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Reducing chemical inputs in agriculture requires a system change

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Many countries have implemented policies to reduce the use of chemical inputs in agriculture. However, these policies face many obstacles that limit their effectiveness. The purpose of this paper is to review the main challenges associated with reducing chemical inputs in agriculture and to propose potential solutions. Our analysis, based on a literature review linking agronomy and economics, shows that several agronomic options have proven effective in reducing chemical inputs or mitigating their negative impacts. We argue that the organization of the agri-food system itself is a major barrier to their implementation. Involving all stakeholders, from the chemical input industry to consumers, and designing appropriate policy frameworks are key to address this issue. We recommend combining different policy instruments, such as standards, taxes and subsidies, in a simplified and coherent way to increase effectiveness and ensure better coordination in the adoption of sustainable practices.

On average, global crop production has soared since the Green Revolution although, in certain regions, crop yields have either remained stagnant or declined[1–3]. Meanwhile, population growth and increasing living standards have led to a significant rise in food demand. The use of pesticides and mineral fertilizers has played a crucial role in enhancing crop yields and improving food security[4]. However, their excessive use in some parts of the world has resulted in substantial environmental and human health risks, which are becoming increasingly evident on a large scale[5–8]. Indeed, the excessive use of fertilizers has contributed to the transgression of the planetary boundary for biogeochemical flows of nitrogen and phosphorus[9,10]. Agricultural nitrogen amendments also contribute to destabilizing the soil nutrient cycle, leading to increased emissions of nitrous oxide, a potent greenhouse gas with a high global warming potential[11]. Pesticides are also highly pervasive in the environment, with about 7% of net annual applied pesticides leaching to aquifers, and more than 10% residing in soil[12], leading to several pollution hotspots presenting risks to the environment, biodiversity and human health[13,14].

Given these environmental and human health concerns, the United Nations has called for global actions to reduce reliance on synthetic fertilizers and pesticides as part of the Sustainable Development Goals, and numerous public policies have been implemented at the national or regional level in this regard. For instance, in the European Union, regulations such as the Sustainable Use of Pesticides Directive adopted in 2009 and the Directive concerning the Protection of Waters against Pollution caused by Nitrates from Agricultural Sources adopted in 1991 aim to address these issues. However, there is limited evidence to suggest that these regulations have been successful in achieving their intended outcomes in the European Union[15] and, more widely, in the countries exporting goods to Europe[16]. Other initiatives, such as the Kunming Montreal global biodiversity framework, the Colombo Declaration on Sustainable Nitrogen Management, the Stockholm Convention on Persistent Organic Pollutants and Natural Farming practices in the Indian state of Andhra Pradesh have led to some achievements, but in some cases have also encountered implementation difficulties that have limited their effective impact[17,18].

The aim of this work is to shed light on the factors contributing to the limited effectiveness of policies and initiatives aimed at reducing the use of chemical inputs in agriculture. Specifically, we provide an overview, without claiming to be exhaustive, of the barriers to reducing the overuse of chemical inputs in agriculture and we suggest potential strategies to overcome these challenges. A key challenge is that barriers and solutions to this issue involve both environmental and social sciences making a mono-disciplinary approach inappropriate. Therefore, our work is based on a multi-

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disciplinary agronomy-economy vision, incorporating insights drawn from a workshop held in February 2022, where a panel of academic experts from different disciplines convened to delve into this crucial topic (for further details please visit https://cland.lsce.ipsl.fr/index.php/events/2022/rcia).Our analysis has a global scope since efforts to curtail chemical inputs use span numerous countries worldwide. Nonetheless, it is crucial to acknowledge that the use of chemical inputs varies significantly from one region to another. As such, the endeavor to reduce their use is contingent on the unique regional context[19]. Notably, this concern is less relevant in countries facing food security challenges and where chemical inputs use is currently low, such as many countries in sub-Saharan Africa[20]

Chemical inputs in agriculture

Mineral fertilizers use in agriculture

In 1898, the British Academy of Sciences warned that the world population would reach its limit due to a shortage of nitrogen, and would peak in the 1930s, unless means could be found to convert atmospheric nitrogen into its reactive form for use as fertilizer[21]. This goal was eventually achieved through the Haber-Bosch process and modern ammonia synthesis, making it one of the greatest technological advances of the 20th century, enabling agriculture to feed the growing global population[22]. However, the extensive use of fertilizer in agriculture has resulted in a series of negative environmental consequences. Two planetary boundaries have been crossed, posing a high risk of significant environmental impact[10,23]. The OECD suggests that human disturbance of nitrogen flows may prove to be the impact that causes the most irreversible damage[24]. In 2017, the International Nitrogen Management System was created on behalf of the UN Environment Programme (UNEP) in partnership with the International Nitrogen Initiative. The objective of this "nitrogen equivalent of the International Panel on Climate Change" is to bring scientific evidence together to inform policies and the public on the multiple benefits and threats of reactive nitrogen.

Agriculture and land-use change are responsible for most nitrogen-related issues[25]. In particular, the intensive use of nitrogen fertilizers in agriculture contributes significantly to greenhouse gas emissions, air, soil, and water pollution, as well as biodiversity and ecosystem loss. Europe is particularly alarmed, as it is a nitrogen hotspot, with high organic and mineral nitrogen exports through rivers to the coast, high concentrations of NOx and particulate matter in the atmosphere, and 10% of the world's N2O emissions[26].

Chemical pesticides use in agriculture

Pesticides are a diverse group of products containing active ingredients designed to protect plants from pests, mostly insects and weeds, and to a lesser extent other species. The pesticide industry has experienced rapid technological progress, leading to the introduction of new and improved active ingredients and the discontinuation of others. The wider adoption of chemical control has concurrently resulted in an increase in per hectare pesticide rates from 1.22 to 2.26 kg of active ingredients/ha between 1990 and 2021[27], and an increase in toxicity[28]. The most recent global land budget of pesticide use suggests that about 82% of agricultural pesticides breaks down into a cascade of byproducts (mostly uncharacterized), while 7.2% leaches to deep soil causing aquifer contamination and about 10% stays as residue in the topsoil, where it is prone to mobilization by erosion and transport to surface waters and oceans[12]. For this reason, pesticide use in major crops is still a critical issue in most developed countries and in countries with major agricultural production. The use of pesticides in agriculture has provided various benefits, including better crop protection from pests and diseases, reduced management costs, decreased weeding labor for control of invasive species, increased food processing efficiency, and control of human and livestock disease vectors. However, pesticide use also causes a multitude of risks to human health. While this is well elucidated in the Lancet Commission on Pollution and Health[29], pesticide exposure is a widespread issue, with 36 countries having PHRIc >1 (i.e., Pesticide Health Risk Index greater than the world average[30]). The intake of mixtures of pesticide residues can have neurological—developmental and behavioral—effects in humans even when they are exposed to concentrations below the safety limit[31,32], causing dysfunctions in the endocrine system[33] and reduced thyroid function[34]. Pesticides can also have adverse effects on non-target organisms including pollinators[35], birds[36], soil microbial species[37], soil invertebrates[30] and aquatic biodiversity[38]. In a feedback loop, these effects may negatively impact agricultural production when pollinators or natural enemies of crops pests and diseases are negatively[39] impacted by pesticides[40]. Moreover, the extensive use of these products raises the issue of pesticide resistance, which tends to reduce their efficiency over time.

Chemical pesticides and mineral fertilizers: similarities and differences

The concept of potential yield has played a pivotal role in the field of crop science. This refers to the maximum achievable yield in a specific location taking into account the prevailing climate and soils, cultivar characteristics and sowing dates. The difference between this potential yield and the actual yield, known as the "yield gap," arises from various limiting factors. These factors are typically categorized into two groups: biotic factors (such as pests and diseases) and abiotic factors (including nutrients and water availability). Within this framework, fertilization and irrigation are considered practices capable of mitigating abiotic limiting factors, while pesticides are seen as a means to control biotic reducing factors. Consequently, agronomists have historically posited that the application of pesticides and fertilizers could help narrow the gaps between potential and actual yields[41], and they have devoted considerable effort to developing decision support systems to help farmers apply the right doses of fertilizers and pesticides[42].

In the economic literature, a distinction is made between specific inputs that either reduce damage or enhance productivity. For instance, fertilizers and water are typically categorized as productivity-increasing inputs. On the other hand, capital and labor are considered both productivity-increasing (e.g., sowing and harvesting), and damage-reducing (e.g., mechanical or manual weeding). The case of pesticides has received extensive discussion in the literature, with numerous studies investigating their role in reducing damage compared to the productivity-enhancing role of other inputs[43,44].

Another interesting point regarding fertilizers and pesticides concerns their role in farmers' risk management, and it seems that there is no consensus between agronomists and economists on that point, at least for fertilizers. In agronomy, fertilizers are usually considered as a risk-decreasing input, especially because they help to achieve good product quality (e.g., protein content in wheat grain) and have a stabilizing effect on agricultural production, i.e., reducing the variance around the mean[45]. On the other hand, fertilizers are commonly considered as a risk-increasing input by economists, as they have the potential to enhance the expected mean (or modal) crop yield, and thus the risk of crop loss defined as the gap between the mean (or modal) crop yield and the minimum yield.

Pesticides are generally considered as a risk-reducing input since their main purpose is to control pest damage to crops which decreases the variance in crop yield. Economists also recognize that the use of pesticides can increase yield variability, particularly when pest/weed risks are small compared to other sources of yield variability (e.g., weather risks). However, the other associated risks—such as pollution and adverse effects to non-target organisms as well as human health[46]—are generally neglected.

Barriers

Many policies and initiatives are already in place to regulate the use of chemical inputs in agriculture. Overall, the use of chemical pesticides is highly regulated in an increasing number of countries. In particular, over the last decade, the number of pesticides allowed has been substantially reduced in many countries. For example, some pesticides cannot be applied in all regions and on all crops and the doses and number of treatments are strictly regulated. The use of mineral fertilizers is also regulated but this is often more limited (e.g., no fertilizer application near some water catchments). In many cases, however, these regulations have faced a number of barriers that have hampered their implementation or limited their effectiveness.

A globalized agri-food system steered by the consumption of animal products…

The major challenge in reducing chemical inputs in agriculture comes from the structure of the agri-food system itself, which prioritizes growth of agricultural production through industrial processes and global supply chains. Across most regions worldwide, the agri-food system remains influenced by the consequences of the green revolution and/or the livestock revolution[47]. These revolutions have led to a rapid increase in per capita calorie consumption over the past six decades (especially, but not only, protein), driven by extensive use of chemical inputs in crop production[48]. The cultivation of crops for livestock feed, which now represents approximately three-quarters of global protein production from crops[49], has particularly contributed to this surge. The use of nitrogen in livestock feed crops rose sharply between 1960 and 2009, accounting for nearly 60% of the total nitrogen applied[49,50].

At the same time, globalization and the growth of international trade has fueled the emergence of specialized, high-yielding agricultural systems in various regions of the world. Such agricultural practices necessitate relatively high levels of crop protection, which are challenging to achieve without the use of chemical inputs[51], although genetically modified insect-resistant crops have reduced the use of chemical pesticides to some extent[52]. Global pesticide consumption has surged by 50% over the past three decades, reaching 2.7 million tons of active ingredients in agriculture by 2020 (equivalent to 1.8 kg of active ingredients per hectare per year or 0.37 kg per person per year)[27]. Consequently, there has been a widespread diffusion of pesticide pollution across agricultural land, with approximately 64% of global agricultural land (around 24.5 million km^2) being at risk of pesticide pollution from multiple active ingredients[14]. Interestingly, several major countries that ban highly toxic pesticides are net importers of pesticide hazard embodied in commodities from countries that do not adopt bans on those same pesticides[16].

Within the globalized agri-food system, farmers are relatively small stakeholders, and their input choices are often constrained by contractual, economic, and regulatory obligations. Unlike point-source pollution, chemical input pollution in agriculture is diffuse in nature, arising from a wide range of farmers who exhibit considerable heterogeneity in terms of farming practices, soil and climatic conditions, risk aversion and skills[53,54]. This makes any policy even more difficult to enforce and monitor compared to a smaller, more concentrated group of stakeholders[55]. Overall, the disparity between the nitrogen use efficiency (NUE) of the crop sector (43%) and the NUE of the entire agri-food system (16%) highlights a large loss of efficiency beyond the farm level and points to the need to target the appropriate stakeholders to initiate the transition[19].

… And fostering the economic advantages of chemical inputs

In the context of productivity-oriented agricultural and food systems, various practices, technologies, and industrial organizations have developed together in a mutually reinforcing manner. These interactions have been facilitated by self-reinforcement and cross-reinforcement mechanisms[56,57]. These mechanisms encompass the distribution of technology through extension services, the sharing of information, and the adoption of productive crop varieties along with their associated technological packages. Additionally, agricultural systems that exhibit regional specialization tend to have reduced natural mechanisms for controlling pests, diseases, and weeds. As a result of these dynamics, the use of chemical inputs has become widespread[51]. Therefore, the structure of the agri-food system has been designed to ensure convenient accessibility, technical efficiency, and relatively affordable availability of agrochemicals. Even though positive impacts on farmers' incomes are possible in some contexts[58], production practices aimed at reducing chemical inputs are often less economically profitable for farmers compared to conventional methods, in particular for high-yielding crop management practices and highly specialized production systems. Indeed, farmers tend to use pesticides since these inputs are the most efficient for controlling pests or weeds in monocultures, easy to use and relatively cheap[59]. Pesticide saving practices are, by definition, designed while refraining from using pesticides (as well as relying on prophylactic strategies). Imposing binding constraints on uses of inputs that are economically efficient generally leads to losses in economic returns. As a result, farmers with low and insecure incomes may be compelled to rely on pesticide-intensive practices in such an agricultural system, and the perceived risk of significant crop losses due to pests, diseases, and weeds becomes a significant barrier to reducing pesticide use[60].

A regulatory context favoring the use of chemical inputs

Policies on the use of chemical inputs in agriculture are characterized by a degree of ambivalence, regulatory policies coexisting with promotional policies. In terms of nitrogen use, approximately two-thirds of nitrogen-related policies in the agricultural sector either encourage or regulate its use, while only a quarter of them establish quantifiable constraints on nitrogen pollution[61]. At the regional level, nearly half of the nitrogen-related policies in OECD countries are pro-nitrogen or focus on regulating the fertilizer trade. Non-OECD countries with low nitrogen input have a particularly high number of pro-nitrogen policies, reflecting the tension between nitrogen regulation and the imperative to enhance food security[61]. Regarding pesticide use, some policies aimed at reducing use may actually promote it instead, such as subsidized insurance which contributes to the expansion of economically riskier crops often requiring a higher intensity of pesticide application[62,63]. The Écophyto program launched in 2008 by the French government is another example. With the objective of halving pesticide use in 10 years, the use of phytosanitary products has actually slightly increased and the target of −50% pesticides has been postponed until 2025[64,65].

Adverse impacts on food production and potential conflict with food security

In recent years, the percentage of people experiencing food insecurity has been increasing, despite the rise in agricultural production[8]. This phenomenon is known as the "high productivity, low nutrition paradox"[66–68]. Issues related to food access, such as poverty, conflict, climate change, and supply chain disruptions from events like disease outbreaks, are linked to inefficient crop allocation for livestock feed or biofuel, unbalanced and unequal food consumption, and uneven distribution of irrigation and nitrogen inputs, with especially low nitrogen inputs in sub-Saharan Africa.

Overall, the use of chemical inputs, although varying between crop types, leads to 20–25% lower yields on average in organic agriculture compared to conventional agriculture[69,70]. This yield gap results from ineffective control of pests, diseases, and weeds, and most importantly, inadequate nitrogen crop nutrition[71–73]. Although organic agriculture offers potential benefits for overall biological pest control in temperate regions, mainly due to increased diversity of animal and microbial species[74], the challenge becomes greater when it comes to nitrogen management. Alternative nitrogen sources, such as animal manure, biological nitrogen fixation, and compost from urban sources, are limited in total quantity and unevenly distributed across regions, and their use can also result in substantial environmental impacts[75]. Consequently, the literature consistently suggests that feeding the world solely through 100% organic farming would require a profound transformation of our production and consumption systems[76–78]. Achieving a 60% global agricultural area under organic farming would only be possible with substantial reductions in food waste and losses, as well as significant changes in human diets[76].

Solutions

The nature of the barriers identified points to solutions oriented toward system redesign, rather than technological solutions aimed at efficiency or substitution[79]. This involves engaging multiple stakeholders at the farm level and beyond, with the aim of monitoring pollution throughout the entire food value chain[15,68,80,81]. This approach should also encompass an integrated perspective, recognizing that chemical inputs intersect with various environmental policies, including those related to climate, water, and biodiversity. It is essential to prevent the potential risks associated with pollution swapping, where one form of pollution is unintentionally replaced by another[82–84].

At farm level

The scientific literature proposes a variety of farm-level solutions to reduce pesticide use, such as decision support systems allowing farmers to adjust their inputs to local environmental characteristics[85], increasing hedgerows in the landscape[86], crop diversification from field (crop rotation) to landscapes[74,87,88], breeding and using cultivars resistant to pests and diseases, or precision farming[89]. However, these solutions may often not be profitable, and therefore need to be supplemented by public support[90].

Agronomic options are more limited for reducing mineral nitrogen inputs given the constraints on its availability[76]. Including legumes either as a main crop (e.g., soybeans in rotation with corn), in companion crops (e.g., wheat-pea or corn-soybeans in the same plot at the same time), in cover crops (between two harvested crops) or in intercrops (with another crop grown at the same time but not harvested) can provide biologically fixed nitrogen, but this remains insufficient to achieve significant reductions in mineral or organic nitrogen requirements[91].

Many solutions focus on reducing losses with improved nitrogen use efficiency (NUE), such as precision farming, nitrification inhibitors, controlled-release fertilizers and improved cultivars (other techniques such as GMO and new breeding techniques—e.g., CRISPR CAS9—could also help to design resistant cultivars, although they face acceptability issues in many parts of the world). However, these innovations may inadvertently lead to an increase in chemical inputs, as improved efficiency may lead to increased use in a rebound effect logic[92]. Therefore, careful consideration and monitoring are essential to ensure that the adoption of new technologies aligns with the objective of reducing chemical inputs in agriculture. Also, such high-tech solutions are costly and not affordable for all the farmers in the world, particularly in low-income countries. In this regard, changes in practices, such as the innovative dynamic fertilization method, may be an interesting option to improve NUE[93].

Another option is to emphasize the use of organic manure by promoting circularity between crop and livestock production[76,77]. This solution necessitates a profound shift in the geographical distribution of production areas and a reconsideration of regional specialization to achieve a balanced spatial allocation between crop and livestock regions. However, this solution does not solve all environmental problems, as the use of organic fertilizers may also be associated with some environmental problems (greenhouse gas emissions, water and soil pollution). Furthermore, this transformation should be accompanied by a change in crop composition, reducing the production of cereals while increasing the area dedicated to temporary grasslands and legume cultivation to enhance biological nitrogen fixation.

Improving the organic matter content of soils may also be an option to reduce mineral nitrogen inputs. The first evaluation of the Community-Managed Natural Farming initiative in Andhra Pradesh (no synthetic pesticides or fertilizers, poly-cropping with home-made inputs soil inoculums and bio-pesticides, mulch etc.) shows significant yield gains over organic and conventional farming[94].

Beyond farm level

As shown in the "Barriers" section, the implementation of farm-level solutions is often hampered by off-farm constraints. An effective strategy should therefore focus on designing governance schemes that target non-farm stakeholders capable of unlocking farmers' decisions on sustainable intensification.

The chemical inputs industry, which is already strongly regulated, is characterized by its significant concentration with a few companies dominating the market (e.g., five companies control over 80% market share in the US fertilizer industry), thus offering a sound entry point for cost-effective regulation[95]. By implementing design and/or performance standards for the industry to produce more environmentally efficient products, a new market for alternative solutions could be created, incentivizing the demand for such products at a premium price. The success of the Montreal Protocol in protecting the ozone layer provides a noteworthy example, showcasing the fact that it has evolved into a major economic opportunity for producers of non-ozone-depleting substances. Promisingly, certain technical solutions already exist, such as coated urea, which delays the release of nitrogen into the soil[96].

On the consumption side, reducing the intake of animal products is an essential issue, given the large amounts of chemical inputs used to feed livestock (see section "Mineral fertilizers use in agriculture"). Reduced consumption of animal products could benefit farmers' incomes in Europe, but some countries and regions highly specialized in livestock production are likely to lose income[97]. Food companies may also have a vested economic interest in marketing products without chemical inputs, as consumer studies have indicated a preference for reduced chemical use[98–100]. Food companies may wish to coordinate upstream supply chains by imposing specific standards[101]. While this preference may be limited to specific consumer segments, labeling can serve as an effective tool, generating higher willingness to pay among consumers, particularly when targeted and specific (e.g., "integrated pest management" compared to a more general "organic" label). Along with the popular organic food label, a successful example of a labeling initiative is the "pesticide-free" label for bread in Swiss food retailer Migros, where 50% of wheat production falls under this label, and a complete pesticide-free production system is envisioned, supported by governmental direct payments and price premiums[102].

Chemical input management policies: from theory to concrete examples

Economic evaluations of policies to reduce chemical inputs show that they are likely to reduce agricultural production, reduce competitiveness, and increase food prices for consumers[103,104]. They also lead to a complex set of trade-offs and synergies between food, climate, and biodiversity, which depends fundamentally on the type of economic response from the agricultural sector[105]. Therefore, an appropriate policy framework is key to properly guiding agent behavior and implementing a successful system-based approach to reducing chemical inputs pollution.

Typically, three types of regulatory instruments can be implemented, each with varying advantages and drawbacks in terms of efficiency, transparency and equity: Command and Control (CC), Market-Based Regulation (MBR), and Information and Voluntary Action (IVA). CC tools involve the imposition of norms, quotas, and standards, while MBR instruments create economic incentives such as taxes and subsidies to encourage innovation. IVA instruments include support for research and development (RD), information dissemination, and knowledge transfer.

Economists usually favor MBR instruments as they are considered to be the least costly tool for achieving environmental goals, especially in sectors like agriculture that exhibit significant heterogeneity in the marginal cost of pollution reduction. Although they belong to the same category of market instruments, taxes and subsidies have different characteristics. On the one hand, subsidy schemes are costly to implement (they need paperwork and control systems) and require selection of the technologies/practices to be subsidized. Their incentive power does not go beyond the subsidized target. However, subsidy schemes preserve farmers' incomes and can be implemented at small scales. On the other hand, taxes have lower implementation costs compared to other instruments and can provide strong incentives without prescribing specific solutions. Taxation offers farmers the advantage of flexibility in selecting solutions that align with their specific circumstances. However, it is crucial to highlight the fact that the implementation of such tax policies is not widely embraced. Indeed, given the inelasticity of demand for chemical inputs in relation to their prices[104,106], the tax rate would need to be set at a relatively high level to achieve significant reductions, which would directly reduce farmer's income. Furthermore, this impact on farmers' incomes should be taken into account by establishing a redistribution plan that targets the most vulnerable.

MBR instruments also require a large amount of information and data to determine the optimal level of taxation or subsidies. It is necessary to know the marginal costs and benefits of regulation for both society and

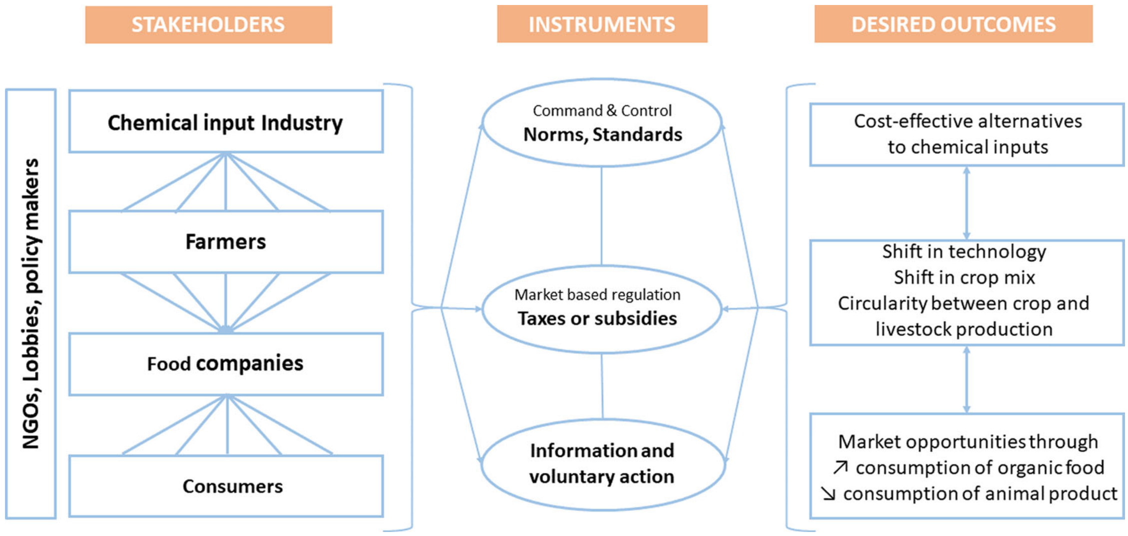

Fig. 1 | Framework for the design of policies to reduce excessive use of chemical input in agriculture. This diagram provides a summary of the approach proposed in the paper for reducing chemical inputs in agriculture. Our approach involves all stakeholders in the chain value, combining different public policy instruments to enhance their effectiveness, and sets precise targets for each stakeholder in the supply chain (desired outcome).

businesses[107]. Additionally, taxes or subsidies are not appropriate for adapting to particularly dangerous environmental or health situations that require a drastic response (e.g., bans on persistent organic pollutants such as chlordecone or DDT). In contrast, bans or restrictions can provide practical short-term solutions to such situations[108].

For these reasons, it is essential to view policy instruments as complementary and capable of enhancing each other's effectiveness. In this regard, a mixed regulatory system could combine both taxes and direct controls[108]. In typical circumstances, pollution taxes are set by the environmental authority to meet prescribed environmental standards. However, in unforeseen circumstances, direct controls can be employed.

By promoting the availability of cost-effective alternatives through appropriate sequencing, the combination of regulatory instruments can also help to reduce the financial burden of MBR instruments on farmers in the case of taxes, or on governments in the case of subsidies, and to ensure that international competition is not distorted. Denmark, which achieved a 40% reduction in N-surplus over 30 years by combining CC, MBR, and IVA-based measures, provides an instructive example. The implementation of CC measures before MBR and IVA measures led to better coordination between stakeholders and facilitated the acceptance of the regulation, as it was simply economically attractive for farmers to comply with the new restrictions, since the new technology was not too costly[109]. Voluntary actions were also particularly effective in paving the way for sustainable and economically feasible practices[110].

Finally, a combination of public policy instruments may be useful in broadening the adoption of low chemical input farming practices. Drawing on the Swiss initiative for pesticide-free agriculture, it was found that convincing future adopters requires specific information and data on the economic and environmental effects of changing practices, for which producers' expectations are a key determinant of adoption[102]. It may therefore be appropriate to combine IVA instruments (e.g., information on production risks, potential yields, extension service advice on agronomic techniques and mechanical weed control) with other market instruments—in the Swiss case subsidies in the form of price add-ons—to help shape expectations and encourage the transition to more sustainable practices.

Conclusion: a policy framework for reducing chemical inputs

Agriculture is confronted with several challenges due to the growing global population, limited land availability, climate change, and the health and environmental consequences associated with the use of chemical inputs. To ensure sustainable agriculture and safeguard the environment and public health, it is essential to reduce the excessive use of chemical inputs. While a large variety of agronomical options existing to reduce the use of chemical inputs, our analysis highlights the systemic nature of the barriers to reducing chemical inputs, as it appears that the regulations governing the agriculture sector as well as the organization of the agri-food system itself are designed to ultimately encourage the use of chemical inputs. Solving this conundrum requires a comprehensive redesign of the agri-food system, involving various stakeholders such as chemical input producers, farmers, companies, consumers, and policy makers. Balancing the need for increased food production to meet the demands of a growing population with the imperative of mitigating environmental impacts necessitates trade-offs. Consequently, it is crucial to identify feasible solutions that strike a balance between food production and environmental sustainability[25].

Proposed strategies for reducing chemical inputs should encompass both economic and regulatory measures for public decision-makers, as well as collective actions for private stakeholders. Following this logic, we present Fig. 1 as a framework for designing future regulations. This diagram adopts a systemic approach, considering all stakeholders involved at the farm level and beyond, from the chemical inputs industry to final consumers, as well as non-governmental organizations (NGOs), lobbies and policy makers. Within this landscape, it is important to recognize that each part of the value chain can be a barrier to another part: the lack of technical alternatives from the chemical industry or the lack of market opportunities for zero-inputs products can be barriers to the agricultural sector, which in turn can be a barrier to the other components of the chain. To enable systemic change, the policy framework should be appropriately designed to guide the different stakeholders towards the desired outcomes. In particular, the paper highlights the importance of combining different policy instruments to enhance their effectiveness, to ensure better coordination between stakeholders and reduce the financial impact, and to broaden the adoption of low chemical inputs farming practices.

This approach is relevant in areas where there is excessive use of chemical inputs. In nutrient-deficient countries, mainly in Africa, other strategies need to be considered, possibly involving incentives for the use of larger amounts of nitrogen fertilizer[111], or payment for environmental services for upscaling high-yield and highly diversified and decentralized chemical-free agroecological practices[17]. In addition, developing countries encounter specific barriers, such as difficulties in enforcing regulations and limited resources for policies and services to support transitions.

Box 1 | Policy recommendations for a system change towards reducing chemical inputs in agriculture

Policy makers should implement simplified and coherent public policies that avoid distorting international competition, with tailored solutions for pesticides and fertilizers separately: (1) For pesticides: minimize transition costs through incentive-based voluntary agreements and market-based instruments; (2) For fertilizers: reduce losses and optimize nitrogen use efficiency, especially in livestock production, and explore agronomic solutions to reduce nitrogen use.

Regulations should use a combination of policy instruments aimed at specific stakeholders to achieve the following objectives:

(1) Improve Consumer information
- Simplify product labeling to transparently communicate production methods and potential impacts.
- Promote the choice of sustainably produced and organic products.

(2) Support farmers
- Provide incentives to adopt low chemical inputs and agroecological practices.
- Facilitate peer-to-peer learning and train farmers to use lower-risk agricultural inputs.

(3) Engage food companies
- Establish sustainable sourcing policies with strong standards.
- Contracting with farmers to adopt sustainable practices.

(4) Promote innovation in the chemical input industry
- Promote investment towards environmentally friendly alternatives such as biopesticides and precision nutrient tools.
- Provide incentives for the production of environmentally friendly products.

In this systemic approach, the sequencing of actions is important, as technological alternatives and price signals need to be available at the right time so that the desired outcome in one part of the system can become a driver for change in the next, and so that implementation is not too costly. To facilitate system change, comprehensive information is required at an early stage to enable stakeholders to understand their options fully. Each stakeholder needs clear insights into the barriers hindering the reduction of chemical inputs in agriculture and the potential solutions for collective transition.

To summarize, reducing the use of pesticides and fertilizers in agriculture effectively requires a concerted effort by all stakeholders. Box 1 presents a set of policy recommendations for reorganizing agri-food systems in a way that involves consumers, farmers, lobbyists, food companies, and the chemical input industry to leverage existing solutions. By involving all stakeholders in the agricultural value chain, from consumers to the chemical input industry, we can take collective action to reduce the use of pesticides and fertilizers. This will ensure sustainable food production while protecting the environment.

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