innovation and technology development in agriculture is high and towards new technology farming like connected or indoors farms. The free market makes that there is no environmental policy, regulation or financial support to agriculture and food systems. A part of innovation and technology development reduces insecticides usage, but the pressure of climate change and the absence of regulations results in insecticides being the chosen adaptation solution to secure food production for the increasing population. Public awareness for the impact of insecticides in the environment is limited. **Insecticide emissions in freshwater systems increase.**

3.21.5. Step 4. Consistency check

Similar as for the development of Eur-Ant-SSPs, Eur-Ins-SSPs output narratives scenarios as well as the results represented in Table 5 were repeated and verified to ensure consistency with results from the exploratory review and with Eur-SSPs storylines. When consistency was considered satisfactory, the output narratives scenarios were considered fully developed.

4. Discussion

Comparison of our results with the literature was difficult because, to our knowledges, this represents the first attempt at developing future chemical emission scenarios. Nevertheless, possible change in antidepressants and insecticides emissions in the future have been studied in the literature. Articles usually focus on a single future situation. There is, to be best of our knowledge, no consideration of multiple alternative futures.

Human health or diseases was studied under the influence of climate change (Barrett et al., 2015; Epstein, 2009; McMichael et al., 2006; Mills et al., 2010). More specifically to antidepressants, similar dynamics between key drivers and antidepressant consumption or emissions were found in the literature. Antidepressant consumption was found to increase in the future because of climate change, and more specifically because of increase in floods and naturals disasters (Redshaw et al., 2013). Projections of population size and gender was found to increase consumption by 61 % by 2090 in a study conducted in the Netherlands (Van Der Aa et al., 2011). Schlüsener et al., 2015 found an increase of antidepressant consumption in the future due to climate change but concluded that demographic development and change in lifestyle was probably more important. In our scenarios, demographic change was considered to have a bigger impact on antidepressant emissions in the environment as well, but a lesser impact compared to human developmental drivers.

Regarding insecticides, usage and costs were found to increase under extreme weather events (Rhodes & McCarl, 2020), precipitation and rainfall (Chen & McCarl, 2001), pesticide efficacy (Matzrafi, 2019) and climate change and land-management (Kattwinkel et al., 2011) in the future. The influence of technological change was debated in a study looking at pesticide efficiency: authors found that increased pesticide consumption could be related to pesticide decreases in efficiency. Consistent with our findings, change in molecule design could therefore play an important role in reducing pesticide consumption and, consequently, pesticide emission in the future (Matzrafi, 2019).

These studies are relevant to understand the influence of a single or few key drivers on a thematic focus. They are, however, less informative of future conditions as they do not consider a society as a complex system where socio-economics, technological and climate change interact and influence each over. They, by default, disregard current societal debates (e.g economics degrowth), actions (e.g. Fridays for Futures and Extinction Rebellion movements) on global change and their impacts on the society. Despite being uncertain, those societal dynamics should be included in future research. In our framework the society is considered as a whole. Socio-economics, technological and climate change drivers interact with each other and can be weighed against each other. In Eur-Ant-SSPs, human development drivers were considered to have the greatest impact on antidepressants emissions. For Eur-Ins-SSPs, land-use, policy and climate drivers had the greatest impacts on insecticides. This framework adapted from the methodology of Mitter et al. (2019) permits for the first time the study of chemical emissions in the future under the shared socio-economics pathways scenarios and in dynamic complex socio-economics societies. The framework is applicable to single molecules or groups of chemicals sharing similar features with an easily applicable methodology.

The two sets of scenarios developed demonstrates the ability of the framework to fit different chemicals. We studied antidepressants with an exploratory review of 23 relevant articles and insecticides, with 25 articles. Antidepressants and insecticides had 10 and 9 key drivers defined respectively. Population growth, technological development and education were key drivers in common for both examples. Our final scenario showed that antidepressants and insecticide emissions both decreased in SSP1 and increased in SSP4. SSP5 had opposite future trends: antidepressant emissions decreased while insecticide emissions increased. The reason is that human development and wellbeing are highly emphasised in SSP5 (which decrease consumption of antidepressants), but environmental regulations and financial investment in the agricultural sector are low due to a desired-liberal society (which increase insecticide usage). Moreover, the impact of climate change is more relevant to insecticide usage and socio-economic trends do not permit an overall reversal of insecticide emissions trends. For Eur-Ins-SSP1, climate change makes the reduction of insecticide usage difficult but is compensated by socio-economic trends.

Scenario development, whether it is for the development of single future trends for each key driver or for the development of storylines, involves uncertainties. There are more uncertainties when literature is limited and when there are multiple sources of chemicals in the environment. For future chemical scenarios, we recommend involving experts and shareholders to discuss the thematic focus and to develop scenarios. Involvement of shareholders from academia, regulatory agencies, and industry is highly encouraged in all steps of the framework. Depending on scenario developers' financial and time resources, experts' judgement can be collected by various methods from surveys sent online to individual interviews where the thematic focus can be discussed in detail. Note that involvement of experts and shareholders also introduces other challenges, for instance, motivate shareholders' participation or maintain this motivation (Alcamo & Henrichs, 2008; Mcbride et al., 2017).

To evaluate our output scenarios, we used the six quality criteria (plausibility, consistency, salience, legitimacy, richness and creativity) proposed by Mitter et al. (2019). These quality criteria were developed to enhance plausibility and consistency with other scenarios. Plausibility of our scenarios is established by the systematic review. Incorporation of the systematic review ensures the storyline is consistent with evidence-based results. Consistency with global SSPs or other scenarios is ensured by the inclusion of these scenarios' outputs within the scenario development. European SSPs or Global SSPs outputs were directly considered on the future of the thematic focus, ensuring consistency with their storylines. Salience, defined as social and/or political relevance of the output scenarios is possible with the characteristics of scenarios wanted in step 1. A scenario's characteristics should focus the framework on a defined goal to ensure salience. Output scenarios should then relate to a specific context within the chemical sector, which would ensure their utility to the targeted audience. Richness of the scenario is emphasized by the consideration of all global SSP drivers in the systematic review covering socio-economic, technological and climate drivers. Inclusion of expert's judgements largely increase richness of the output scenarios with the inclusion of expertise and opinions on the thematic focus. Legitimacy, defined as the inclusion of multiple stakeholders and multiple visions, will depend on scenarios developers' resources and time. In the scenarios we developed, we solicited academic experts for the determination of key drivers, but, as mentioned before, involvement is encouraged in all steps of our framework. The final quality criteria is creativity. Creativity is limited in our framework. The structural approach of linking already defined SSPs drivers to a thematic focus and including results from previous studies restricts out-of-the-box thinking. As mentioned in Mitter et al. (2019), trade-off between quality criteria can happen. In our framework, plausibility and consistency are prioritised over creativity.

A key step in the process of scenario development is comprehending the current situation. This requires the understanding of the past and current trends in chemical release and occurrence. However, the data needed to assess chemical emissions (e.g. production, consumption and trade) are limited to select regions of the world and are often only available for select groups of chemicals such as pharmaceuticals and pesticides. Where data does exist, this is often commercially sensitive so is not always freely available. There is a need to generate data on chemical usage in regions where these data do not exist and for increased data transparency so that researchers can more easily access existing datasets. Access to improved emissions data will facilitate the development of chemical emissions scenarios and, subsequently, support the development of mitigation and adaptation strategies to avoid the negative impacts of chemicals in the future.

5. Conclusion

In this article, we present a framework to study the future of chemical emissions under climate, socio-economic and technological changes. The framework was tested for antidepressants and insecticide emissions in Europe in 2050. Both chemicals had 10 key drivers: for antidepressants, drivers were mainly related to human development while for insecticides, drivers were also related to climate change. Output scenarios describe multiple future emissions depending on the SSP societies described. For both chemicals, emissions were forecast to decrease under SSP1 and increase under SSP4. SSP5 gave conflicting future trends: antidepressant emissions decreased while insecticides increased. The high impact of climate change is compensated by socio-economic trends in SSP1 for insecticides emissions but not in SSP5.

This framework adapted from the methodology of Mitter et al. (2019) permits for the first time the study of chemical emissions in the future under the shared socio-economics pathways scenarios and in dynamic complex socio-economics societies. The framework proved to be adaptable to different chemical uses and allowed the development of detailed scenarios but could also be adapted to other research fields. The more chemical emission scenarios that are developed using this framework, the more researchers, regulators, politicians, governments, or private sector representatives will be able to envision and anticipate the future of chemical emissions to the environment. The knowledge generated will be essential to focus and develop mitigation and adaptation strategies in support of national and international policy initiatives such as the EUs vision to move towards a non-toxic environment.

Declaration of Competing Interest

The Authors declare no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.futures.2022.103040.

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