How Agriculture 4.0 solutions can reduce the environmental impact of viticulture?

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Abstract — Digital technology solutions could help reduce the amount of pesticide distribution in vineyards. In this study, a Life Cycle Assessment of digital technology application in vineyard defence is presented. The analysis was conducted using both primary data obtained from two farms and secondary data from databases and specific models. Two functional units were compared: surface (1 ha) and mass (1 ton of grape produced). The results showed that the adoption of digital technology reduced the environmental footprint of grape production in all the farms. These findings support the digitalization of viticulture, even if a holistic evaluation of environmental and economic aspects is necessary.

Keywords—Life Cycle Assessment, Climate Change, Agriculture digitalisation

I. INTRODUCTION

The wine sector represents an economically and culturally important sector in Europe and, in particular, in Italy. However, it is also associated with several environmental impacts that can negatively affect local and global ecosystems [1], [2]. As for the rest of intensive agriculture, the use of phytosanitary products became a vital element for the production and marketing of products of sufficient quality and to ensure a good economic yield [3], [4]. Not surprisingly, among the main environmental criticalities related to this production stage is the production and use of products intended for plant protection, which are necessary for the control of certain biotic adversities such as fungal diseases (caused by *Plasmopara viticola*, *Uncinula necator/Oidium tuckery*, *Botritis cinerea* etc.) and generated by phytophagous diseases (*Lobesia botrana*, *Eupocelia ambiguella*, *Scaphoideus titanus* etc.) [5], [6]. On the European continent, an average of around 350,000 tonnes of pesticides are sold each year, of which an average of 13% is destined for Italian consumption, which, in 2022, ranked fourth in Europe in terms of mass of marketed products, preceded by France, Spain and Germany [7]. Furthermore, it is estimated that 20% of pesticides are used in viticulture [8]. It is therefore not surprising that the agricultural phase of wine production, according to some authors, is one of the most impactful stages. Therefore, it is necessary to implement solutions to reduce its environmental impact [9], [10], [11]. Among the main environmental issues related to the use of pesticides we can mention [12], [13]: - pollution of the aquatic, air and soil environments, - toxicity to ecosystems (terrestrial and aquatic) and human health, - killing of beneficial organisms (non-target), - increased resistance of harmful organisms (target). What is more, increased resistance of harmful organisms could lead to a vicious circle, necessitating an ever-increasing use of plant protection products, with negative repercussions on both the economic performance of companies and the environmental impact [3]. Finally, another issue to take into account when dealing with plant protection products is the impact generated during the production of these products, which require high volumes of energy to be produced, with consequent negative impacts on greenhouse gas emissions and the use of fossil and mineral resources [1], [14]. Among the objectives contained in the European Community's Farm to Fork (F2F) strategy is to limit dependence on pesticides by reducing their use by 50 % by 2030 while promoting sustainable agricultural practices. The introduction of innovative digital solutions can accelerate this transition towards less dependence on the use of pesticides. The smartphone application PocketSPRAY® (Fig. 1), integrates direct leaf area index measurements with satellite remote sensing in order to create prescription maps for variable rate vineyard treatment [15]. Furthermore, it allows the winegrower to be alerted to the presence of conditions favourable to the development of certain diseases such as powdery mildew and downy mildew, thanks to predictive risk models [15]. The use of this application allows a reduction in the doses of pesticides and water used for treatments, without disrupting the quality of grapes intended for processing [15].

The aim of this study is to: a) evaluate the potential impact of pesticides application in vineyards with or without the help of digital solutions; b) focus on the impact of *P. viticola* defense in vineyards.

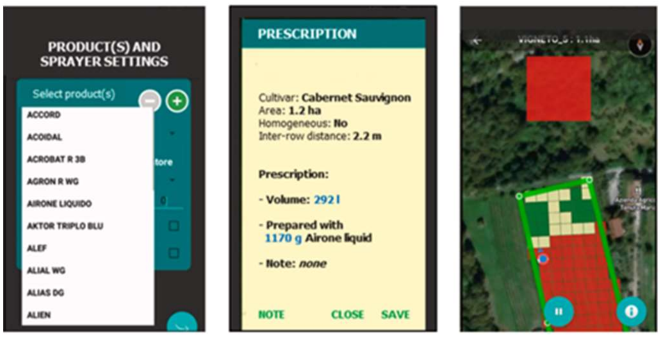

Fig. 1. Screenshots showing the user's interface of PocketSPRAY application. Picture credit [15].

II. Materials and Methods

In this study, a comparative Life Cycle Assessment (LCA) of grape cultivation without (base) and with the support of PocketSPRAY app for pesticide distribution (smart) was evaluated.

The study was conducted within "from cradle to farm gate" boundaries (Fig. 2). Impacts associated to vineyards infrastructures and their maintenance, planting and explanting, as well as PocketSPRAY® application development, functioning and data storage were excluded from the present analysis. The impacts were calculated considering two functional units (FUs): 1 ha of vineyard and 1 ton of grape produced under the BASE and SMART scenario considering the historical yield of both farms.

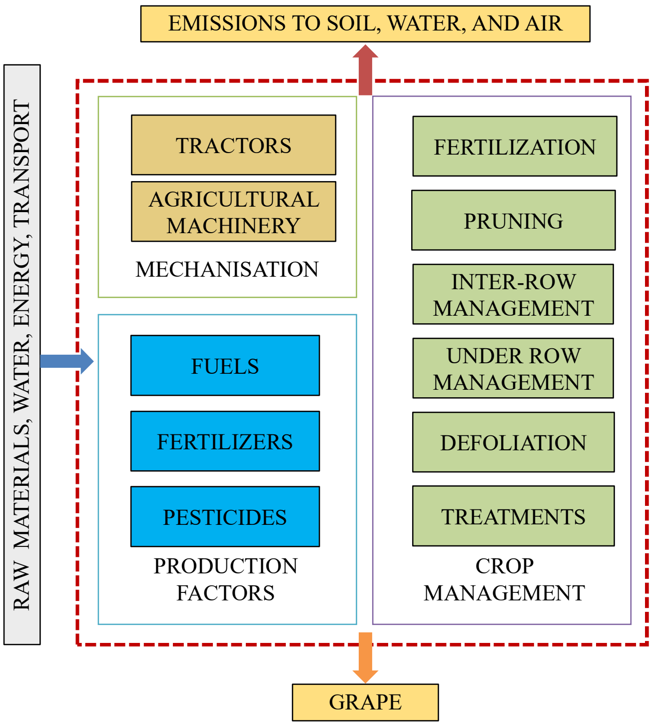

Fig. 2. System boundaries considered in the present study. Process highlighted with numbers are specific of Farm 1 (1) and Farm 2 (2).

Data were obtained from two farms in which the technology was tested during 2023. Farm 1 produced Marzemino grapes under conventional agriculture (IPM), while Farm 2 produced Chardonnay under organic agriculture. All two farms are located in Lombardy (Italy). Primary data regarded vineyard management such as mechanisation (i.e., type and number of interventions), input consumption (i.e., pesticides (Table I), fertilizers, fuel), and grape production were directly collected from farmer through surveys. Regarding the pesticide applications, interesting reductions of the application dose were observed. In particular, Cu-based pesticides were reduced of 17% and 2% in Farm 1 and 2, respectively (from 3.07 kg/ha of active ingredient in Farm 1 and from 4.15 to 4.06 kg/ha in Farm 2).

Databases (i.e., Ecoinvent® and Agribalyse®) were used to model sub-processes such as fuel, pesticide, and fertiliser productions. For the estimation of fertilizers and pesticide emissions, specific models were used [16].

In this study, the SimaPro® software was used to carry out the analysis. The potential environmental impact was calculated using Environmental Footprint (EF 3.0 v.1.03) characterisation method. The following impact categories (ICs) were considered: climate change (CC) as kg CO_2 eq; acidification (AC) as mol H+ eq; eutrophication, freshwater (FEU) as kg P eq.; eutrophication, freshwater ecotoxicity (ECOTOX) as CTUe; resource use, minerals and metals (MRD) as kg Sb eq.

TABLE I. Life cycle inventory of pesticides use in IPM (Farm 1) and organic (Farm 2) vineyards during 2023.

Product	Farm 1 Base (kg ha^{-1})	Farm 1 Smart (kg ha^{-1})	Δ[b] %	Farm 2 Base (kg ha^{-1})	Farm 2 Smart (kg ha^{-1})	Δ[b] %
Cu-based	14.6	12.1	-17.5	19.0	18.7	-2.0
S-based	42.1	37.4	-11.2	72.0	70.2	-2.6
Fungicides[a]	30.4	26.0	-14.4	-	-	-
Insecticides	0.7	0.7	Nd	0.8	0.8	nd
Erbicides	1.5	1.5	Nd	-	-	-
P. viticola defense	39.2	33.2	-15.2	19.0	18.7	-2.0

[a] excluding Cu- and S-based fungicides; [b] calculated as (smart-base)/base; nd, no differences

III. Results and Discussion

The results of the environmental impact assessment of both farms using two different phytosanitary managements are showed in Table II.

Concerning the comparison between the two scenarios, the impacts in the smart scenario resulted always lower than in the base scenario for all the evaluated impact categories. In Farm 1, the largest reductions were in the impact categories ECOTOX (-15.8%), MRD (-12.9%), and FEU (-8.8%). In Farm 2, the reductions were smaller: -2.4 % for ECOTOX, -1.7% for MRD, and -1.1% for FEU. As expected, the higher impact reductions were achieved for the toxicity related impact categories the one more affected by the pesticide productions and related emissions.

Regarding the comparison between the two farms, similar impacts were achieved in terms of CC and ECOTOX. In particular, CC was less sensitive to the crop protection management strategies. For this impact category the main contributors to the impact are the mechanisation and the emission related to fertilizer application (and not the pesticide production and related emissions). With regard to AC, FEU, the impact is lower in Farm 2 than in Farm 1 while, on the contrary, the impacts on the MRD category were higher in Farm 2 than in Farm 1. The impact variation regarding AC is related to the difference in the cultivation practice and, in detail, to the fertilisation strategies.

These results achieved in term of absolute results as well as in term of contribution analysis (e.g., identification of the processes mainly responsible of the impact for the different impact categories) were consistent with literature data on pesticide use in conventional and organic vineyards [16], [17].

The results of environmental impact expressed on a mass FU (i.e., 1 ton of grape produced considering historical yield of both farms) are showed in Table III. Considering the same yield, no differences were observed between the relative impacts of the two pesticides management strategies. The difference of impacts on MRD between the two farms was less pronounced considering the mass-based FU.

TABLE II. POTENTIAL ENVIRONMENTAL IMPACTS OF IPM AND ORGANIC VITICULTURE WITHOUT (BASE) OR WITH (SMART) THE USE OF POCKETSPRAY APP. FUNCTIONAL UNIT 1 HA.

Impact category	Unit	Farm 1 Base	Farm 1 Smart	Farm 2 Base	Farm 2 Smart
CC	kg CO_2 eq	2466.76	2444.21	2461.79	2460.98
AC	mol H+ eq	25.18	24.59	15.84	15.76
FEU	g P eq.	521.35	479.16	297.10	293.91
ECOTOX	CTUe/1000	1398.52	1207.72	1311.78	1280.96
MRD	g Sb eq	27.84	24.67	30.76	30.24

CC, climate change; AC, acidification; FEU, freshwater eutrophication; ECOTOX, freshwater ecotoxicity; MRD, resource use, minerals and metals.

If the application of pesticides using the PocketSPRAY® app would lead to a yield reduction in the smart scenario, it was decided to calculate the maximum tolerated yield loss such that the environmental impact of the smart scenario would equal that of the base scenario. The results of these calculations are showed in Table IV. The maximum yield loss in Farm 1 is 1.11 t/ha for the ECOTOX category. Also in Farm 2, the maximum tolerated yield loss is observed in the ECOTOX category, and it corresponds to 0.19 t/ha.

Figure 3 shows the contribution analysis to the impact categories of the different process stages. Farm operations including pesticides distribution, represented the main hotspot for CC. The impact on AC resulted particularly affected by farm operations in Farm 2 while in Farm 1 a large contribution of fertilisers emissions could be highlighted. Regarding FEU, the largest impact was associated with pesticides production in both farms. While ECOTOX and MRD were mostly affected by pesticides emissions and pesticides production, respectively.

TABLE III. POTENTIAL ENVIRONMENTAL IMPACTS OF IPM AND ORGANIC VITICULTURE WITHOUT (BASE) OR WITH (SMART) THE USE OF POCKETSPRAY APP. FUNCTIONAL UNIT 1 TON.

Impact category	Unit	Farm 1 Base	Farm 1 Smart	Farm 2 Base	Farm 2 Smart
CC	kg CO_2 eq	352.4	349.2	307.7	307.6
AC	mol H+ eq	3.6	3.5	2.0	2.0
FEU	g P eq.	74.5	68.5	37.1	36.7
ECOTOX	CTUe/1000	199.8	172.5	164.0	160.1
MRD	g Sb eq	4.0	3.5	3.8	3.8

CC, climate change; AC, acidification; FEU, freshwater eutrophication; ECOTOX, freshwater ecotoxicity; MRD, resource use, minerals and metals.

TABLE IV. THEORETICAL YIELD LOSS IN SMARTSCENARIO THAT ALLOWS TO OBTAIN THE SAME IMPACT OF THE SCENARIO BASE. VALUES ARE EXPRESSED AS T/HA.

Impact category	Farm 1 Smart	Farm 2 Smart
CC	-0.06	-0.003
AC	-0.17	-0.04
FEU	-0.62	-0.09
ECOTOX	-1.11	-0.19
MRD	-0.90	-0.14

CC, climate change; AC, acidification; FEU, freshwater eutrophication; ECOTOX, freshwater ecotoxicity; MRD, resource use, minerals and metals.

Figure 4 shows the relative contribution of P. viticola defence on the analysed impact categories on the total pesticides impact (including emissions). In all the impact categories, except ECOTOX, the impact of P. viticola defence represented more than 50 % of total pesticides impact. Regarding ECOTOX, the relative contribution of P. viticola defence was about 40 % in Farm 1 and about 10 % in Farm 2.

IV. CONCLUSIONS

The results illustrated in the present manuscript showed that the adoption of digital technologies in viticulture could help to reduce the consumption and the environmental impact associated to pesticides. The reduction of the impact is particularly relevant in freshwater ecotoxicity and use of minerals and metal resources. A potential yield reduction associated with the reduced use of pesticides could be tolerated in terms of environmental impact. Among others, the defense against *Plasmopara viticola* represent one of the main sources of impact in almost all the impact categories considered. However, to strengthen these observations, the trials should be repeated in 2024. Moreover, also economic and social aspects should be considered to reach a holistic evaluation of pesticides reduction in vineyards. Therefore, these data will be included in a multi-criteria analysis.

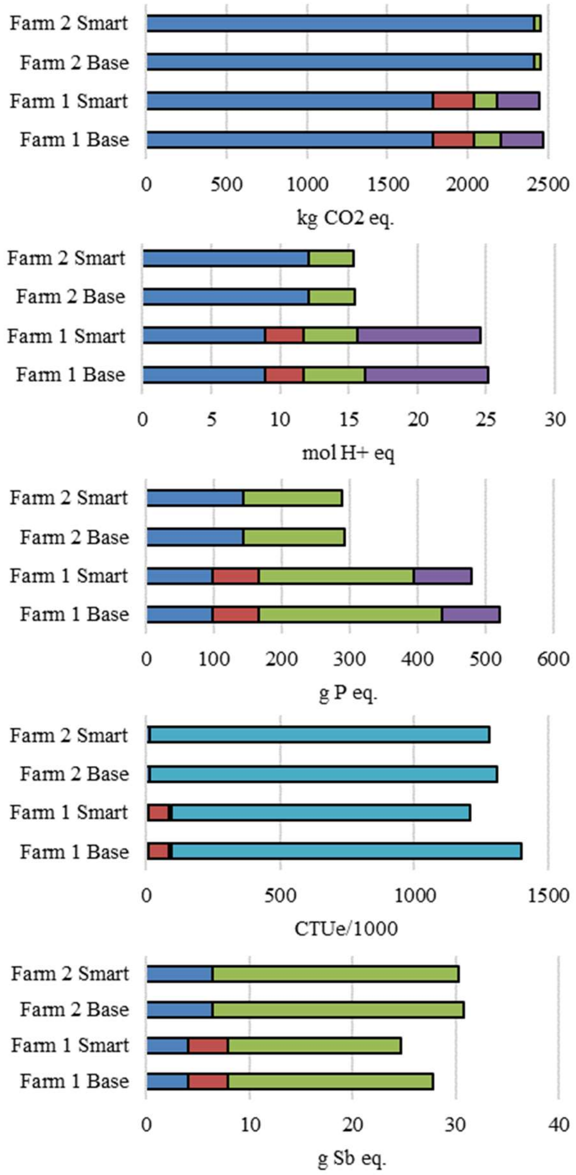

Fig. 3. Contribution analysis of farm operations (•), fertilisers (•), pesticides production (•), ferilisers emissions (•), pesticides emissions (•), and water (•) in IPM (Farm 1) and organic (Farm 2) vineyards without (base) and with (smart) the use of PocketSPRAY® app for the climate change (CC), acidification (AC), freshwater eutrophication (FEU), freshwater ecotoxicity (ECOTOX), and resource use, minerals and metals (MRD). Functional unit: 1 ha.

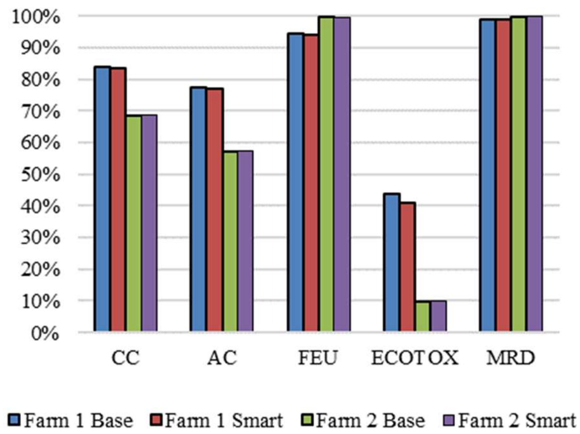

Fig. 4. Relative contribution of *Plasmopara viticola* defense on total pesticides impact (including emissions) on climate change (CC), acidification (AC), freshwater eutrophication (FEU), freshwater ecotoxicity (ECOTOX), and resource use, minerals and metals (MRD) in IPM (Farm 1) and organic (Farm 2) vineyards without (base) and with (smart) the use of PocketSPRAY app.

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