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REVIEW ARTICLE

# Framing the future of the Koronivia Joint Work on Agriculture from science-based evidence. A review

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## Abstract

The Koronivia Joint Work on Agriculture (KJWA) and the Sustainable Development Goals (SDG) have brought agriculture onto the agenda of solutions to tackle climate change and sustainable development. The first KJWA roadmap came to an end in 2020. The conclusions will be reported at the UNFCCC COP 27 in 2022. Several options for the future of KJWA are on the table. We review the literature to take stock of the contribution of science to the first KJWA period and discuss on how research could help to strengthen the case for keeping up the work of KJWA. This paper reviews 175 peer-reviewed publications on technical (agricultural practices), socioeconomic, and policy actions or innovations that support and strengthen the role of sustainable agriculture on the global development agenda. The considerable diversity of science-based actions and innovations presented in the agricultural sector should contribute to the success of KJWA in putting agriculture on the climate agenda. In addition to the climate agenda, the review highlights the multi-functionality of sustainable agriculture which targets food security issues, of course, but also the 17 SDGs. Our review shows that KJWA has been extensively documented in the scientific literature on agricultural practices, the socioeconomic dimensions, and policies supporting actions. Nevertheless, research has to make special efforts (i) to set up methods that allow data comparisons and collections, and at the same time (ii) to tackle synergies and trade-offs in the achievement of the SGDs. The nexus approach could also provide a framework for the future of the KJWA process. The science-based evidence should continue to pave the way for the future KJWA to become an actionable structure within the UNFCCC arena. Echoing the previous assessment, the KJWA process should keep all stakeholders on board, including researchers.

**Keywords** UNFCCC · Climate change · Food security · Sustainable Development Goals · Multifunctionality · Nexus approach

## 1 Introduction

Agriculture plays a vital, multifunctional role for humanity, providing people with food and supplying industry with raw materials. However, agriculture generates a series of environmental problems. Agriculture uses 70% of freshwater resources (Contestabile and Kabat 2013) and is responsible for deforestation, particularly in the tropics (Franco-Solís and Montanía 2021). Among these environmental impacts, 23% of total net anthropogenic greenhouse gas (GHG) emissions, which drive climate change, derive from Agriculture, Forestry and Other Land Use (AFOLU) (IPCC 2019). Agriculture is also largely impacted by climate change. The predicted changes in climate are expected to have profound effects on soil fertility and water availability, crop yields (Abd-Elmabod et al. 2020; Assad et al. 2020; Defrance et al. 2020), global food supplies, prices, and the world economy (Liu et al. 2020). In the twenty-first century, agriculture faces important challenges in terms of production and environmental preservation, which will deeply impact people in every country.

Considering these global issues on food security and climate change, the United Nations introduced the Sustainable

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Development Goals (SDGs) and 169 targets to eradicate poverty, end hunger, improve human well-being, reduce environmental threats, and achieve sustainable development worldwide by 2030, ensuring that no one is left behind. Given that 821 million people go hungry, and every third person is malnourished, agriculture is at the core of this 2030 Agenda. Implementing sustainable agriculture is a key driver for achieving many SDG targets (FAO 2018). The Paris Agreement calls for an urgent plan of action to limit global warming to 1.5°C. Echoing this agreement, the 23rd Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) brought agriculture into international climate negotiations through the Koronivia Joint Work on Agriculture (KJWA) decision (UNFCCC 2018, COP decision 4/CP.23). KJWA requests the two Subsidiary Bodies of the UNFCCC [the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation] to jointly address issues related to agriculture with particular focus on the vulnerabilities of agriculture to climate change and essential support for food security (Drieux et al. 2019).

Several scientists have been involved in the KJWA process to bring science-based evidence into the debates held at the meetings addressing the five interrelated thematic topics of KJWA: (i) methods and approaches for assessing adaptation, adaptation co-benefits and resilience (topic B); (ii) improved soil carbon, soil health and soil fertility under grassland and cropland as well as integrated systems, including water management (topic C); (iii) improved nutrient use and manure management towards sustainable and resilient agricultural systems (topic D); (iv) improved livestock management systems (topic E); and (v) socioeconomic and food security dimensions of climate change in the agricultural sector (topic F). Topic A meant to deepen preliminary work before KJWA broadly covers all the 5 specific topics. The added value of the multi-stakeholder mechanism set up by KJWA has been recognized, along with the contribution of science. The first KJWA roadmap came to an end in 2020. The conclusions will be reported at UNFCCC COP 27 in 2022. Several options for the future of KJWA are on the table: "(i) Parties make full use of the opportunities represented by KJWA to move on from formal discussions to concrete actions on the ground, (ii) technical and/or financial priorities are clearly stated "No-regrets options," the modalities to guarantee their realizations paving the way for the next KJWA roadmap, (iii) extending the existing roadmap, or (iv) no agreement between Parties" (Drieux et al. 2021).

As a part of the process, research may inform decisions about the future of KJWA. The objectives of this review are (1) to strengthen the credibility of the Koronivia process to target food security, climate change, and most of the 17 SDGs and (2) to provide science-based evidence to plan the topics for the next round of workshops and expert meetings framing the future of the KJWA process.

Does science-based evidence point to a specific working agenda for the future of the KJWA?

To answer this question, this scientific review aims to synthesize the scientific knowledge related to past KJWA topics as regards the 17 SDGs. We hypothesize that, through this review, a large diversity of agricultural practices, socioeconomic organizations or policies that benefit farmers, society and the environment will help to underline scientific inputs into the KJWA process. Finally, we discuss how science could support the case to keep up KJWA work within the UNFCCC organization and, more broadly, boost the position of sustainable agriculture on the 2030 Agenda (Fig. 1).

## 2 Material and methods—identification of the articles reviewed

The literature review comprised four main steps: (i) identification, (ii) screening, (iii) eligibility, and (iv) analysis (Fig. 2). The identification process included the search for keywords related to KJWA and SDG targets to provide database publications for the screening process. This step combined the A, B, C, D, E, and F topics KJWA and SDG keywords (Supp. Info. Tables S1 and S2) to determine all the publications that establish links between KJWA topics and the SDG targets, using the Web of Science (WoS) database (43,000 references). Topic A represented the KJWA broadly with unspecific keywords (i.e., agriculture, climate change and development). Topics B, C, D, E, and F focused on specific keywords on soils, nutrient use, water, livestock, methods for assessing adaptation, socioeconomics, and food security dimensions (see Table S1). For this step, we used PubMed as an additional database to complement the WoS results, particularly for SDGs 4, 5, 7, and 16. For this step, we used a combination of three conditions:

- The function "AND" between KJWA keywords, to obtain specific documents about KJWA topics,
- The function "OR" between SDG keywords to obtain multiple documents about SDGs,
- The function "AND" between the first and second condition to obtain a combination of papers that talk about both KJWA topics and SDGs

We next collected 7221 papers [6,350 from the WoS database and 921 from PubMed, 1 April 2020 (Defrance and Ramifehiarivo 2020)]. The screening and eligibility process (the second and third steps) applied a set of criteria to select publications by period, study type, and country studied. Our identification process includes the search for keywords in

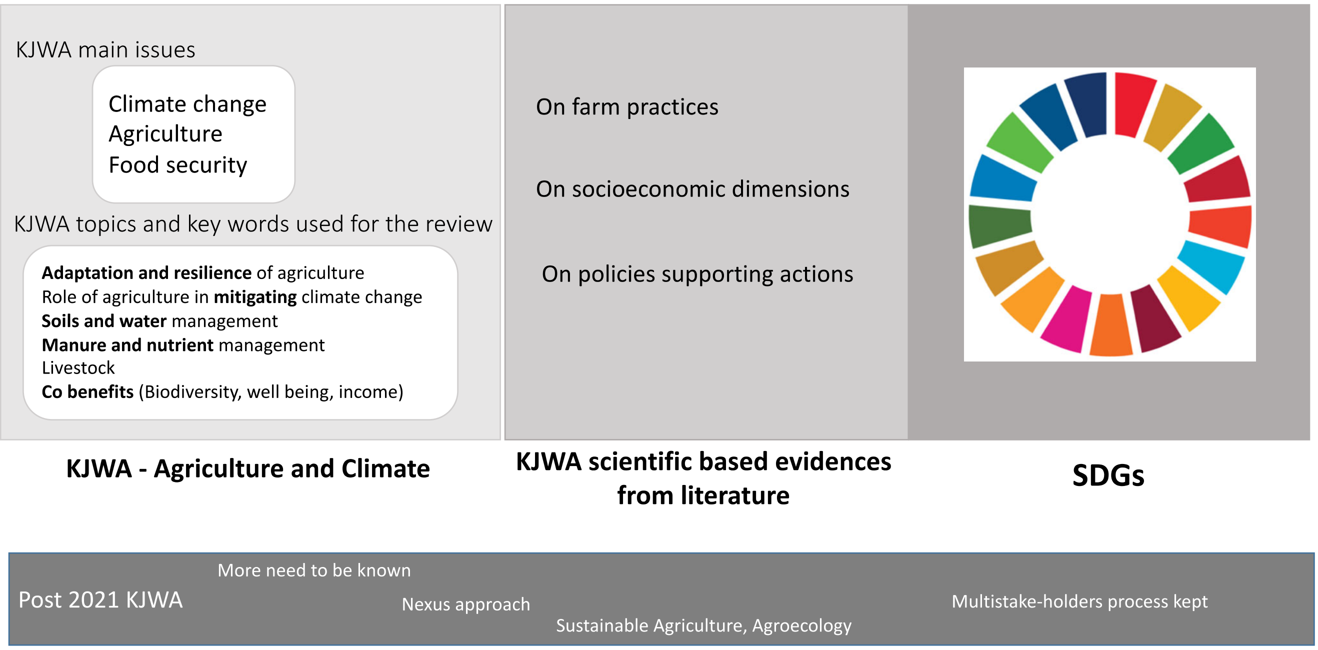
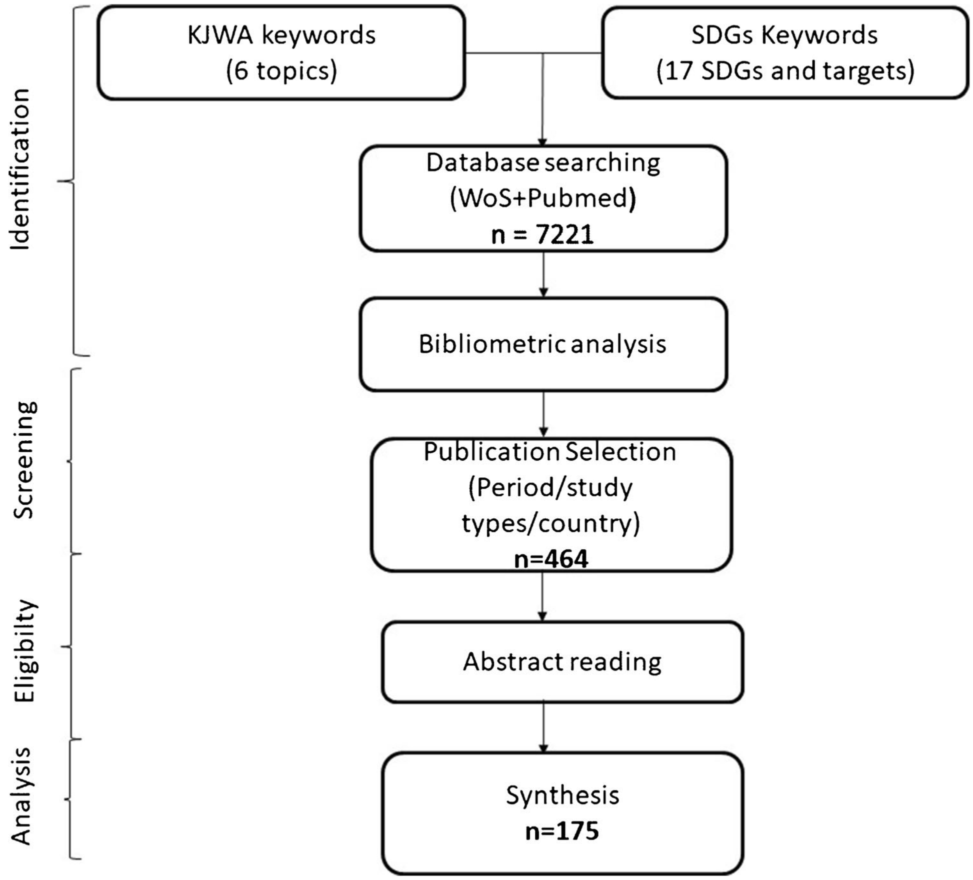


**Fig. 1** Framework of the paper: an iterative approach from KJWA to SGDs to conclude on Post 2021 KJWA key issues

papers published before the KJWA decision. The period 1990–2018 was chosen, and we aimed to analyze the science inputs into the KJWA process launched in 2017. We based the analysis of the evolution of relevant keywords on this time series. To select study types, R software was used to automatically read the title, abstract, keywords and journal types in our database (WoS + PubMed) to search for all publications that mentioned at least one of the following words: “review,”

**Fig. 2** The four steps for the literature review



"article," "analysis," "meta-analysis," "synthesis," "study case," "case of study." Any publications without these words were excluded from our analysis.

The same method was used for all abstracts or titles that mentioned the country studied according to the World Bank list, or at least one of the following words: "Global," "Regional," "United Nations," and "FAO." After the screening process focussed on the 2008–2018 period, we reduced our bibliographic database to 464 papers. We also classified the papers by considering country income based on the World Bank classification proposed in 2019 (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519) for bibliometric analysis.

The eligibility process meant reading the titles and abstracts of the 464 articles. Articles (title, abstract) documenting research perspectives on (i) agricultural practices, (ii) socioeconomic dimensions of agricultural systems at local or global scale, or (iii) policies supporting action which could benefit farmers or nurture decision-makers and target agriculture were selected for in-depth reading. Once the eligibility process was completed, we moved on to the analysis, based on a synthesis of the 175 selected papers, supplemented by recent citations completing the argumentation. The list of the references at the end of the paper only includes the references quoted in the manuscript. The lists of the references selected by the screening ($n = 464$) and the eligibility ($n = 175$) steps of the bibliographic analysis were available in Defrance and Ramifehiarivo (2020).

The three main points—(i) agricultural practices, (ii) socioeconomic dimensions, and (iii) policies supporting actions—structured the synthesis of the 175 papers read in-depth. For each of these points, we identified existing practices, organization, actions or any innovations that help target climate issues, i.e., adaptation and mitigation issues; agricultural issues, i.e., resources (soil, water, organic and nutrient resources), livestock, and plant productivity issues; and food security issues, i.e., plant productivity, food utilization, food accessibility, and food stability issues.

## 3 Scientific literature on KJWA focused on several SDGs

Our results show that the scientific literature publication dynamic is influenced by the political agenda. Although there were publications prior to 2010, a jump in the numbers for each KJWA topic is particularly noticeable after 2010. As topic A was very broad and covered agriculture, climate change and development keywords (Supp. Info Table S1), it featured most commonly, with nearly 200 references in 2018. By contrast, topics B and D appeared in only around 15 references in 2018 (Fig. 3). The scientific literature anticipates political agendas, but the number of papers being published has accelerated, echoing their main deliverables (e.g., IPCC AR4, UN SDGs, UNFCC KJWA topics, Fig. 3).

The scientific literature covers all countries, even though there are disparities in the number of articles and in terms of the KJWA keywords evoked (Table S3, supp info). The number of articles on or from rich countries (high-income country (HIC)) is higher in all years and for all topics. The number of references remains limited for lower middle-income countries (LMC) and low-income countries (LIC), especially for studies which target topic B of KJWA (Methods and approaches for assessing adaptation, mitigation co-benefits and resilience).

The scientific literature selected on the KJWA keywords refers to all the SDGs, but especially to SDGs 2 (Zero hunger), 15 (Life on land) and 13 (Climate action) (Fig. 4). These three SDGs were included in 80%, 60% and 25% of the references, respectively. By contrast, SDGs 4 (Quality education) and 5 (Gender equality) were rarely referenced in papers related to KJWA topics, accounting for less or just over 10% of references across topics A, B, C, D, E, and even topic F focused on the socioeconomic dimension.

Moreover, this bibliometric analysis shows that the topics targeted by the Koronivia process concern every country around the world and concern all 17 SDGs. Research on these topics is very active to formalize knowledge on agricultural practices and the organization (socioeconomic actions, public policies) of markets and territories to achieve the objectives of Koronivia and of the 17 SDGs.

## 4 Three main agricultural dimensions addressed by KJWA keywords

### 4.1 Agricultural practices

The scientific-based evidence identified by the review concerns plant and livestock potential, improvement of their management including manure management, and the natural resources (soil, water and nutrients) for crop growth. The most abundant references describe the interactions between "Promoting soil organic matter management," "Enhancing water use efficiency," and "Enhancing nutrient use efficiency" and adaptation, mitigation, soil and water productivity agriculture issues (Table 1). We have not been able to establish an exhaustive list of all the technical means proposed in the literature to combat climate change, and have only briefly detailed some of them to highlight the diversity of the technical means proposed by science, while showing how these techniques also target several SDGs (Fig. 5).

#### 4.1.1 Towards adaptation

**Enhancing plant potential by crop diversification.** New cultivars, diverse crop rotations and intercropping were put

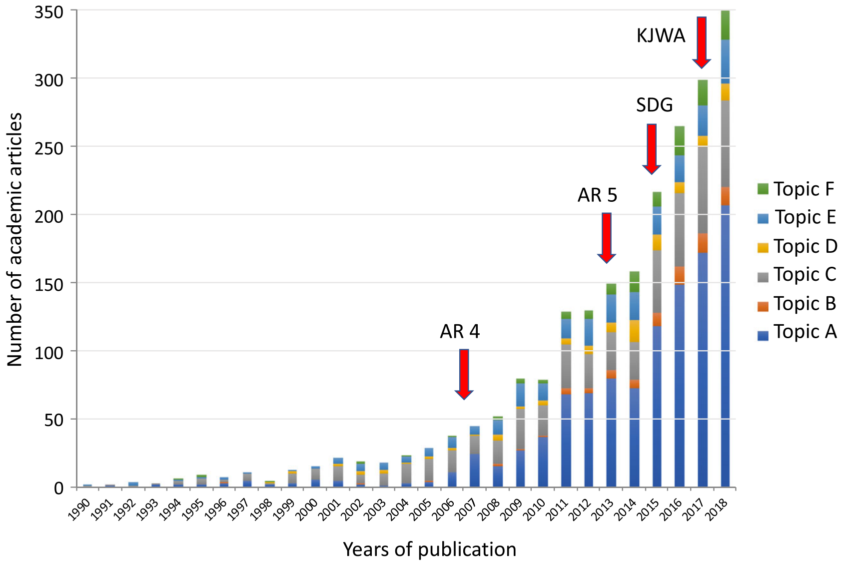


**Fig. 3** Number of publications (Web of Science) which reference the different Koronivia topics (1990–2018). Topic A: meant to deepen preliminary work before KJWA broadly covers all the 5 specific topics. Topic B: methods and approaches for assessing adaptation, adaptation cobenefits and resilience. Topic C: improved soil carbon, soil health and soil fertility under grassland and cropland as well as integrated systems, including water management. Topic D: improved nutrient use and manure management towards sustainable and resilient agricultural systems. Topic E: improved livestock management systems. Topic F: socioeconomic and food security dimensions of climate change in the agricultural sector. AR 4 and AR 5: Fourth and fifth Assessment Report of IPCC

forward as ways of enhancing plant potential, meeting nutritional needs, and increasing biodiversity. New cultivars for cereals or grain legumes were selected for their high yield and high quality potentials. At the same time, these cultivars could enhance the diversification of cropping systems, increase plant potential (Singh et al. 2015) and strengthen crop

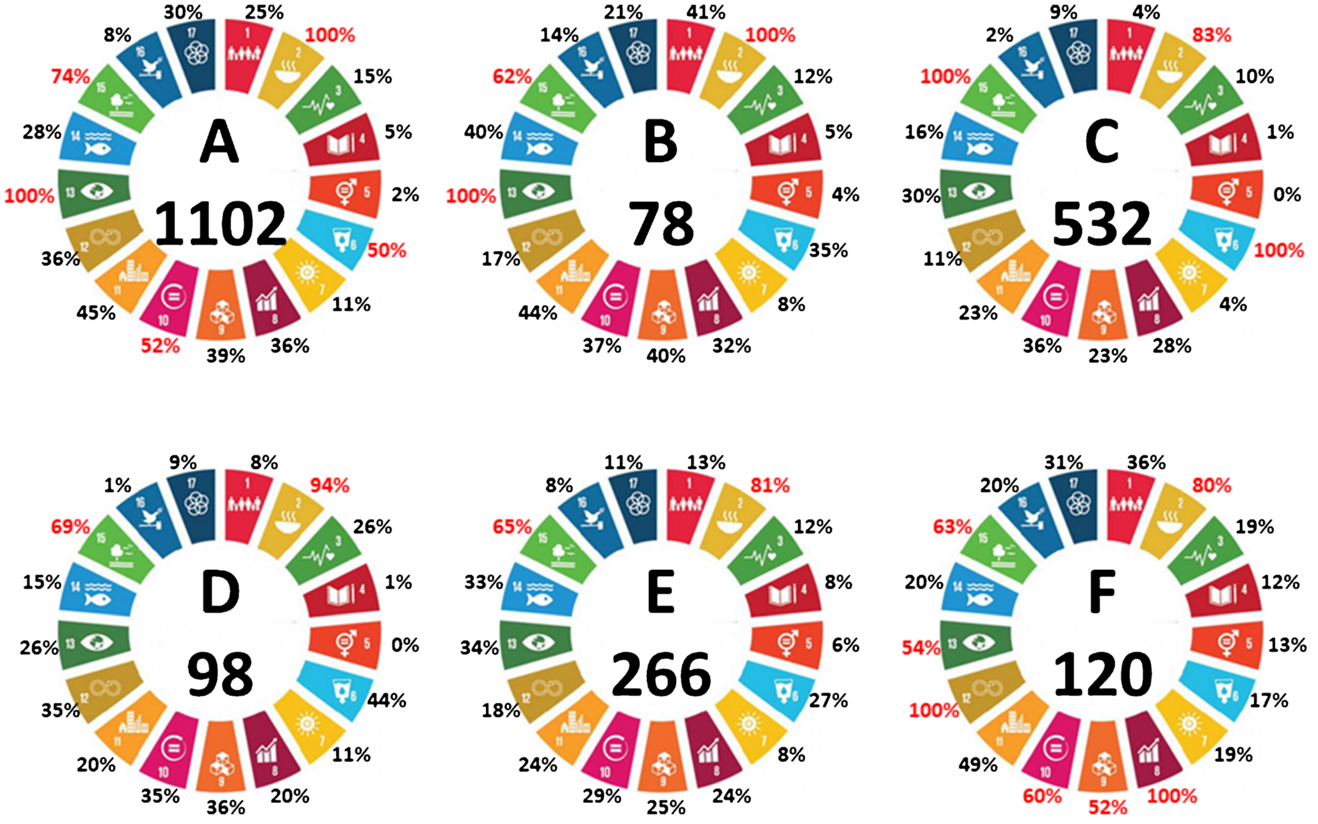


**Fig. 4** Scientific papers related to Koronivia topics and referencing SDGs. For each KJWA topic, the number in bold indicates the number of publications, and the percentage refers to the proportion of these papers that reference each SDG (with percentages higher than 50% in red)

**Table 1** Publication references distribution according on farm agricultural practices research perspectives and global issues. *Co-benefit is included. Details of the paper numbers are visible in Defrance and Ramifehiarivo (2020)

| Issues | | Enhancing plant potential by crop diversification | Enhancing livestock potential by breeding , nutrition and pasture management | Improving crop management to reduce GHG | Optimizing manure management to reduce CH4 and N2O | Enhancing livestock potential through genetics, nutrition and animal welfare to reduce GHG | Promoting soil organic matter management | Promoting a mixed crop-livestock farming system | Enhancing water use efficiency and soil conservation | Enhancing nutrient use efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| Climate change | Adaptation* | 187, 193, 101, 237, 410, 63, 28, 172, 240, 20, 353 | 424, 410, 341, 79 | | 171, 384, 341 | | 233, 171, 28, 166, 187, 24, 248, 192, 106, 193, 136, 169, 101, 250, 247, 465, | 318, 341, 399, 436, 106, 47, 20 | 203,360, 233, 171,187, 193, 101, 250, 247, 465, 231, 147, 352, | 109, 265, 276, 361, 250, 277, 384, 389, |
| | Mitigation* | | | 148, 277, 265,150, 156, | 390, 384, 268, 265, 389, 419, 394 | 214, 399, 424, 410, 341, 79, 232 | 231, 147,299, 334, 204, 370, 295, 63, 203, 180, 199, 8, 379, 94, 17 | | 364, 354, 295, 56, 363, 277, 370, 354, 136,180,237, 379, 8, 17 | 364, 394, 359, 199, 136 |
| Agriculture | Soil | | | | 384 | | 233, 295,187, 193, 101, 250, 203, 136, 247, 180,299, 193, 199, 192, 334, 106, 370, 169 | | 233, 187, 193, 101, 250, 203, 136, 247, 295, 180, 237, 363, 364, 17, 8 | 136, 389, 364 |
| | Water | 187, 237, 352 | | | 384 | | 233, 187, 193, 101, 250, 203, 247, 295, 370, 379 | | 233, 187, 193, 101, 250, 203, 247, 295,56, 363, 360,277, 352, 364, 370, 354, 379 | 364, 361 |
| | Manure management | | | | 390, 384, 268, 265, 389, 394, 419 | | | 318 | 295 | 389, 394 |
| | Nutrient management* | | | | 148,394 384, 419 | | 247, 295, 465, 192, 199, 334 | 318 | 247, 295, 465, 363, 364 | 109, 265, 276, 361, 250, 277, 384, 389, 364, 394, 359, 199, 136, 8, 379, 463, 353 |
| | Livestock | | 47, 20, 318, 410, 417, 341, 79, 319, 426, 400, 232 | | 394, 47, 268, 419 | 47, 318, 424, 417, 214, 341, 79, 319, 232 | | 436, 106, 318, 341, 399 ;47 | | 359 |

**Table 1** (continued)

| Issues | | Enhancing plant potential by crop diversification | Enhancing livestock potential by breeding , nutrition and pasture management | Improving crop management to reduce GHG | Optimizing manure management to reduce CH4 and N2O | Enhancing livestock potential through genetics, nutrition and animal welfare to reduce GHG | Promoting soil organic matter management | Promoting a mixed crop-livestock farming system | Enhancing water use efficiency and soil conservation | Enhancing nutrient use efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| | Plant productivity* | 338, 240,147, 20, 353 | 319 | | | 319 | 233, 171, 28, 166, 187, 24, 248, 192,106, 193, 136, 169,101, 250, 247, 465, 231, 147, 299, 334, 204, 370, 295, 63, 203, 180, 199, 8, 379, 94, 17 | 318, 341, 399, 436, 106, 47, 20 | 180, 465, 8, 379, 353, 17, 147,360 | 463, 8, 379, 353 |
| Food security | Food access* | 231 | 319 | | | 319 | 180, 8 | 318, 341, 399, 436, 106, 47, 20 | 180, 8, 379 | 8, 379 |
| | Food utilization* | 172, 147, 353 | 319 | | | 319 | 180, 8, | 318, 341, 399, 436, 106, 47, 20 | 180, 8, 379, | 8, 379 |
| | Food stability | 338, 240, 231, 172, 147 | 319 | | | 319 | 180, 8 | 318, 341, 399, 436, 106, 47, 20 | 180, 8, 379 | 8, 379 |

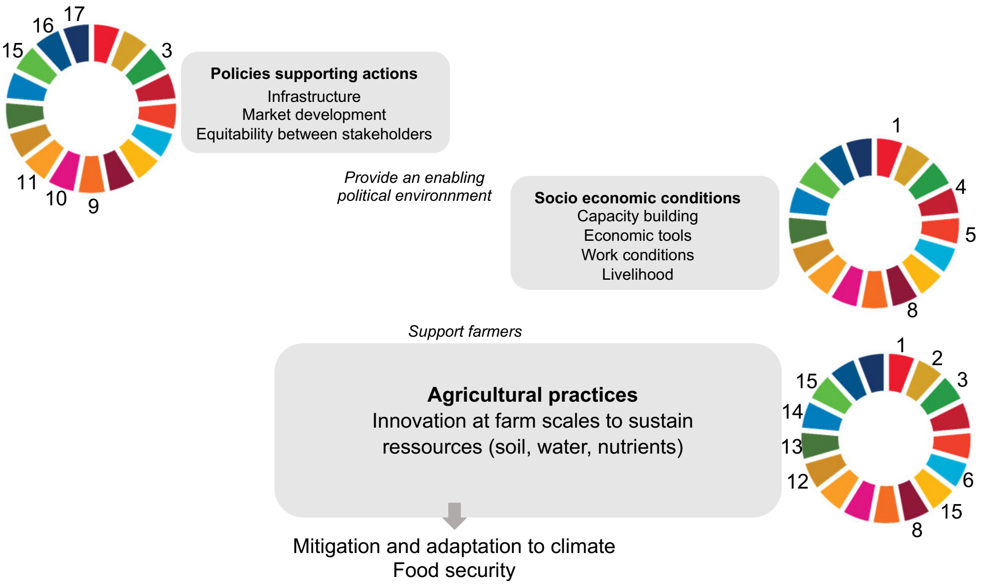


**Fig. 5** Actions, conditions, and practices in agriculture identified in the scientific literature addressed by KJWA keywords and targeted SDGs. The size of the boxes indicates the number of scientific papers captured by the review. Agricultural practices: 73 publications. Socioeconomic conditions: 36 publications. Policies supporting actions: 35 publications

capacity to adapt to environmental changes (Bedoussac et al. 2015; Ortiz et al. 2008). The diversification of cropping systems, such as cereals intercropped with grain legumes, is also often put forward as a way of sustaining agriculture (Bedoussac et al. 2015; Chuku and Okoye 2009; Ortiz et al. 2008). Some studies reported that with intercropping, total grain production increases, the protein concentration of cereal grain improves, while weeds, pests, and diseases are reduced, and soil properties are improved (Lopes et al. 2016; Smith and McSorley 2000). Atmospheric $N_2$ fixed by N-fixing legumes could benefit associated cereal crops, reducing the need for N mineral fertilizer, and therefore lowering the environmental footprint of manufactured mineral fertilizers (Crews and Peoples 2004, 2005; Partey et al. 2018). Nevertheless, all these practices need to consider the possible crop competition for water, nutrients, and light.

Because a mere 1% of available tree species have been studied for their agricultural potential (Shelef et al. 2017), investing in the diversification of agricultural products could be a priority for not only climate but also health, biodiversity, or the farmer's financial income. The diversification of crops provides consumers with a wider variety of commodities, providing a large spectrum of vitamins and micronutrients leading to better health (SDG3) (Misselhorn et al. 2012). The use of native and local plants to increase genetic diversity and enhance dietary options could also be promoted. In addition, the use of wild species is likely to enhance biodiversity (SGD15) (Lidder and Sonnino 2012).

**Enhancing livestock potential by breeding, nutrition, and pasture management.** Four main incremental adaptations to enhance livestock capacity under climate change are reported (Escarcha et al. 2018): (i) breeding, i.e., alleviation of heat stress by selection of heat-tolerant species and breeds, disease-resistant breeds, and adapting animals to local conditions; (ii) improving nutrition in quality and in quantity (Moore et al. 2009; Scasta et al. 2016); (iii) increasing the efficiency of land and water use by managing pastureland differently (e.g., pasture irrigation, area enclosure); and (iv) enhancing livestock management by managing pests, weeds, and disease. Adapting the health, diet, and productivity of livestock to climate change is essential for a large majority of people who depend on livestock for their own diet, jobs, or income. Fostering higher animal welfare and productivity achieves a set of SDGs targets (Keeling et al. 2019).

### 4.1.2 Towards mitigation

**Improving crop management to reduce GHG.** In the agricultural sector, several mitigation strategies have emerged: (i) avoiding emissions by planting energy crops (SDG 7), by converting agricultural waste to fuel ($CO_2$ reduction), by using organic and slow-releasing N fertilizer ($N_2O$ reduction), or by controlling soil drainage ($N_2O$, $CH_4$ reduction); and (ii) increasing carbon capture by increasing biomass production with, for instance, agroforestry or cover crops (e.g., Lin and Xu 2018; Tongwane and Moeletsi 2018; Wang et al. 2017).

**Optimizing manure management to reduce $CH_4$ and $N_2O$** Manure is a source of GHG emissions, mainly methane $CH_4$ and nitrous oxide $N_2O$. The emissions discharged depend on manure composition, local management practices (treatment, storage, and field application), and climatic conditions (Petersen et al. 2013). Composting to manure is an efficient mitigation option (Novak and Fiorelli 2010), but a combination of techniques seems to increase this efficiency (Chadwick et al. 2015). For example, adding straw to manure or dewatering manure reduce GHG emissions. Improving manure storage and techniques for rapid incorporation into soil are also proposed (Minet et al. 2016; Nicholson et al. 2004). Moreover, these composts could be sold at higher prices than standard composts, thus enhancing producers' incomes (SDG 2 and SDG 1). Composts could also be used to control crop pests by removing the need for chemicals (Murrell 2017), the production of which results in GHG emissions (SDG 12.4). Producing biogas from manure and waste processing is another practice proposed to avoid emissions from fossil sources (SDG 7) (Tsai and Lin 2009).

**Enhancing livestock potential through genetics, nutrition, and animal welfare to reduce GHG.** Genetic strategies include breeding (e.g., cross-breeding with a native breed) to improve the animals' efficiency leading to a reduction in the total number of heads, and thus in the total GHG emissions, required for a given production level (Escarcha et al. 2018). Nutritional strategies include increased crop and tree fodder cultivation, competition (feed-food) for cereal grains in ruminant diet, balanced feed rations, provision of clean drinking water, and improved feed storage for periods of scarcity. For instance, a good mitigation option for ruminants is the supply in high digestibility forages, and the inclusion of energy-dense feeds (e.g., cereal grains) in the ration (Pereira et al. 2015). Welfare management strategies include (i) shade and shelter available in grassland and silvo-pasture to decrease heat stress, and (ii) hygienic practices to prevent vector-borne-diseases and epidemiological surveillance (Shinde and Sejian 2013).

### 4.1.3 Towards both adaptation and mitigation

**Promoting soil organic matter management.** As soil organic stock is the biggest carbon reservoir in the terrestrial ecosystems, increasing that stock drew much attention. Soils and agriculture have been recognized as part of the solution to limit climate change (Minasny et al. 2017; Soussana et al. 2019). All forms of crop management that favor soil organic matter inputs, such as cover crops, grassland, crop residue management, or agroforestry, are practices aimed at increasing or maintaining soil organic carbon stocks (Cardinael et al. 2018; Chenu et al. 2019; Fujisaki et al. 2018). These agricultural practices based on soil organic carbon management achieve three outcomes: (i) increased productivity for improved food security (SDG 2, SDG 1, SDG 8); (ii) improved adaptation and resilience to climate change and variability; and (iii) reduced greenhouse gas emissions (mitigation) (SDG 13) (Lipper et al. 2014). Some of the main practices are (Zougmoré et al. 2018):

- Conservation agriculture, which is referred to as (i) soil conservation by non-inversion tillage or no tillage, ii) crop rotations, and (iii) soil cover with cover crops, managed natural flora, stubble, mulching or crop residues (Stagnari et al. 2010; Zheng et al. 2016). These practices can also limit soil erosion, reduce the risk of surface water pollution, increase drainage and water-holding capacity (SDG 6 and 12), improve soil structure and stability, increase soil organic carbon (SOC) and soil biodiversity (SDG 15) (Busari et al. 2015; Dumanski and Peiretti 2013; Lal 2009; Powlson et al. 2011).
- Organic farming, which prohibits the use of chemicals (SDG 12) to produce healthier foods (SDG 3) and allows higher sales prices to generate economic growth and help combat poverty (SDG 8 and SDG 1) (Bedoussac et al. 2015; Mie et al. 2017; Rahmann et al. 2009). As tillage is generally considered to increase SOC mineralization, in organic farming, soil perturbation to control weeds could be counterproductive to enhance C stocks. However, recent meta analysis showed high variability of the impact of no tillage on SOC sequestration. There was may be an additional SOC storage in superficial soil layers, but no or little SOC sequestration for the whole soil profile (Chenu et al. 2019). The origin of these impacts must be more thoroughly studied.
- Agroforestry, defined as the integration of trees and shrubs with livestock and/or crops. This is widespread on all continents (Andrieu et al. 2017; Arevalo 2016; Manalo et al. 2016; Mbow et al. 2014; Stavi and Lal, 2013; Zougmoré et al. 2018). For example, improved fallows mean planting mainly perennial legume trees (as in the case of a fertilizer tree system) and shrub species (e.g., *Cajanus cajan*, *Sesbania* sp., *Glyricidia* sp.) in rotation with cultivated crops (e.g., maize). This is popular because it increases soil carbon sequestration, reduces GHG emissions, improves the soil's physical properties, enhances water filtration, and leads to reduced water runoff and soil erosion relative to the production systems. Improved fallows, in the case of shrub species, are likely to increase fodder availability during dry periods and provide substantial biomass for charcoal production (SDG 7) (Partey et al. 2017). Agroforestry also provides co-benefits by increasing biodiversity (SDG 15) and produces socioeconomic benefits (SDG 1, 8) (Hernández-Morcillo et al. 2018).

Other practices have been studied, but their carbon and energy balance need to be evaluated and their effects on fertility transfers at different scales are undocumented. Among these practices, the use of stable compounds such as biochar as a soil amendment, or as part of an organic amendment (e.g., compost or manure), may be a cost-effective and low-risk alternative to improve agricultural productivity and to mitigate climate change over the long term (Lal 2009; Mehmood et al. 2017).

**Promoting mixed crop-livestock farming systems.** The mixed crop-livestock systems are extensively documented and promoted as a way of adapting to and mitigating climate change. It enhances the efficiency of the nutrient cycle, promotes the sustainable management and efficient use of natural resources (SDG 12, 15), strengthens soil functioning and health (SDG 3) while maintaining or improving economic returns (SDG 1, 8) (Hassen et al. 2017; Luscher et al. 2014). Moreover, integrated crop-livestock systems have been described as being less vulnerable to disease and climate variability and as increasing profitability (SDG 8) (Stark et al. 2016). Mixed crop-livestock systems are very diverse. Some examples include temporary grassland or sod-based crop rotations (2–10 years of perennial forage, i.e., sod with 1–8 years of crops), grazing winter cover crops in cash-crop rotations, crop residue grazing, and dual-purpose cereal crops for grazing and grain harvesting (e.g., wheat) (Faust et al. 2018). Other examples also exist combining aquaculture with crop production such as the shrimp and rice system (SDG 14). Promoting aquaculture and seafood production is highly recommended for better health (SDG 3) and can also contribute to food security (Bostock et al. 2016).

**Enhancing water use efficiency and soil conservation.** Given the importance of soil (SDG 15) and water resources (SDG 6) for agricultural production, there is a need for practices designed to combat soil degradation and water scarcity (Raclot et al. 2018). Diverse soil and water conservation techniques have been documented, such as conservation agriculture (see Sect. Promoting soil organic matter management), to combat these threats. Many of them can greatly influence GHG emissions (SDG 13) (Kassam et al. 2011). Enhancing water use efficiency and soil conservation maintains or promotes biomass production and benefits carbon capture from the atmosphere through the biomass, while soil organic carbon stocks increase. These techniques could imply irrigation equipment or techniques based on slope correction to avoid water losses (Batey 2009; Ramos and Martínez-Casasnovas 2007; Williams and Weil 2004). The modification of irrigation equipment, e.g., conversion of flood, sprinkler, and microjet irrigation to drip systems could save up to 34% irrigation water (Goodwin and O'Connell 2017; Thacker et al. 2008). Nevertheless, by maintaining soil moisture, irrigated soil affects soil microbial activities and soil respiration. The overall $CO_2$ balance must be monitored under such contexts, which remain poorly studied at this stage.

Water-saving irrigation technologies and strategies also include (i) water management such as alternative wet and dry, which is used in "System of Rice Intensification" to reduce water depletion, increase nutrient availability, decrease $CH_4$ and $N_2O$ emissions, and increase farmers' income (Humphreys et al. 2010; Li et al. 2009), and (ii) plant management such as de-branching and canopy hedging to reduce transpiration (Goodwin et al. 2006).

**Enhancing nutrient use efficiency** Fertilizer application should always be based on plant demand and soil nutrient status to reduce the environmental impact of fertilizer uses. Integrated Soil Fertility Management (ISFM) is seen as a key element in the transformation towards a sustainable intensification of agricultural practices (Holden 2018). ISFM relies on (i) proper fertilizer management, (ii) use of improved varieties, (iii) the combined application of organic inputs and fertilizer, and (iv) adaptation of input application rates to within-farm soil fertility gradients (Vanlauwe et al. 2010). Mapping of soil properties and yields will help to calculate fertilizer dose, i.e., composition, time of application, and location to a very precise scale (plots of less than 1 $m^2$) (Arrouays et al. 2020; Iticha and Takele 2019). ISFM echoes SDG 12 for achieving sustainable management (efficient use of natural resources in synergy with increasing yields, SDG 12.2) and the adoption of the 4 Rs (right source, right rate, right time, right place) fertilization techniques (Tongwane and Moeletsi 2018). The objective of these techniques, along with a modification of the fertilizer types, is to reduce environmental impacts such as phosporus or nitrate leaching and $N_2O$ emissions, while maintaining yields (King et al. 2015; McNeill et al. 2005; Pan et al. 2017; Stoate et al. 2009; Wakeel et al. 2017).

## 4.2 Socioeconomic dimensions

There is much less scientific-based evidence on the socioeconomic dimensions than scientific-based evidence on agricultural practices (Tables 1 and 2). Research proposes innovations but the adoption of any kind of technology would depend on productivity options, climate risk efficiency, and the ability to meet end-user and market demands (Siddique et al. 2012). This review does not look in-depth at innovative local practices that are important for enhancing the sustainability of agriculture. However, the review identified socioeconomic (Table 2) and political supports needed to successful upscal science-based on-farm practices (Table 1) (Makate 2019; Giller et al. 2009; Ojiem et al. 2006, Table 3). Technology proposals are reportedly less widely adopted when their benefits or effects have to be considered over the long term. Transition towards and adoption of all these practices involves more than education, policy and outreach. It also requires consideration of nonmaterial factors associated with culture, values, ethics, identity and emotion that operate at individual, household and community scales, and interact with regional, national, and global processes (Gosnell et al. 2019). The references identified by this analysis show that supporting capacity building of all stakeholders, developing economic tools, and improving working conditions and farmers' livelihoods are the main entry to reducing vulnerability and improving adaptation of agricultural systems and rural populations. We noticed a surprising abundance of references on "enhancing farmer's knowledge" and "increasing market access"

(Table 2). This could echo the need to implement innovations concerning agricultural practices proposed in Table 1, especially the need to diversify agricultural productions. As in Sect. 4.1, we have not been able to establish an exhaustive list of all the scientific-based evidence in the papers, so have only briefly detailed some of them to highlight the diversity of the socioeconomic actions proposed by science and show how these actions may also achieve several SDGs (Fig. 5).

### 4.2.1 Supporting capacity building

**Enhancing farmers' knowledge.** Farmers need to acquire the basic knowledge before they can adopt and implement technology on their own farms. This capacity building will help them to plan any changes in their traditional practices, i.e., to plan and potentially choose between all the technical options on offer. For example, the conservation agriculture approach needs a lot of information before it can be adapted and then adopted in a specific environment. Farmers need to know about soil and plant vulnerabilities (erosion, pests, etc.), along with the methods available to combat these vulnerabilities (i.e., genotype choice, crop rotation, nutrient management, hedges, fungicide application, etc.) (Stagnari et al. 2010).

Professional expertise should be mobilized to train farmers, extension services and organizations in new agricultural techniques. Technicians should promote the best land-use system for carbon sequestration, or GHG mitigation potential and productivity (Lin and Xu 2018; Wang et al. 2017).

Capacity building should not only focus on technical operations but should also spotlight the economic and marketing specificities of production to help farmers to be included in the overall food value chain (Adenle et al. 2018).

**Encouraging experience sharing and community-based approaches.** Sharing experiences among primary producers not only improves their technical knowledge but also encourages community resilience and social relations (Cheng et al. 2017), while reinforcing their confidence and empowerment. In addition, farmers' knowledge is valuable in enlightening the results of research. For example, Kenyan farmers adapted researchers' proposals by integrating their need to boost maize yields in 2008. During experiments, the Kenyan researchers showed that the most successful arrangement for boosting maize yields was crop rotation with the inedible legume mucuna (*Mucuna pruriens*), using fertilizers. However, the farmers intercropped maize with edible soya beans and did not use fertilizers. The reason given was that it was deemed socially unacceptable to grow a crop that could not be eaten. In addition, the farmers found new uses for mucuna (Watts and Scales 2015).

The creation of platforms to enhance experience sharing is put forward as a way of supporting the dissemination of sustainable agriculture (Partey et al. 2018). Participatory research and farmers' networks contribute to reinforcing these platforms (Weber et al. 2018). Providing these platforms brings together stakeholders with different backgrounds and interests (men and women farmers, traders, food processors, researchers, government, etc.) and offers a wide diversity of technologies. They could play a key role in promoting sustainable agriculture at local, regional and national scale.

**Empowering women.** Across developing countries, where smallholder family farms prevail, gender equity (SDG 5) is a key challenge for sustainable agriculture. Women perform the majority of agricultural tasks and are highly affected by food and cash shortages due to imbalances intra-household and in society. The lower level of adoption of new techniques among women is explained by lower access to resources and less secure tenure. Women are also often neglected by information and service providers (Kristjanson et al. 2017), even though they are key stakeholders. For example, in the livestock sector, where about two-thirds of poor livestock keepers (farm animals) are estimated to be women (Nirmala et al. 2012). Adequate support with training, integration of good practices, and livestock management knowledge and skills building (feed, management of animal diseases) are likely to improve women's capabilities and lead to higher productivity while improving the well-being of poorer households (Bain et al. 2018; Mottet et al. 2018; Shang et al. 2016). It appears essential to provide women with technical education (SDG 4) (Brandth 2006; Trauger et al. 2008) and encourage them to participate in agricultural income management programmes and microfinance opportunities.

However, all these education programmes must be adapted to the specific needs and knowledge of women. They should be based on prior socioeconomic and gender analysis to build gender-appropriate information to support sustainable agriculture (Jost et al. 2016). Agricultural development decision-makers and project designers need to "design with gender in mind" (Negin et al. 2009). Stronger female participation in participatory research approaches could also provide some insights into women's adaptive capacity and identify new proposals to develop sustainable agriculture.

Empowering women through agriculture also has the potential for cascading effects through households and communities due to women's role as managers of daily life, including health, children's education and welfare, and market activity (Negin et al. 2009). Thus, agricultural development needs to address persistent gender gaps to achieve sustainable agriculture (Misselhorn et al. 2012; Doss et al. 2018; Pattnaik et al. 2018).

Our review did not capture youth and vulnerable people as the keywords selected to represent SDG 5 on gender equality only focused on women (Mat Sup. Table 1). Young people

**Table 2** Publication references distribution according to socioeconomic dimensions and global issues. *Cobenefit is included. Details of the paper numbers are visible in Defrance and Ramifehiarivo (2020)

| Issues | | Enhancing farmer's knowledge | Encouraging experience sharing and community based-approaches | Empowering women | Increasing market access | Favouring access to microfinance | Developing insurance tools | Improving working conditions and farmers' livelihoods |
|---|---|---|---|---|---|---|---|---|
| Climate | Adaptation* | 85, 418, 319, 421, 338, 155, 277, 254, 106 | 193 | 85, 134, 155 | 79, 421,155, 277 | 85, 63, 254,46 | 418, 63, 193, 46 | 405 |
| | Mitigation* | 85, 319,56 | | | | 63 | 63 | |
| Agriculture | Soil | 85, 454, 254, 334 | | | 454, 247 | 454 | | 454 |
| | Water | 85, 454, 254 | | | 454 | 454 | | 454 |
| | Manure management | 85 | | | | | | |
| | Nutrient management* | 384, 276 | | 85 | 384 | 85 | | |
| | Livestock | 418, 319 | 79 | 229.418 | 229, 79 | 229 | 418 | |
| Food security | Plant productivity* | 180 , 465 , 212, 8, 431, 454, 47, 240 | 463, 251 | 180 | 180 , 212, 463, 454, 240 | 180 | 180 | 307 |
| | Food access | 180, 465, 8, 454, 47, 240 | 251 | 180 | 180, 454, 240, 463 | 180.436 | 180, 240 | |
| | Food access* | 180, 8, 431, 454, 47 | 251 | 180 | 180, 454 | 180, 436 | 180, 307 | 307 |
| | Food utilization* | 180, 8, 454 | 251 | 180 | 180, 454 | 180 | 180 | |

**Table 3** Publication references distribution according to policies supporting actions and global issues. *cobenefit is included. Details of the paper numbers are visible in Defrance and Ramifehiarivo (2020)

| Issues | | Investing in infrastucture | Investing in market development | Securing land tenure | Supporting credit provision | Regulating the use of pesticides and genetic resources | Gathering data and farmers' perceptions on agricultural practices | Developing tools to monitor and assess progress |
|---|---|---|---|---|---|---|---|---|
| Climate | Adaptation* | 166, 37, 192, 217, 150 | 166 | 166, 192 | | | 106 | |
| | Mitigation* | 150, 189 | 271 | | | | 192 | |
| Agriculture | Soil | 189 271 | | | | | | |
| | Water | 217 | | | | | | |
| | Manure management | 109, 268 | 109 | | 109 | | 109 | |
| | Nutrient management* | 276, 271 | | | | | 199 | |
| | Livestock | 268, 400, 79 | 412, 79 | 421 | 79, 421, 319 | 426, 307 | 405, 421 | 79 |
| | Plant productivity * | 434, 338, 147, 374, 208 | 240 | 374 | 434 | 454, 258, 212, 440, 338, 8, 20, 307 | 436, 47, 379, 353, 208 | |
| Food security | Food access | 147, 338, 189, 374 | 240 | 374 | 434 | 454, 258, 338, 8 | 436, 47, 379, 353 | |
| | Food access* | | | | | 454, 440, 212, 8, 307 | 436, 47, 379, 353 | |
| | Food utilization* | | | | | 212, 440, 20, 8 | 208 | |

often do not have access to land, input or financial capital and they do not participate in decision making of the household or villages, their voices are poorly studied (Amsler et al. 2017). Yet, young people have probably an understanding of climate change and idea and opinions on how to adapt to it. Specific research and attention are needed on youth population.

#### 4.2.2 Economic tools to reduce vulnerability and improve adaptation

**Increasing market access.** Using innovative technologies could increase farmers' income. There are several examples in the literature. Conservation agriculture can improve rural incomes and livelihoods by reducing production costs, especially on small and medium-scale farms (Hobbs et al. 2008; Marahatta 2014). Organic farming could be a lever to enhance economic growth and fight poverty, as organic farm produce is usually sold at a higher price than conventional farm produce (SDG 8 and SDG 1) (Rahmann et al. 2009). Agroforestry practices could improve farmers' livelihoods, enhance their income, and reduce their economic vulnerability through the diversification of agricultural and forestry products while reducing GHG emissions (Rakotovao et al. 2021).

Improvement of opportunities and diversification of marketable products are the most commonly identified proposals for providing a safe economic route for farmers (Hernández-Morcillo et al. 2018). In developing countries, markets rely on infrastructures such as roads to be developed to reduce transportation costs and boost access to output markets (Altieri et al. 2012; Holden 2018). These opportunities and diversification are possible when there is greater diversity in the crop production system, and if farms are able to integrate a carbon market. Integrating trees, compost, SRI or any other agricultural techniques that limit GHG emissions are ways of securing a range of multiple ecosystem services and perhaps, in the medium term, earning money on the emerging carbon market for agriculture (Bryan et al. 2010; Rakotovao et al. 2021; van Oosterzee et al. 2014). However, this market for farmers is still disconnected from the current financial realities.

**Favoring access to microfinance.** Microfinance appears as a potential solution for supporting direct climate change adaptation actions in the agricultural sector. Microfinance is a formalized financial service to low-income and disadvantaged households that are not served by the conventional banking sector. Supporting households with micro-credit reduces their vulnerability to the adverse impact of climate change and enhances their access to agricultural inputs (Antwi-Agyei et al. 2015). However, micro-credit may not be enough to cover all requirements for agricultural climate action (Peterson 2012).

**Developing insurance tools.** Agriculture insurance is a valuable tool for managing climate-related shocks and supporting farmers willing to change their agricultural practices. Insurance helps reduce farmers' losses in the event of a climate disaster (Budiman et al. 2016). Index-based weather insurance is one such financial tool. It pays out benefits based on predefined levels of weather variables such as annual rainfall, temperature, floods or droughts. Furthermore, providing index-based weather insurance reduces the production risk and enhances technology adoption (Holden 2018). Agriculture insurance has to secure the whole agri-food value chain. It could also be a proposal for reinforcing the links between all stakeholders in that production value chain (Janzen et al. 2016).

#### 4.2.3 Improving working conditions and farmers' livelihoods

Better working conditions and productivity gains are the two main incentives that support farmers. Different approaches have been put forward to evaluate the extent to which farmers' gains meet their needs and match their way of life. For example, in livestock farming, the Qualification and Evaluation of Work method (QuaeWork) is one such approach, used by stakeholders (advisors and researchers) to identify the trade-offs in resources as well as the labour allocation of a livestock system. The QuaeWork method takes into account (i) the duration of routine work and of the seasonal work in the calculation of the system's productivity and (ii) the flexibility (room for manoeuvre) and adaptability to internal and external events. The QuaeWork method should help to improve work efficiency and flexibility with regard to unknowns (e.g., climatic hazards, uncertainties over labour availability) and to other farm activities, including free time (Hostiou and Dedieu 2011).

### 4.3 Policies supporting actions

Financial or/and resource constraints denote economic disincentives to investment in agriculture (Giller et al. 2009). Time can also be a deterring factor to investment into new farming systems (Baudron et al. 2007). Farmers tend to consider arguments about the immediate costs and benefits in light of the production constraints or food insecurity they face. It can be difficult to adopt proposals that bring benefits in the medium or long term, or that involve potential risks. Consequently, although biophysics, techniques and socioeconomic drivers (Tables 1 and 2) must be taken into consideration, the political environment and policy decisions also influence the future sustainability of agriculture (Archer et al. 2008; Fałkowski 2017). There is less scientific-based evidence on policies supporting actions to invest in the agricultural sector for climate change issues than for food security or global agricultural issues (Table 3). The references identified during our analysis include a few references on policies that support investments in infrastructure or in market development, but very few policies that protect farmers and equitable decisions with knowledge shared between stakeholders. An urgent need for references on developing tools to guide policy is also apparent (Table 3). The on-farm and socioeconomic proposals seen in the previous paragraphs need to be supported by political incentives and investments if they are to be applied effectively. Again we have not produced an exhaustive list of all the policies supporting actions reported by the scientific analysis and papers, and instead only briefly detail some of them, while showing how these policies can also achieve several SDGs (Fig. 5).

#### 4.3.1 Investing in sustainable agriculture

Smallholding agriculture produces the largest share of food calories and supports 2–2.5 billion people on the planet, most notably in developing countries. A vast majority of Nationally Determined Contributions (NDCs) propose action in the agricultural and forestry sector to mitigate climate change or to adapt to it. However, only 10% of the Green Climate Fund budget finances projects in agriculture or forestry (Buto et al. 2021). Considering the multifunctional role of agriculture in economic, social and environmental issues, especially targeting SDG 10 – Reduced inequality (Rusu and Simionescu 2016), investment policies should increase the focus on the agricultural sector to encourage and support farmers to adopt or maintain sustainable practices.

**Investing in infrastructure.** Increasing investments in agricultural extension and infrastructure, especially irrigation, roads, and energy, should enhance the rates of return on investments in the agricultural sector. For example, in landscape and water management, agricultural policy should promote flexible crop irrigation through investment in irrigation infrastructure (SDG 9) to protect the water ecosystem (Froger et al. 2012; Rodenburg et al. 2014).

In addition to rural areas, agricultural policies should also invest in the promotion of urban and peri-urban agriculture with tree planting, crop farming and waste recycling activities. This could support both agricultural production and sustainable cities (SDG 11), i.e., livelihood improvement, poverty reduction, global warming reduction, and urban food security (Lwasa et al. 2015).

**Investing in market development.** To promote sustainable agriculture, policies have an important role to play through the development and support of local or regional markets. Policies that support small farms by correcting for the market failures inherent in smallholder agriculture, especially in the early phases of agricultural development, are a particularly promising strategy to achieve pro-poor growth (Birner and Resnick 2010). The necessary market information systems should provide support with product valuation and deliver comprehensive, analytical information on other aspects of the markets. Policies should promote local or inter-regional trade for agricultural products, support market prices, and develop product marketing (e.g. organic product, Fair Trade) and new markets. For instance, the success of agroforestry systems also depends on the existence of and access to a market for all agroforestry products. This potential market would encourage farmers to improve genetic resources and tree planting (Mbow et al. 2014). Another recommended strategy is promoting conservation agriculture, creating another income stream for resource-poor farmers through payments for ecosystem services, e.g., carbon sequestration in terrestrial ecosystems (Lal 2009). However, access to this market for smallholder farmers is still a mirage (Lestrelin et al. 2019).

#### 4.3.2 Protecting farmers' well-being, economic self-sufficiency and health

**Securing land tenure.** Land is one of the few productive assets owned by the rural poor. Insecure access to land or land tenure often contributes to the unsustainability of agriculture. Land tenure policies are important when faced with the case of large-scale land acquisition for agriculture. While such acquisitions can provide benefits for host governments, they also have negative impacts on food and tenure security, and on the livelihoods and peace of local communities (SDG 16) (Carter et al. 2017).

Insecure land tenure undermines the incentives for smallholders to invest in crop diversification and other techniques (Mbow et al. 2014; Rodenburg et al. 2014). This is felt even more strongly among women farmers. However, the willingness of policymakers to create a policy environment that secures people's position on their own land would improve the adoption and upscaling of the proposed technologies (Partey et al. 2017). In many parts of the world, land tenure depends on "co-viability where the social system relies on the ecological system in which they live and on which they remain dependent for their reproduction and survival." Therefore, policies need to focus on environmental rights that reflect cultural and ecological realities to be effective in the long term (Barrière 2008).

**Supporting credit provision.** Farmers' income and capital can lead to better adoption of practices (Prokopy et al. 2008). Policies should promote the provision of credit to enhance farmer productivity through improving livestock, purchasing agricultural inputs and acquiring land (Hassen et al. 2017; Holden 2018). For example, supporting credit for livestock could help farmers because farm animals are a major asset, representing both capital and, in many cases, a source of income (Mottet et al. 2018).

**Regulating the use of pesticides and genetic resources** There is a strong requirement (SDG 17) to protect farmers and people's well-being (SDG 3) from threats from agriculture. Biodiversity, including soil biodiversity (SDG 15), is also targeted by agri-environmental policies (Putten et al. 2010). For example, because of the (environmental and health) risks associated with pesticide use, Latin American countries have established laws and regulations to control the production and use of pesticides (Furley et al. 2018). All these regulations targeted more food security issues than climate issues (Table 3). However, regulating the use of pesticides and genetic resources can indirectly affect the adaptation and mitigation of agricultural practices to climate change through crop diversification and livestock welfare (see Sect. 4.1).

### 4.3.3 Supporting equitable policy decisions with knowledge shared between all stakeholders

**Gathering data and farmers' perceptions on agricultural practices.** Agricultural adaptation and mitigation policies should be inclusive, considering the equality of opportunity, and should benefit vulnerable regions and people (SDG 10) (Luo et al. 2017; Tongwane and Moeletsi 2018). The lack of data and scarcity of long-term studies on agricultural practices at all scales and all over the world impede the development of sustainable agriculture adapted to each specific environment. Thus, it is more important than ever to document and provide figures on current agricultural practices and their agronomic, socioeconomic, and environmental performances. Specific policies should aim at improving knowledge and information sharing and include all stakeholders, from extension services to farmers and research and development, to identify and disseminate best practices both at local and national scale. Policies should encourage interdisciplinary and transdisciplinary research (Chevallier et al. 2020). Knowledge on traditional and local indigenous practices should be incorporated into the design and implementation of climate adaptation strategies (Antwi-Agyei et al. 2015). A key recommendation for policies is to reinforce bottom-up and top-down synergies with monitoring, evaluation and learning actions, considering both research contributions and farmers' views (Bizikova et al. 2015, 2014). In particular, this participatory research and knowledge sharing should focus on smallholders, women, youth, and poor resource-dependent communities, on the networks that facilitate linkages among sector stakeholders, and on extension officers through increased staff numbers and staff training (Hernández-Morcillo et al. 2018).

Investment in research and monitoring should also support long-term studies to provide data and inventories on the overall diversity of agricultural production systems in order to inform public policy on their potential impacts on different issues (e.g., health, livelihood, economy and environment). Special efforts are needed to set up methods that allow data comparisons and collections.

**Developing tools to monitor and assess progress.** The scientific literature offers tools and frameworks to improve agricultural and climate policies. For example, calculators to assess the GHG balance of agricultural and forestry scenarios at landscape scale, or the use of the marginal abatement cost curve (MACC). The MACC approach is a framework commonly used to summarize information on potential mitigation efforts and can help in identifying the most cost-effective managerial and technological GHG mitigation options (Eory et al. 2018). To guide policy, research needs to develop models that can evaluate adaptation technologies in different environmental and socioeconomical contexts (Furuya et al. 2015; Pellerin et al. 2017; Rakotovao et al. 2021). There is also a need to better align international support and national priorities by promoting better monitoring of the agricultural projects implemented across multiple funding agencies (Tongwane and Moeletsi 2018). Tools to appraise the social dimension (e.g., labor conditions, quality of life, and societal impacts) of sustainable agriculture are still under debate and development.

Empirical evidence shows that it is difficult to implement policies and to explain why and how policy changes leading to pro-poor agricultural growth happen. Inconsistency between different policies focusing on different stakeholders or scales need to be identified to limit the inequities and support sustainable agriculture at a global scale. For example, in the case of European Union (EU), subsidies for production and exports helped EU farmers but made competition difficult for local producers in developing countries (Bureau and Swinnen 2018). Thus, the success of policies depends on diverse factors. For example, in China, rural institutional innovation, technology change, market reform and investment in agriculture are the four major drivers that contributed to China's agricultural growth in the past, but the challenge of resources and environmental degradation have intensified, while concerns about sustainable agricultural development are rising (Huang and Yang 2017). There is a need to consider interactions and interdependency between all the drivers of sustainable agriculture (Chevallier et al. 2020).

## 5 Document synergies and trade-offs within the different components of sustainable agriculture

Our review shows that KJWA has been abundantly documented in the scientific literature. Because the multiple dimensions of agriculture could be seen as part of the global food systems, where climate, land, soil, and biodiversity converge, scientific papers reviewed pointed out the fact that KJWA topics are also targeted towards several SDGs (Fig. 5) and not only climate issues. Indeed, sustainable agriculture could be considered as one of the most efficient ways of achieving a "just and safe space," i.e., a space that considers both the planet's limits

(Rockström et al. 2009) and socioeconomic concerns (O'Neill et al. 2018; Raworth 2017). However, only few papers concurrently documented the synergies and trade-offs of the agricultural practices, or economic and political incitations proposed to tackle climate change mitigation. While mitigation and adaptation programs would bring immense benefits to society, it could also be disruptive and costly for some, at least in the short term. Thus, research on climate policy has to focus on how low-carbon transitions in agriculture, or in any other sector, can be implemented justly, equitably, and politically smoothly (Green and Gambhir 2020). Similarly, the adoption of the Sustainable Development Goals has paved the way for a transformative agenda to "leave no one behind." To do so, interdisciplinary, inclusive and participatory research are progressively developing, through different framework and approach (e.g., nexus, value-chain or agroecology).

Since 2015, the United Nations considers the nexus approach as key to supporting countries to achieve this ambitious agenda. Exploring and documenting these interactions between SDGs could help to achieve the SDGs (Nilsson et al. 2016; Pedercini et al. 2019; Pradhan et al. 2017). The nexus method integrates multiple sectorial elements, energy, climate, soil and water, and food production within an overarching governance approach. Nexus thinking is normatively argued to help transition societies towards greener economies and the wider goal of sustainable development (Benson et al. 2015). The nexus approach needs: (i) to consider all selected approaches—technical, socioeconomic, and political—with the same weight; (ii) to support farmers with all aspects: food security, income, and climate; and (iii) to reduce farmers' exposure to shocks and to strengthen their resilience by enhancing their individual and collective capabilities and by addressing these interconnected difficulties. Progress in implementing the nexus approach has been hampered by a lack of clarity about what it means, both in theory and in practice, and how it meaningfully contributes to supporting achievement of the SDGs. Howe (2019) proposed four changes that make the approach more effective: the common acceptance of impacts, an alignment of efforts across the SDG targeted by the nexus, a focus on collective outcomes, and more holistic assessments. There is also a need to reinforce nexus implementation both at a local scale and national scale. In our review, few nexus emerged from 12 of the 175 publications reviewed (Albrecht et al. 2018; Benson et al. 2015; Elum et al. 2017; GhaffarianHoseini et al. 2016; Harvey 2014; Kristjanson et al. 2017; Lal 2013; Misselhorn et al. 2012; Mpandeli et al. 2018; Singh et al. 2015; Sonwa et al. 2012; Tian et al. 2018). We have identified four major nexus to be considered:

- The *Water-Energy-Food nexus* considers the three most important resources to human life and well-being (Benson et al. 2015; Fabiani et al. 2020; Misselhorn et al. 2012; Mpandeli et al. 2018; Sonwa et al. 2012; Tian et al. 2018).
- The *Food-Energy-Climate nexus* stresses interactions between food and bioenergy demand under climate change, emphasizing several tensions: (i) more food results in more climate change; (ii) burning fossil fuels accelerates climate change; (iii) failure to find alternative energies results in unending economic depression; (iv) biomass energy alternatives increase demand for land; and (v) climate change negatively impacts land productivity, requiring more land for food supply (Albrecht et al. 2018; Elum et al. 2017; Harvey, 2014; Renzaho et al. 2017; Turner et al. 2018).
- The *Water-Soil-Waste nexus* stresses interlinkages between the use of water and waste in agriculture, land tenure, and soil management. It emphasizes several tensions: (i) economic growth and an increase in gross domestic product lead to the generation of waste or by-products, along with the contamination and eutrophication of soil and water resources; (ii) the international trade in food/feed products involves the transfer of virtual water, which is a serious issue when water-scarce countries export virtual water to water-endowed countries; (iii) the sustainable intensification of agroecosystems (Avellan et al. 2017a, 2017b; Bouma 2021; Lal 2013).
- *Agriculture-Biodiversity-Climate nexus.* Although not documented in our bibliometric analysis, the relationships between SDGs 2, 15, and 13 are at the heart of recent international panels (IUCN = Common ground; restoring land health for sustainable development; UNEP = Making peace with nature; IPBES-IPCC = Biodiversity and climate change). In our analysis (Sect. 4.1), we also discussed the synergies between biodiversity conservation or enhancement in or between agricultural plots and adaptation/mitigation of climate change. Better documenting synergies and trade-offs between these two joint challenges (biodiversity and climate change) in agriculture, however, remains essential to consolidate the role of agriculture and sustainable food systems on the 2030 agenda.

In order to propose "no-regrets" actions taking into account trade-offs and synergies within these nexus, different points of view and perspectives from diverse stakeholders are needed. "No-regrets" actions should be actions increasing resilience, dealing with different types of hazards in a timely, efficient, and equitable manner. Research can be envisaged through:

- Value chain approach in agriculture: Historically, agricultural production has focused on producing generic commodities for the feed. Today, agricultural production is seen as a segment of sustainable food system, which is defined as "a food system that ensures food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition of future generations are not compromised" (HLPE 2017). Value chain that is a broad spectrum of activities that are required to bring a product or service from conception, through the different phases of production, delivery to final consumers, and final disposal after use (Gomez and Ricketts 2013), should be documented accordingly to the various food systems. In today's telecoupled world, the interplays between diets and production systems need to be documented to support sustainable development, conserve biodiversity, climate mitigation, land degradation (Chotte and Orr 2021; Pradhan and Kropp 2020; Wang et al. 2022).

- Agroecology could be seen as a lever for synergizing these nexus, since agroecology is seen as going beyond mere food production, being part of the global food systems (Caron et al. 2018). Agroecology brings together technical and socioeconomic aspects and targets the multiple functions of agriculture. It is gaining in importance in discussions about sustainable food systems (Gascuel-Odoux et al. 2022). This is reflected in the ten principles defined by the FAO and their links with the SDGs (FAO 2018).

## 6 Conclusion: research needs for the implementation of this new KJWA

The science-based evidence has paved the way of the KJWA which has came to an end in 2020. Our review reveals few research gaps which need to be addressed to keep nurturing the future KJWA process.

Based on this rewiew and analysis, we would recommend an extension of the KJWA process. For this extension, we recommend to align the future Koronivia to the nexus approach and to promote

- Research on implementations and impacts of public policy at different levels and for diverse stakeholders. This could include the effects of setting up grants or implementing qualifications/certification of the production/distribution practices, and the role of the private sector in innovative incentives on diverse targets, not only climate targets.
- Research on multicriteria analyses on value-chain and on various territories need to be developed. The monitoring tools are currently lacking.
- Research for scaling up agroecology and on how to assess its multi-functionality (Wiget et al. 2020). Methods with large sets of indicators have been published to assess how agricultural systems target multiple challenges and SDGs. However, improvements in these assessments are needed to better understand societal, environmental and technological dynamics, the possible conflicts between values within agricultural systems (Renn et al. 2020) and the positive and negative drivers in the transition of agriculture towards agroecology.
- Research to propose effective monitoring methods. For example, the definition of the criteria and indicators required to evaluate the impacts of policies need to be addressed. This definition could be itself a research topic: e.g., which indicator, to what reference or baseline to compare, are the criteria and indicators appropriate and legitim for all the stakeholder of the system assessed.
- "In situ" experimentations, meta-analysis of data from these experimentations but also modelisations to identify trade-offs and synergies of agricultural practices and economic or policy actions on several SDGs in various context. We have noticed that case studies, on agronomy, water and soils, production systems are numerous. It is necessary to promote in situ experimentations and data organization of these case studies in various contexts to allow meta analysis on the impact of these case studies on several SDGs.
- Research on the vulnerability of rural youth, and the role of women, the working conditions that affect production systems, as well as the need to share the financial risks of innovation.

To conclude, we think that interdisciplinary and participatory research programs would boost the future of KJWA. Research should help to evaluate the impacts of the multi dimensions of agriculture and identify their synergies and their trade-offs to make KJWA contributing a sustainable development for all.

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## Declarations

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