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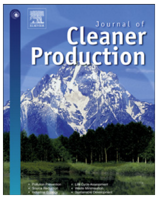

Sustainable options for paints through a life cycle assessment method

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ABSTRACT

In recent years, the paint industry has addressed the development of products, technologies, and packaging to build conditions to improve environmental performance in accordance to the circular economy goals. For these reasons, a life cycle thinking approach allows for the understanding of the most important steps for pursuing closed-loop strategies and related goals. This paper provides a twofold analysis: first, a comparison of two paints, characterised by different chemical compositions, has been carried out according to the current production cycle (baseline scenario); second, for each product, two additional and alternative scenarios have been hypothesised. These scenarios focus on the use of waste paint blended with virgin paint, and the use of a high rate of recycled inputs of packaging materials. The aim is first to assess the environmental impacts of the life cycles of the paints and identify feasible measures to reduce these impacts. The second aim is to choose the better option between scenarios, according to a circular economy approach. The results highlight that the production and supply of raw materials have the greatest impact on both paints, for all impact indicators. Consequently the use of waste paint reduces environmental impacts by roughly 48%, on average. Furthermore, the packaging options allow us to determine that the use of 50% recycled polypropylene had a better environmental performance than 100% recycled aluminium, although the contribution of packaging is negligible in the total impact indicators. Confirming the results, the sensitivity analysis on the waste paint use has been undertaken.

1. Introduction

Paints are pigmented coating materials that come in liquid or paste form. They create a film, using a decorative, protective or specific technical properties (Heba, 2011; Londhe et al., 2019), with the substrates on which they are applied, extending their useful life (Bonoli and Franzoni, 2019).

The composition of these products depends on the distribution of four main components:

- resin/polymer, which provides the chemical and physical properties, such as hardness, flexibility, and water resistance of the dried film. The main resins include alkyd, vinyl, bitumen and polyurethane.
- pigment, which gives the colour and opacity, as well as some of the physical properties of the paint. The main pigments are titanium dioxide (TiO_2) (widely used as white), iron oxide (mainly used as red and ochre) and carbon black (as black).
- solvent, including organic solvents (such as alcohols, esters, and ketones), usually added to water to allow the resin and pigment to spread on the surface and to avoid hardening of the paint.
- additives, used to improve the functionality of the paint, such as its mould resistance and spread rates; moreover, they prevent foaming and prolong shelf life. Even though additives are the minor constituents in the paints, hundreds of types exist.

The combination of the four components above is different for each kind of paint and varnish. Hence there is no standard formula; there are thousands of types of products.

According to the Prodcom nomenclature (European Commission, 2015) common to all European Union (EU) Member States, paints are classified in around 25 categories. The main ones are listed in Table 1.

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Table 1
Prodcom nomenclature of the main paints categories.

PRODCOM	Description
NACE: 20.30	Manufacture of paints, varnishes and similar coatings, printing ink and mastics
20.30.11.50	Paints and varnishes, based on acrylic or vinyl polymers dispersed or dissolved in an aqueous medium (including enamels and lacquers)
20.30.11.70	Other paints, varnishes dispersed or dissolved in an aqueous medium
20.30.12.29	Paints and varnishes, based on polyesters dispersed/dissolved in a non-aqueous medium including enamels and lacquers excluding the weight of the solvent > 50% of the weight of the solution
20.30.12.90	Other paints and varnishes based on synthetic polymers n.e.c.
	Others

The EU paints sector is significant, counting over 19,400 billion euros in revenue in 2018 (Table 2). Italy follows Germany, as the primary producing country (Eurostat, 2020). The paints and varnishes sector holds a significant share of the Italian chemical industry, with around 5% of the industry's total value (Eurostat, 2020; ISTAT, 2020; Federchimica, 2020a) if only the main categories of paints are considered (Tables 1 and 2).

The most widespread Prodcom categories are 20.30.11.50 and 20.30.11.90, which jointly represent almost 60% of the total value and over 65.5% of the total volume in the EU market. In Italy, the same categories amounted to roughly 55% of both the total value and volume. Table 2 provided a piece of significant information about characteristics and market positioning of these products. In particular, the category 'Prodcom code 20.30.11.50' is the highest in terms of quantity (about 31% of the total volume), but not the value (26% of the total value). It represents a medium quality product that is utilised in many sectors, particularly in construction (Ingrao et al., 2018b).

For these reasons, the authors have identified two paints belonging to this average and commercial category. They used Life Cycle Assessment (LCA) to investigate their environmental impact. LCA is the most useful tool to evaluate the environmental performance of paints because the multiple compositions of paints affect the environment and human health differently. Although the impact of their manufacturing is high, paints allow for reducing the environmental impact, because the films protect substrates and slows decay (Kougoulis et al., 2012). Hence, the lifespan of these products must be considered to evaluate the entire environmental impacts.

Generally, the chemical industry has a significant, and highly debatable, role in most user sectors. For many years, the industry has sought to decouple the economic, environmental, and social indicators to overcome some burdens that affect the environment and human health. The innovations implemented in this industry have brought about great environmental improvements. Since 1990 the entire chemical industry in Italy has decreased its greenhouse gas emissions. In more detail, from 1990 to 2018, the reduction was by 69.2%, also due reduction of energy consumption by roughly 50%, joint to over 55% improvement in energy efficiency over the same period (ENEA, 2019); currently these emissions account for almost 3% of the total Italian CO_2 eq emissions (ISPRA, 2020); in addition to reducing its emissions, chemistry allows greenhouse gases to be reduced in all user sectors. According to the following estimate, one ton of CO_2 eq emitted by the chemical industry saves 2.6 t CO_2 eq emissions by the final customers or other industries (Federchimica, 2020b). As a consequence, if 12.4 Mt of CO_2 eq are the direct and indirect emissions of chemical production and 32.24 Mt of CO_2 eq the emissions avoided by the use of the chemical product, the net balance is equal to almost 20 Mt of CO_2 eq savings. The environmental impacts of the chemical industry continue to be significant. Other enhancements have been made in recent years, in particular from 2005 to 2018, such as the increase of waste recycling (equalling to over 24%) and the reduction of water consumption (−39% for total consumption and −63% for drinking water) (ENEA, 2019).

Moreover, the emissions in water, in particular Chemical Oxygen Demand (COD) and nitrogen, decreased by 77% and 70% respectively, as air emissions of sulphur dioxide and nitrogen oxides decreased by 99% and 92%, respectively, over the period between 1990 and 2017 (ISPRA, 2019).

Overall, it becomes important to study solutions that tackle the environmental issues in the chemical industry, particularly in the paints industry. In steering such an innovative, green initiative there is support for the circular economy (CE) strategy. Although it has existed for a long time, the CE is a relatively new concept (Frosch and Gallopoulos, 1989). 'Its practice has almost exclusively been developed and led by practitioners, i.e., policy-makers, businesses … ', as underlined by Korhonen et al. (2018); consequently, even if scientific research has to build the CE conceptual framework and assess this approach, the supply chain (Hazen et al., 2017) 'plays a key role in the transition towards a CE'.

In the light of the CE, it is important to map approaches and opportunities for implementing new business models and for identifying different and circular strategies (Ingrao et al., 2018a) to be linked to structural approaches (Blomsma, 2018; Chen et al., 2020; Reike et al., 2018). In the paint industry, the main structural approach is to analyse the whole value chain. From these considerations emerged the need for a multidisciplinary approach, capable of analysing the life cycle of a chemical and identifying the environmental priorities that accelerate the development of sustainable practices and actions (Ingrao et al., 2018b), such as recycling of paints and coatings, transforming waste materials to redesign new products (Hens et al., 2018), or finding substitute sources of raw materials (Keijer et al., 2019; Barros Galvão et al., 2018).

Table 2
EU and Italian paints production by main categories, value and volume (2018). Source: Personal elaboration by the authors on data Eurostat (2020); ISTAT, 2020.

Prodcom code	Value UE28 (€000)	Volume EU28 (t)	Value IT (€000)	Volume IT (t)
20301150	6,983,400	3,548,100	741,150	303,004
20301170	2,312,228	946,938	405,601	154,314
20301229	1,988,239	562,718	357,347	134,035
20301290	4,464,353	1,115,849	845,378	228,576
Others	3,724,467	945,019	518,258	150,068
Total	19,472,687	7,118,624	2,867,734	969,997

There is still limited scientific literature concerning this multidisciplinary and structural approach toward sustainable improvements in paints, particularly the use of waste paint. For this reason, the novelty of this study is to bridge the gap between literature and knowledge of practical sustainable measures to be implemented in the paints sector. In particular, this study concerns the substitution of a share of raw materials with the waste paints and the improvement of packaging with two alternatives and recycled materials.

It must be highlighted that for all the scenarios hypothesised, the LCA has been carried out, in contrast to most literature that only suggests some sustainable options, sometimes analysing them from chemical and technical point of views.

Furthermore, the match between industry and scientific research enhances the current baseline production cycle by implementing suitable proposals in the short to medium term.

This paper investigates both approaches and provides a twofold analysis. First, the use of LCA allowed for the comparison between two products identified and characterised by different chemical compositions. Second, on the basis of LCA results for each product, additional and more sustainable measures are hypothesised. In particular, three scenarios are constructed: baseline, based on the current production cycle using both virgin paint and primary polypropylene packaging; scenarios A and B both provide an enhancement due to the blend of recycling of waste paint with virgin paint, to which there is added 50% recycled polypropylene (scenario A) and 100% recycled aluminium (scenario B) for packaging. The aims of this study are to assess the environmental impacts of the life cycle of the products (baseline scenario), to identify feasible measures to reduce these impacts, and to evaluate how the alternative measures (scenarios A and B) affect the total environmental impact. The researchers choose the best scenario based on a CE approach, defined by Ormazabal et al. (2020) as ‘the recirculation of resources and energy, the minimisation of demand for resources, and the recovery of value from waste’.

This paper has been structured in five sections: 1) the introduction explains the chemical, technical, and economic features of the paints, highlighting the relevance of this economic sector in Italy and the EU; 2) the literature review regards the sustainability of paint products and their packaging; 3) the materials and methods section describes the methodology, the goal of the LCAs, system boundaries, Life Cycle Inventory (LCI), and the Life Cycle Impact Assessment (LCIA); 4) this section shows the results of LCA in the three scenarios considered, whereas the discussion also underlines the limitations of this research; 5) the sensitivity analysis was undertaken for the waste paint; 6) the conclusive consideration highlights the valuable use of the LCA in this chemical sector to choose the best environmental performance between the available alternatives.

2. Literature review

In the last decade, the original concept of sustainability within the paint industry shifted focus from individual products and their ingredients to the entire value chain, analysing the sustainability drivers for paints, such as the reduction of toxic ingredients, and transforming the industry from solvent to water-based.

Another important step has been to study ways to produce paint by replacing raw materials with recycled materials. Doing so addresses the concept of the CE in minimising the environmental impact of the production phases.

Furthermore, paint packaging is also considered when assessing the environmental performance of this chemical sector.

For this reason, the following literature review provides two sub-sections related to packaging and paint sustainability.

2.1. Packaging

Recently, there has been a growing interest in studying new sustainable packaging solutions that reduce and minimise environmental impacts. Considering the paint manufacturing process, metal packaging is currently used because it can be sterilised successfully and it is more durable during the transport phase. Alternatively, plastic packaging is commonly used due to their low cost and beneficial physical properties, such as resistance to many chemical solvents. There is limited scientific literature and studies on paint packaging. Conversely, if we investigate literature on the packaging sector, it is possible to find many studies in other sectors that benchmark the main environmental impacts associated with aluminium, steel tin, and plastic in packaging products. Accorsi et al. (2015) analysed the environmental impact categories associated with the life cycle of bottled extra virgin olive oil (EVOO), in order to choose the best packaging. Del Borghi et al. (2018) investigates the difference in environmental sustainability between a set of legumes packaged in glass bottles or in steel tin cans; this study highlights that the phase of packaging production is principally responsible for the environmental and health impacts, accounting for over 70% of the total environmental impact indicators.

Using the LCA methodology, Navarro et al. (2018) analysed different packaging for the olive oil. This study showed that glass is the main contributor to the environmental loads. The related impact can be reduced by increasing light weighting strategies or the percentage of recycled glass. Also following the LCA methodology, Ferrara and De Feo (2020) compared the environmental performance of the traditional single-use glass bottle for wine packaging with different alternative packaging scenarios, such as a bag in a box or aseptic carton. The box has better environmental performance than the aseptic carton. Three typologies of containers (aluminium, polypropylene, and extruded polystyrene) for take away food have been compared by Gallego-Schmid et al. (2019). They demonstrated that the best option is the extruded polystyrene, considering that its impact is 28 times lower than aluminium and six times lower than polypropylene.

Also Maga et al. (2019) used LCA to compare nine plastic solutions (such as PET, PP, PLA, EPS, etc.) for meat packaging. The main differences among the packaging show that general use of recycling materials for tray production can reduce the negative effects on the environment. For instance, the use of ‘recycled PET instead of virgin PET allows reducing the carbon footprint by approximately 40%.’

Another study performed by Kouloumpis et al. (2020) investigated the substitution of Polyethylene Terephthalate (PET) with glass bottling liquids in the domestic sector. This study highlighted that the substitution of PET with glass can cause glass bottles to reduce by 38% of their weight and increased recycled content can lower the Global Warming Potential (GWP) by 18.9%.

As underlined, literature about paint packaging is limited. For instance, it is possible to cite Tukker (2000), who made an LCA comparison of two options for paint packaging waste separation, i.e. cryogenic versus shredder-flush separation. With the LCA methodology, Raugei et al. (2009) analysed two different packaging and transport scenarios of a chemical batch, by either disposable fibre drums or reusable steel drums.

Gatti et al. (2017) conducted an interesting investigation into the reasons why there was damage to the bottom of some steel cans of water-based acrylic paint for the building industry. The evaluations led the authors to identify the main causes that generate the fracture in steel cans. The presence of micro fissures and depressions in the varnished bottoms of the steel packaging come into contact with the paint, causing possible corrosion that subsequently results in stress corrosion and rupture, due to the tensile stress of the weight of the paint. Regarding the waste bucket, the City of

Copenhagen's Plastic Zero project (2014) used LCA to analyse the environmental impact of incineration of plastic paint buckets compared to recycling. Results show that recycling could cut the emission of global warming gases by 45 tonnes of CO_2 eq.

Although packaging in the paints sector is scarcely studied, it is economically significant. According to the report issued by Grand Review Research (2019), the global paint packaging market totalled more than 21 billion euros in 2018, with an estimated increase of Compound Annual Growth Rate by 4% from 2019 to 2025, due to construction and infrastructure systems.

2.2. Paint sustainability

Many studies concerning the sustainability of paints are associated with the automotive industry, because the painting process has a significant environmental impact in this kind of manufacturing (Giampieri et al., 2019). Particularly, the painting process generates dangerous paint sludge. Salihoglu and Salihoglu (2016) assert that 'paint sludge constitutes a major fraction (~35%) of the hazardous process waste generated by an automotive manufacturing plant, and its management cost is the highest share (~58%) of the total environmental cost of hazardous waste management at the plant'.

For this reason, there is the need to compare scenarios using LCA and to analyse solutions that help replace toxic substances. Zanetti et al. (2018) investigated the use of paint sludge in the automotive industry by modifying an agent of bituminous binders for road pavement. The authors assume this a good alternative to landfilling or incineration. Another study on the use of paint sludge of the automotive sector was carried out by Ruffino et al. (2020). The LCA analysis compared hot mixture asphalts based on the traditional process, with an innovative method that replaces the neat bitumen with a percentage of paint sludge from the automotive painting process. These results encourage innovation, guaranteeing important improvements both in terms of energy requirements and GWP; such innovation represents a significant shift towards the circular approach. To evaluate the impact of the vehicle painting process, Bianco et al. (2020) developed an LCI and environmental assessment that aimed to evaluate results linked to the vehicle painting process in an industrial plant in Italy.

Papasavva et al. (2002) and Oguzcan et al. (2016) considered different paint type combinations based on solvent-borne, waterborne, and powder-borne bases for automotive industry application; the powder paints had the least amount of environmental impact. In the vehicle manufacturing process, Anastassopoulos et al. (2009) highlighted that the main environmental issues were attributable to the painting process. In the last few years, the complexity and specific characteristics of painting for vehicles stressed need for a structured framework for developing a proper LCA analysis of painting metal and plastic surfaces (Rivera and Reyes-Carrillo, 2016).

Solvent-based paint manufacturing was analysed by Dursun and Sengul (2006), with the aim of identifying the hazardous waste generated. The authors propose an innovative system to reduce hazardous waste using a distillation unit that can recover at least 70% of the solvent from wastewater.

An interesting survey on interior wall paints was conducted by Rochikashvili and Bongaerts (2018), who investigated the environmental and health effects linked to the use of these products by consumers and producers. Specifically, analysis focused on consumer perception of eco-friendly labels in Germany.

The resource efficiency applications in the surface coating/painting industry were evaluated by Alkaya and Demirer (2014). They highlighted the economic and environmental improvements in the different areas of the company, as follows: 'as a result of the evaluation it was determined that major environmental issues are related with chemical-intensive processes as it is the case for almost all surface finishing/coating enterprises'.

O'Connor et al. (2018) focused on a global issue: lead-based paint, which represents an important concern worldwide. In many countries, this type of paint has been banned or restricted. For this reason, surfaces painted with lead-based paint, could represent an important health global threat in the coming years. Hischier et al. (2015), compared the facade coatings of three different generic paint systems to analyse the application of manufactured nanomaterials (MNM) along the complete life cycle. The results illustrate that the inclusion of a MNM in the paint composition will positively affect environmental performance along the entire life cycle. In this direction, Kougoulis et al. (2012) underline how the use of nanotechnology in the production of a new paint for hospitals can kill bacteria under the effect of fluorescent light in operating rooms, for example. LCA has been used by Zhang et al. (2019) to compare three different interior wall decorative products: two different interior latex paints and a non-woven wallpaper. Results showed that interior latex is preferable over non-woven wallpaper when considering the integrated impact; human health damage is higher for interior latex. For decorative application, Dobson (1996) used the LCA methodology to compare two alternative processes to illustrate the best environmental options: solvent-based clear coat and incineration of Volatile Organic Compounds (VOC) emissions based on water coat.

Notably, other studies have carried out LCA analysis increase knowledge about how different chemical formulations can improve environmental sustainability (Ingrao et al., 2021). For instance, the Ecobilan company (1994), hired by the French Ministry of Environment, created the eco-labelling criteria based on the LCI of 11 indoor decorative paints. They created a denomination and syllabus for paints, and for identifying the main environmental problems.

Moreover, the same company identified titanium dioxide as the primary environmental concern in paint production.

Another study by Jotun (2008) that compared five paint products showed that, compared to water-based paints, solvent-based paints increase the release of VOC. This study showed that the processes to extend the life of a paint product contributes significant environmental benefits.

2.2.1. The circular economy in the paint manufacturing

Considering opportunities to address the CE approach in the chemical industry, the scientific literature reviewed the different strategies for implementation of a CE in the value chain, by enabling a closed-loop system. Strategies included improvements at the phase of waste management, input substitution with material recovered along the supply chain, and reuse of huge quantities of critical raw materials in the manufacturing system (Acerbi and Tasche, 2020; Mhatre et al., 2021). In the paint industry, the authors recognise two important strategies: a) finding alternative sources of raw materials by replacing compounds usually used in the paint formulation (such as TiO_2, or chemical additives) with components derived from organic substrates; and b) recycling waste paint into new paint products.

In the case of a), the scientific literature is limited, but there are some interesting studies. Miccichè et al. (2005) investigated suitable and environmentally friendly alternatives for co-based driers alkyd paints. Based on available renewable resources, van Heveren et al. (2007) analysed the environmental impact of replacing resins and additives for powder coatings. In line with these authors, Cruz et al. (2019) investigated paint formulation based on different extracts from Spirulina sp. LEB 18 microalgae; replacing the traditional latex resin, pigments, and antimicrobials, providing more sustainable products that are similar to the commercial paints currently available.

Following an LCA study, Lemesle et al. (2020) analysed the impact of bio-based ingredients derived from starch plastics production systems. They compared virgin starch and reclaimed starch-based production in coating industry formulation. Encouraging results show that the use of reclaimed starch (instead of virgin starch) improves all environmental indicators, mostly <10% for GHG emissions.

TiO_2 can be replaced with natural materials or with compounds recovered by waste streams. Ruszala et al. (2015) outlined the best strategies to replace TiO_2 with calcium carbonate or clay minerals without compromising the characteristics. Karakaş et al. (2015), has also investigated the substitution of TiO_2 with precipitated calcium carbonate, by highlighting that the substitution of TiO_2 reduces both cost and environmental burdens. Conversely, some characteristics (such as the opacity of the final product) were not successfully achieved. For a total or partial replacement of the virgin pigments in paint formulations, Karlsson et al. (2019) has studied how to recover titanium dioxide and other pigments from waste paint. This study shows that the use of TIO_2 reduces gloss without decreasing the whiteness or opacity of the paint.

In the case of b), the scientific literature is scarce. Interest in recovering unused paint is relatively new. Through LCA, Dunmade (2012) analysed the benefits associated with paint recycling in Canada. That study showed that technical solutions can be pursued and are replicable on an industrial scale. Other studies come up from specific projects or Environmental Product Declaration (EPD) oriented toward increasing the percentage of paint leftover diverted from landfills. Laurentide (2018) gained the EPD certificate for paint products made of post-consumer paints packaged in containers with 100% of recyclable plastics. The British Coating Federation (2015a) issued a technical report focusing on the need to optimise the use of natural resource for paint manufacturing. After estimating that the majority of leftover paint is sent to landfill, the report analysed the paint industry in the United Kingdom (UK) and proposed a comprehensive action plan to recycle waste paint, as well as to reuse the packaging.

Notably, two projects started in 2018. The first was 'green paints' and the second 'bio-paint'. Project green paint is a joint collaboration between an important Italian paint industry and the Institute of Technology in Genova (Italy), which has studied bio-plastics deriving from corn starch and from orange and cocoa waste as a possible alternative to the traditional pigments used in the formulation of interior paints (Perotto et al., 2018). The bio-paint project was funded within the European LIFE programme (Biopaint, 2018). It has studied technical solutions for recovering and recycling of discarded paints after use, as well as for recovering and recycling bucket paint (which is currently disposed of as special waste and is not therefore not recycled) to produce novel bio-based paints.

3. Materials and methods

The LCA performed was based on data provided by the company involved, Vitalvernici s.r.l., which is an Italian manufacturer of plastic coatings and paints, gaining in 2020 the EPD certificate.

Based on the technical characteristics and chemical composition of paints, we identified and selected two reference products, commercialised as 'Mastercolor Plus' and 'Acrylux'. As pointed out in the introduction, two products were selected, because their characteristics (Table 1) represent medium quality products with high sales in the Italian market (Table 2). Both paints are from the Prodcom code 20.30.11.50 category (Table 1). Fig. 1 illustrates the composition of reference products, broken down into additives, powder, resins, pigments, and water.

The primary goal of the present study is to assess the environmental impacts of the current production life cycle of the two selected paint products; secondarily, on the basis of these results, this study aims to identify the most impacting phases/modules for suggesting specific alternatives and building a more sustainable production cycle.

Considering paint and packaging, three scenarios have been constructed:

- baseline, based on the current production cycle of 100% virgin paint and primary polypropylene (PP) packaging.
- scenario A provides 45% of waste paint and 55% of virgin paint with 50% recycled polypropylene (PP 50%) (Fernandes and Domingues, 2007; CONAI, 2013; IPPR, 2021) and 50% virgin PP packaging.
- scenario B provides again 45% of waste paint and 55% of virgin paint, but the use of 100% recycled aluminium (Al) for packaging.

For all three scenarios, a LCA was made.

It must be pointed out that the packaging of the paint currently used by the company is a pail with a cover and it is made of virgin polypropylene. Taking into account that 93% of paints sold are in 14 L packages and that 7% are in 5 L, the capacity of the packaging varies according to the density of the finished product. The amount of virgin PP per unit of packaged product was assessed as well as the alternative materials, recycled polypropylene and aluminium, were assessed per functional unit, as shown in the sub-section 3.2.1.

Regarding waste paints, they are post-consumer and unused paints from household, public or private building activity, which can be collected, refined and recycled (American Coatings Association, 2016). Italy did not completely implement waste paint recycling, but their separate collection is mandatory. For the purpose of this study, the authors are only referring to the Italian supply. Thus, considering a conservative rate of 10% of waste paint (Kaps and Dodd, 2018) and the amount of paints produced in Italy in 2018 of 303,000 t (Table 2), roughly 30,000 t can be recycled. Considering the annual paint production of the company (330 tonnes), the supply of waste paint required becomes 148 t (0.5% of the Italian available paint waste) and consequently the study's hypothesis is feasible.

3.1. Life cycle assessment goal and scope

The LCA study was performed according to the ISO 14040:2006 (environmental management - life cycle assessment - principles and framework) (ISO, 2006a) and ISO 14044:2006 (environmental management – life cycle assessment – requirements and guidelines) (ISO, 2006b). The reference Product Category Rules (PCR) for this study is the PCR ICMQ-001/15 rev.2.1 'Construction products and construction services' and the reference Central Product Classification (CPC) codes are 35110 (group 351 – paints and varnishes and related products) (Environdec, 2020).

The functional unit (FU) was 1 kg of paint produced. The useful life of paints is identified as 50 years, which corresponds to the guaranteed duration of the product.

The GaBi ts version 8.7.0.18 calculation software and the Ecoinvent version 3.5 database were used for data processing.

3.1.1. System boundaries

The LCA analysis here refers to the 'cradle to gate' methodology.

Fig. 2 shows the system boundary of the life cycle stages of the paint production, pointing out that the analysis was divided into modules A1, A2, and A3 according to the EN 15804. It must be highlighted that waste paints and their transport were outlined by

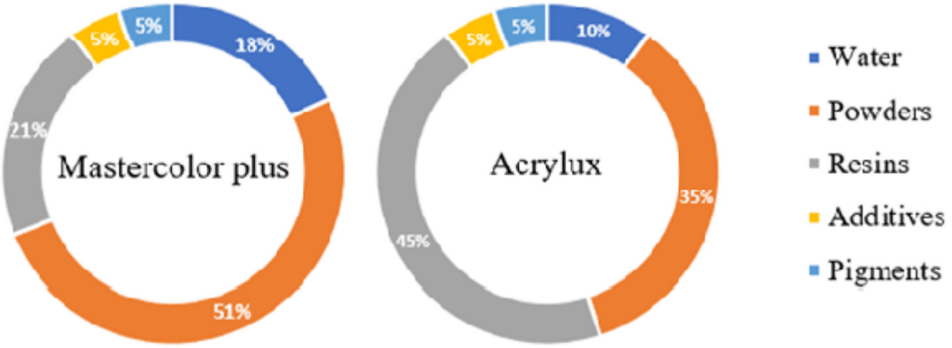

Fig. 1. Composition of selected products.

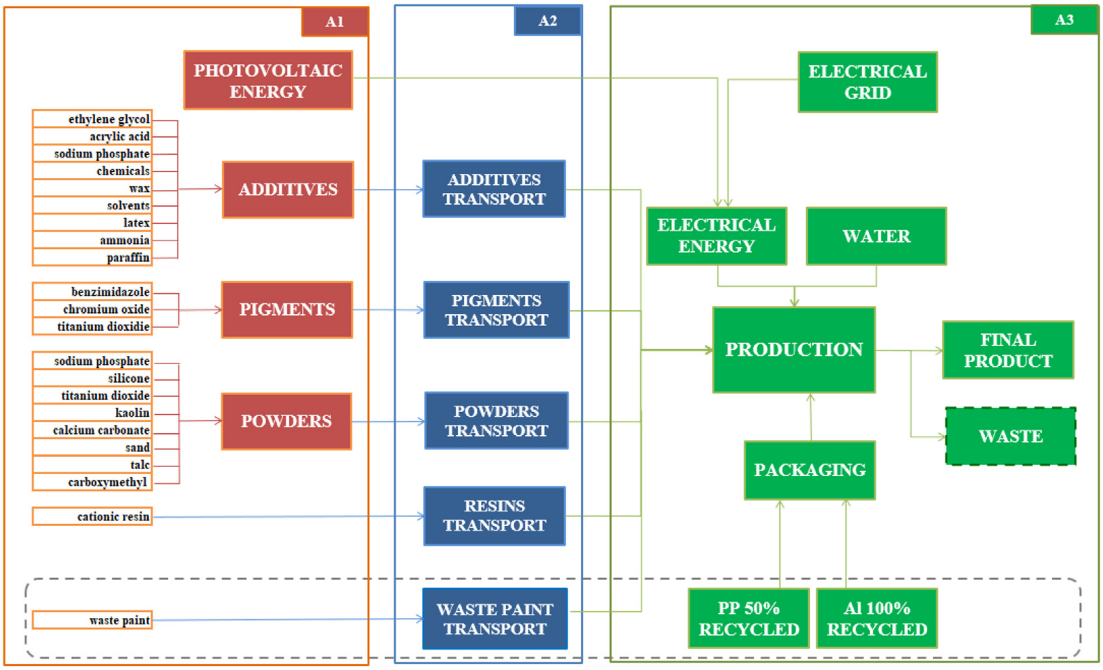

Fig. 2. System boundary of the life cycle stages of the production of the paint.

dashes in the module A1 and A2, referring to the alternative scenarios.

Module A1 refers to the production and supply of raw materials. It also includes the electricity used for the production phase and that generated from a photovoltaic (PV) system, which provides 73% of the electrical energy used and is located on the roof of the warehouse.

Module A2 concerns the ship and road transportation of raw materials to the manufacturing site. The internal handling of raw materials takes place also by electric forklifts. That consumption is embedded in the site's electricity consumption.

Module A3 is related to the production process. This module reports the use of all raw materials, and the consumption of electricity and water in the process. In this module, the production of the PP packaging is included, as well as the alternative packaging (PP 50% and Al) of scenarios A and B.

Unlike the complexity of the production, supply, and transport of raw materials (modules A1 and A2), the production process of paints at the plant in module A3 is straightforward. It takes place in batches and the main phases are the preparation of resins, dispersion, testing, and packaging.

The preparation of resins consists of premixing the raw materials of the paint to produce a homogenous resin mixture. It takes place in a reactor (a boiler), with a cavity in which cold water circulates to keep the reactor at a moderate temperature. As a result of the polymerisation reactions in the reactor, the resin agglomeration is produced and sent to the dispersion process. The dispersion process occurs in a sand mill, which has the shape of a large cylinder. The sand mill is subjected to high-speed agitation. The rotating particles of sand/silica can break the resins into smaller particles. Then, a blending and dispersing phase occurs with the solvents to create a finely dispersed mixture. Also, the colour phase is adjusted with colour pigments. The mixture is then filtered to remove the sand particles, forming a paste that is thinned and then verified for compliance with the standard of a final product. A finished paint is tested for its density, dispersion, and viscosity. Another check consists of applying the paint to a surface and examining the texture, and drying rate. Finally, the paint is packaged in an automated process.

3.2. Life cycle inventory

This phase allows the collection and assessment of data to provide inputs and outputs concerning the two paints. Most data were site-specific (primary), directly collected at the company's plant and secondarily from Ecoinvent and literature. All primary data concern the production in 2017 and came from Vitalvernici S.r.l, through the completion of a data collection survey. In detail the site-specific data regard the typology and amount of each input and output, conversely secondary data refer to both the processes (extraction, processing and refining) utilised for the resources, materials and energies involved (fuels included) and the road and ship transport means, whereas the mode of transport, origin and destination of the raw materials and products were provided by the company. Moreover secondary data for both waste paint and packaging materials have being detailing in the subsection 3.2.1.

These data have been reported in the LCI and reference each kg of paint produced.

The LCI (Table 3) has been split for both paints and provides a comparison of mass consumption, energy use, and waste generation.

It was necessary to perform the cut-off for the raw materials supplied, removing from the inventory iron oxides, perlite, cooked linseed oil, butyl glycol and other substances whose content was ≤0.1%. Only 1% of the total mass of raw material was excluded, respecting the limit required by the PCR concerning the exclusion of data at a maximum of 5%. In this study no allocations or parameterizations were performed.

Raw materials: The materials used vary according to the chemical composition of the two products. Generally, the largest quantity of material supplied includes three main materials: calcium carbonate, cationic resins, and silicones. Together, they represent 78% and 83% of the total materials (excluding water) in Mastercolor Plus and Acrylux, respectively.

Transport: it regards the transport of the raw materials from the suppliers to the manufacturing site. Most of the raw material, like calcium carbonate, come from different Italian locations by truck. However, other materials, like titanium dioxide, come by ship and truck from different nations, such as China, India, Belgium, Germany, and Holland. The supply of silicone comes from Northern Italy. A significant amount of resins (approximately 80%) is supplied from different Italian locations; about 20% are from Germany. Concerning waste paint supply in the Italian territory, the distance considered, based on the authors' hypothesis, is 1,000 km covered by road transport.

Energy resources: On the roof of the building, there is a photovoltaic system for self-consumption, which guarantees about 73.5% of the plant energy requirement. The remaining part comes from the electrical grid, represented by the Italian energy mix. The amount of electrical energy consumption of the manufacturing plant was obtained from the bi-directional electrical metre located in the plant.

Water supply: The water consumption associated with the two products is mainly due to the washing of paints and machinery. The

Table 3
Main inputs and outputs per kg of paint and Ecoinvent reference modules (baseline scenario).

Material	Ecoinvent modules	Amount (per kg)	
INPUT			
Additives (kg)		Mastercolor Plus	Acrylux
Ethylene glycol	RER: ethylene glycol production	1.64E-02	1.64E-02
Acrylic acid production	RER: acrylic acid production	7.32E-03	7.32E-03
Sodium phosphate production	RER: sodium phosphate production	3.51E-03	3.51E-03
Chemical inorganics	GLO: chemical production, inorganic	6.09E-03	6.09E-03
Wax production	GLO: wax production, for lost-wax metal casting	5.86E-03	5.86E-03
Solvent production	GLO: solvent production, organic	2.93E-03	2.93E-03
Latex production	RER: latex production	5.50E-03	5.50E-03
Ammonia liquid	RER: ammonia production, steam reforming, liquid	2.05E-03	2.05E-03
Paraffin	RER: paraffin production	3.66E-04	3.66E-04
Pigments (kg)			
Benzimidazole compound	RER: benzimidazole-compound production	1.67E-02	1.67E-02
Chromium oxide flakes	RER: chromium oxide production, flakes	1.67E-02	1.67E-02
Titanium dioxide	GLO: rutile production, synthetic, 95% titanium dioxide, Becher process	1.67E-02	1.67E-02
Powders (kg)			
Sodium phosphate	RER: sodium phosphate production	6.29E-04	4.32E-04
Silicone	RoW: silicon production, electronics grade	7.23E-02	4.96E-02
Titanium dioxide	RER: titanium dioxide production, sulfate process	4.08E-02	2.80E-02
Kaolin	RER: kaolin production	3.57E-03	2.45E-03
Calcium carbonate	RER: calcium carbide production, technical grade	3.56E-01	2.45E-01
Sand	GLO: market for sand	1.82E-02	1.25E-02
Talc	RER: magnesium oxide production	1.56E-02	1.07E-02
Carboxymethyl cellulose	RER: carboxymethyl cellulose production, powder	2.39E-03	1.64E-03
Resins (kg)			
Cationic resin	RER: acrylic dispersion production, product in 65% solution state	2.10E-01	4.50E-01
Water (kg)			
Tap water	Europe without Switzerland: tap water production, underground water without treatment	2.09E-01	9.64E-01
Energy (MJ)			
Grid electrical energy	IT: market for electricity, low voltage	1.45E-01	8.09E-02
Photovoltaic energy	IT: electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	4.02E-01	2.24E-01
OUTPUT			
Waste (kg)			
Sludge	Europe without Switzerland: treatment of wastewater	2.64E-02	2.64E-02
Paper and cardboard	Europe without Switzerland: treatment of waste paperboard, sorting plant	4.91E-03	4.91E-03
Plastic	Europe without Switzerland: treatment of waste plastic, mixture, sanitary landfill	1.77E-02	1.77E-02
Water (kg)			
Wastewater	Europe without Switzerland: market for wastewater, average	2.88E-02	8.64E-01

values were calculated based on the manufacturing plant's annual consumption. Data also embed the wastewater recycled from mixer washing.

Waste generation: As shown in Table 3, the largest amount of waste is represented by sludge, which represents over 53% of the total waste for each product. There are two significant wastes: plastic (36%) and paper/cardboard (10%). All the waste generated by the production process is managed by different external companies for disposal or recovery. Wastewater from mixer washing represents an output as shown in Table 3 and it is recycled in the process, as previously mentioned.

3.2.1. Packaging

Unlike the inventory data of Table 3, secondary data were used in all scenarios (Table 4) for the waste paints and packaging analysis. It must be pointed out that in the baseline scenario data of the virgin PP and the pails manufacturing were provided by the company, whereas in the scenarios A and B data were developed according to the authors' hypothesis confirmed by the personal communications by two Italian companies (San Marco SpA and Pipail srl) of the paint sector and gathered from the Ecoinvent and literature. It must be noted that Ecoinvent modules used and shown in Table 4 for waste paints, recycled polypropylene and recycled aluminium, only includes their treatment and disposal.

As stated above, the amount of polypropylene per unit of packaged product was calculated and is equal to 0.0271 kg (Mastercolour plus) and kg 0.04 (for Acrylux) in the baseline scenario (Table 4). Concerning the alternative materials hypothesised for packaging, it must be noted that the weight for FU has been calculated, considering the different density of each material (Davis, 2001; Matei et al., 2017).

3.3. Life cycle impact assessment

This study was carried out with a midpoint approach, which is frequently chosen in LCIA applications to the chemical industry. This approach is also suggested by the literature review of Frontera et al. (2020).

Moreover, according to the EN15804 and the reference PCR, the LCIA indicators analysed in this study are the following: Abiotic depletion potential for fossil resources (ADPF); Abiotic depletion potential for non-fossil resources (ADPE); Acidification potential (AP); Eutrophication potential (EP); GWP; Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP). Furthermore, the following resources consumption have been considered: in particular, total use of non-renewable primary energy resources (PENRT); total use of renewable primary energy resources (PERT) and use of net freshwater (FW). The version of CML baseline 2001 (January 2016 version) was used to assess the environmental impacts.

4. Results and discussion

4.1. The environmental impacts and comparison between the two products in the baseline scenario

Overall, through analysis of the total results obtained for each impact indicator in the baseline scenario, we note a significant difference between the two products examined. For most indicators considered, Acrylux represents the least harmful product for the environment in comparison with Mastercolor Plus. ODP is 24% and GWP, EP, and POCP are 22% higher in Mastercolor Plus than in Acrylux. ADPE is the only indicator that has a lower impact in Mastercolor Plus than in Acrylux.

As shown in Fig. 3, the environmental impact of Mastercolor Plus and Acrylux was split in the modules previously described. Particularly, it appears that the production and supply of raw materials (module A1) have the greatest impact on all the impact indicators for both paints, emphasising the role of the inputs as the most significant among the factors.

The results of the resource consumption also confirmed the lower impact associated with the product Acrylux, except for the use of net freshwater (FW); it has a higher value (30%) in comparison to Mastercolor Plus.

4.1.1. Module A1

Analysing in detail module A1, we note a significant impact of silicone production for the two products considered, due to the high requirement of energy occurred in the phases of its production and refining; indeed, this material represents the highest incidence in all indicators (between 42% and 67%), except the ADPE and POCP, in which silicone has a lower weight (Fig. 4).

Resins also have a significant impact; in Acrylux this material has an impact between 11% and 39%, while it is between 4% and 19% for Mastercolor Plus. These differences are clearly due to the composition of the different products, as mentioned above.

Based on the results, two other materials affect the value of the environmental indicators: calcium carbonate and carboxymethyl. The reason for their higher environmental impacts is attributable to their extraction and production process. Calcium carbonate is currently produced by different processes and currently the most used is a carbonated process in which limestone is burned in a lime

Table 4
LCI of secondary data per kg of paint and Ecoinvent reference modules per scenario.

Material/process	Ecoinvent 3.3 modules	Amount (per kg)	
		Mastercolor Plus	Acrylux
baseline			
Virgin Polypropylene	RER: polypropylene production, granulate	2.70E-02	4.00E-02
Blow moulding	RER: blow moulding production	2.70E-02	4.00E-02
scenario A			
Virgin Polypropylene 50%	RER: polypropylene production, granulate	1.35E-02	2.00E-02
Polypropylene 50% recycled	RoW: market for waste polypropylene	1.45E-02	2.10E-02
Blow moulding	RER: blow moulding production	2.81E-02	4.10E-02
Waste paint	Europe without Switzerland: market for waste paint	4.50E-01	4.50E-01
Waste paint transport	GLO: market for transport, freight, lorry, unspecified	4.50E-01	4.50E-01
scenario B			
Aluminium 100% recycled	Europe without Switzerland: market for scrap aluminium	7.86E-02	1.16E-01
Extrusion	RER: impact extrusion of aluminium, 1 stroke	7.86E-02	1.16E-01
Waste paint	Europe without Switzerland: market for waste paint	4.50E-01	4.50E-01
Waste paint transport	GLO: market for transport, freight, lorry, unspecified	4.50E-01	4.50E-01

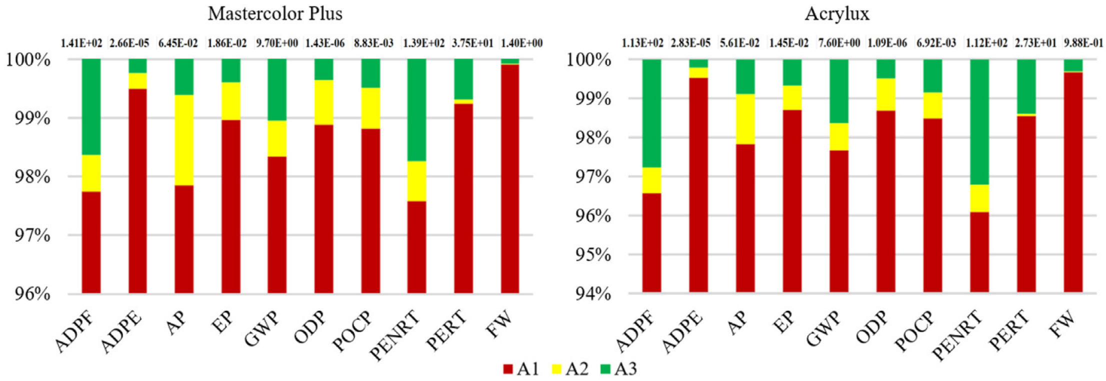

Fig. 3. Impacts per modules in the baseline scenario.

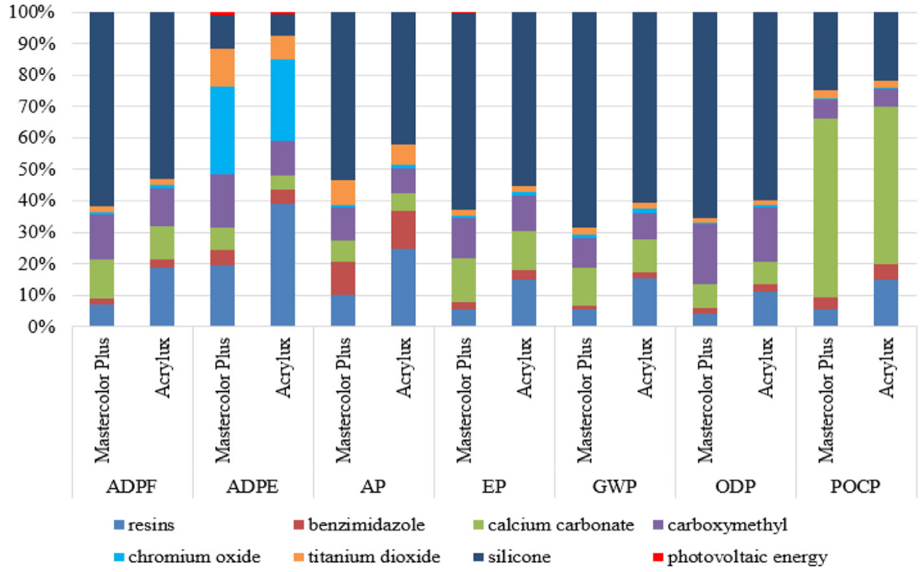

Fig. 4. Module A1 composition for environmental indicators.

kiln at about 1000 °C, later hydrated with water and successively treated with CO_2 gas for the carbonation process. The typology of the kiln and the elevated temperatures in which occur the process are responsible for the higher environmental impact. Nowadays, researchers are studying another process to reduce the environmental impact using another raw material (Teier et al., 2005). The same consideration is for carboxymethyl cellulose. The process consists of converting raw material deriving from cotton or wood into carboxymethyl by the etherification process. The use of chemical products for the treatment of the fibres and the production of raw materials are the main contributors to environmental impacts (Gulati et al., 2014). In both products, calcium carbonate has a variable weight between 5% and 15% in all indicators, except for the POCP, in which this material has a significant impact (50% in Acrylux and 56% in Mastercolor Plus); carboxymethyl shows an average impact of 10% on both paints in all indicators.

Finally, it could be important to highlight the incidence of chromium oxide, which has a high impact (26% in Acrylux and 27% in Mastercolor Plus) only in the ADPE, while in the other indicators it has an impact of about 1%. In this case, the reason for high impacts is the lack of efficiency within the production process. During the production of one ton of chromium product, and according to Zhang et al. (2005), the production plant discharges approximately ‘2.0–2.5 tonnes of toxic chromium-containing residues that are difficult to be detoxified’.

4.1.2. Module A2

Impacts associated with the transport of materials are included in the A2 module. This module is influenced by the high impact of powder transport, in particular by ship, from China and India as mentioned above, which affects considerably (more than 77% on average) the environmental indicators for both products, as shown in Fig. 5.

The ADPE, conversely, is influenced mainly by the road transport both of powder and resins.

Lastly, the transport of additives has the lowest incidence (between 1% and 4%) for all the indicators in both types of products.

4.1.3. Module A3

Results of the impact assessment of module A3 are synthesised in Fig. 6. The results show for both products that the impact more relevant in the production stage is linked to packaging manufacturing. In detail, virgin polypropylene (PP) is responsible for the highest environmental impact in ADPF, AP, GWP and POCP, whereas in ADPE, EP and ODP, the largest incidence is associated with the blowing process and the electrical energy from the grid.

4.2. Environmental impacts of scenarios A and B and comparison with baseline

Based on the LCAs performed and the analysis of the impacts per

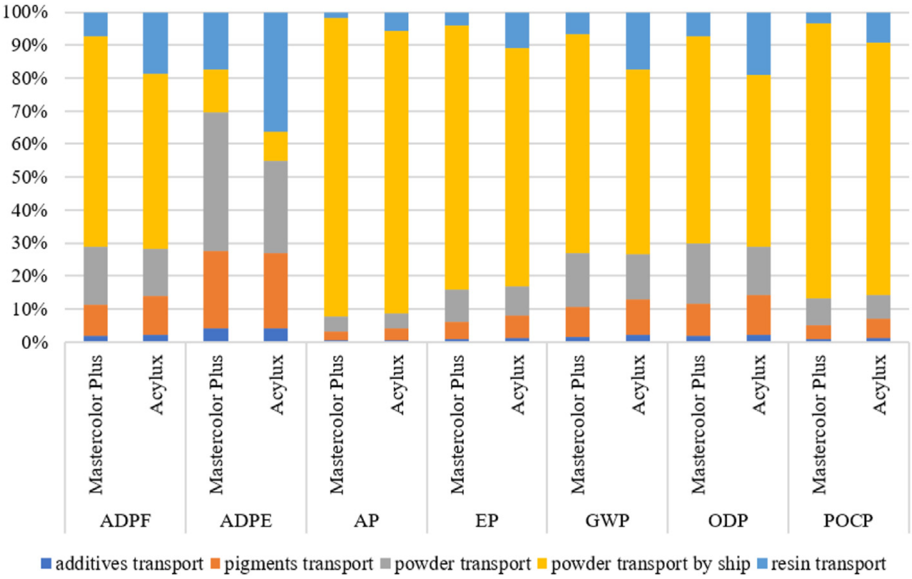

Fig. 5. Module A2 composition for environmental indicators.

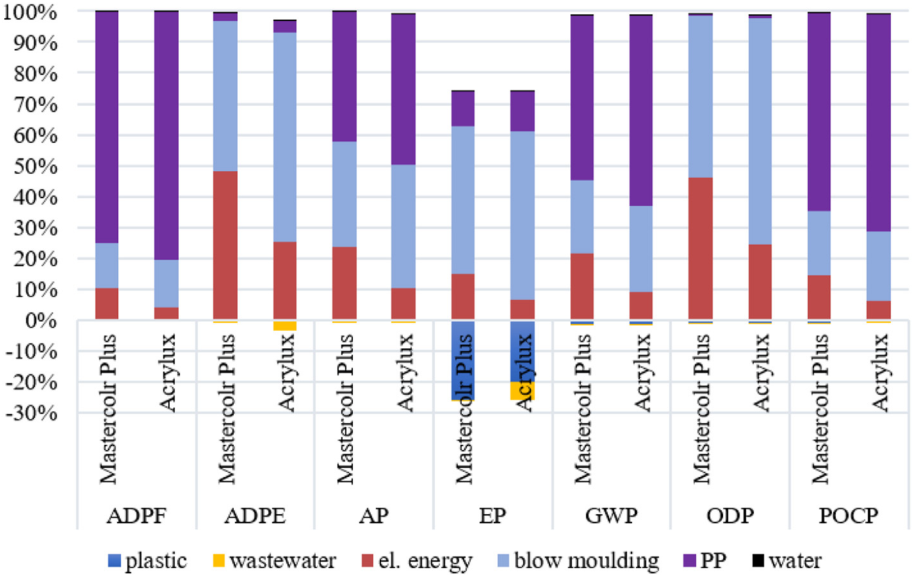

Fig. 6. Module A3 composition for environmental indicators.

module in the baseline scenario, some options have been identified and applied to reducing the environmental impacts and join the CE approach.

As mentioned, the waste paints use, at a rate of 45%, allows to reduce both the raw materials and their transport, thus improving the impacts of modules A1 and A2, whereas the PP 50% recycled and Al recycled use in substitution of the virgin polypropylene could decrease the impact of packaging in module A3, considering that the recycled materials have negative value due to the avoided impacts.

Both alternative scenarios A and B were analysed by the LCA and compared with baseline scenario (Table 5).

Detailing the analysis of the results it emerges how the incidence of the substitution of raw materials by waste paint is remarkable and Fig. 7 suggests the decreasing of impacts due to both the supply and transport of raw materials: the greatest reduction occurs in the GWP, which is 49.7% in Mastercolor Plus and 51.1% in Acrylux.

Regards as the results of packaging, Table 6 highlights the better performance of PP 50% (scenario A) then Al (scenario B) for both the paints. All impact indicators show significant reduction for scenario A compared to the baseline, whereas scenario B increases in almost impact indicators (840% for ADPE), excepting for ADPF and POCP, due to the reduced consumption of energy for the aluminium recycling. The worst performance of Al packaging is due to the weight of aluminium charged to FU (Table 4). The GWP of packaging decreases of over 40% for both paints in scenario A than the baseline but increases of roughly 3% in scenario B compared to the baseline.

For evaluating the impact of different packaging production processes and comparing the blow moulding (scenario A) and extrusion (scenario B), it is important to pay attention on the

Table 5
LCA results per scenarios.

		Baseline	scenario A	scenario B
Life cycle impact assessment				
ADPF [MJ]	Mastercolor Plus	1.41E+02	7.78E+01	7.74E+01
	Acrylux	1.13E+02	6.26E+01	6.20E+01
ADPE [kg Sb eq.]	Mastercolor Plus	2.66E-05	1.48E-05	1.51E-05
	Acrylux	2.83E-05	1.58E-05	1.63E-05
AP [kg SO_2 eq.]	Mastercolor Plus	6.45E-02	3.56E-02	3.58E-02
	Acrylux	5.61E-02	3.10E-02	3.12E-02
EP [kg Phosphate eq.]	Mastercolor Plus	1.86E-02	1.03E-02	1.03E-02
	Acrylux	1.45E-02	8.05E-03	8.16E-03
GWP [kg CO_2 eq.]	Mastercolor Plus	9.70E+00	4.89E+00	4.92E+00
	Acrylux	7.60E+00	3.73E+00	3.78E+00
ODP [kg R11 eq.]	Mastercolor Plus	1.43E-06	8.00E-07	8.02E-07
	Acrylux	1.09E-06	6.12E-07	6.15E-07
POCP [kg Ethene eq.]	Mastercolor Plus	8.83E-03	4.77E-03	4.78E-03
	Acrylux	6.92E-03	3.72E-03	3.73E-03
Resource consumption				
PENRT [MJ]	Mastercolor Plus	1.39E+02	9.00E+01	8.95E+01
	Acrylux	1.12E+02	7.21E+01	7.13E+01
PERT [MJ]	Mastercolor Plus	3.75E+01	1.74E+01	1.73E+01
	Acrylux	2.73E+01	1.27E+01	1.26E+01
FW [m^3]	Mastercolor Plus	1.40E+00	7.74E-01	7.74E-01
	Acrylux	9.88E-01	5.45E-01	5.45E-01

resource consumption indicators shown in Table 6: for both paints, it emerges that the value of PERT is higher than 43% for blow moulding compared with extrusion. Conversely, both PENRT and FW performed better in blow moulding, which is lower than the extrusion at about 76% and 41%, respectively.

The results concerning both the use of waste paint and the alternative materials for packaging suggest that the decrease due to waste paint affects the total impact per each indicators, more than the decrease of packaging materials, because the weight of the packaging materials and processes has a great incidence in module A3 (an average of 80% and 90% for Mastercolor Plus and Acrylux respectively), which conversely has very slight influence on the total impact for all impact indicators, equal to <1% for both products.

The results highlight significant enhancement for both scenarios A and B in comparison to the baseline in the range between −50% of GWP and roughly −43% of ADPE, although the first scenario presents slightly better performances than the second one, except for ADPF.

Regards the environmental impact associated to materials excluded by cut-off, it emerged that it is negligible (Kougoulis et al., 2012; Häkkinen et al., 1999), for example the total GWP would be affected of 0.00095% by iron oxide, thus validating the cut-off applied.

The resource consumption analysis brings out a significant reduction in the results compared to the baseline for both paints, with a slight better rate of roughly 1% in scenario B than A.

Overall, considering the best environmental performance of the life cycle of paints to be proposed to the company's management falls on scenario A, both products are selected.

Notwithstanding the reduction achieved through the scenarios A and B, some impact indicators remain higher than others, then the authors benchmarked the research study with other similar studies. It is important to underline that paint chemical formulation is mixed in different proportions and this makes the comparison difficult to analyse. For instance, making a comparison of GWP with Laurentide (2018) white colour, it emerges that in Laurentide the GWP is equal to 1.40 kg CO_2eq, whereas in our study the GWP for Mastercolor plus paint in scenario A (PP 50%) is equal to 4.89 kg CO_2eq. This difference is due to the different chemical formulation and to the fact that in Laurentide EPD the packaging materials are made from 100% recyclable plastic and that the energy mix differs from the Italian one. Indeed, Laurentide located the production process in Canada where the energy mix counts for 67% to hydro and no-hydro renewable energies, 15% from nuclear, coal and gas 9% and 10% each, so it is more favourable than the Italian energy

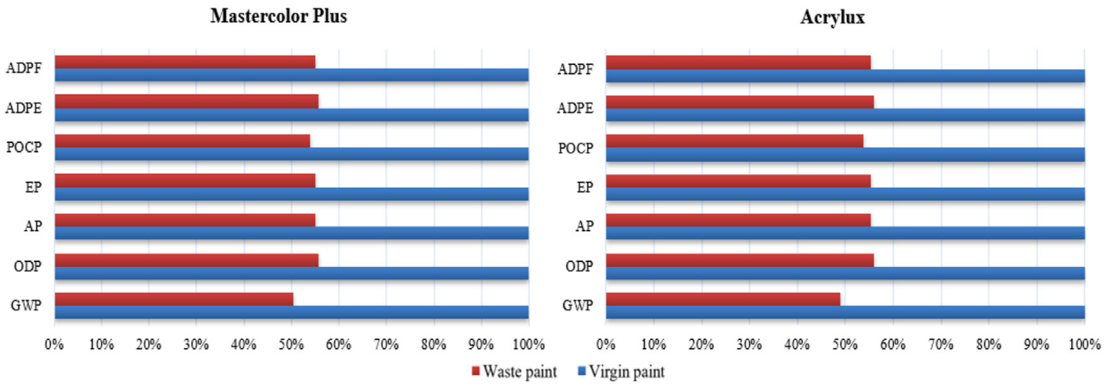

Fig. 7. Comparison between paint (45% waste paint and 55% virgin paint) and 100% virgin paint including raw materials and transport.

Table 6
Packaging impacts results per scenarios.

	ADPF	ADPE	AP	EP	GWP	ODP	POCP	PERT	PENRT	FW
	[MJ]	[kg Sb eq.]	[kg SO_2 eq.]	[kg Phosphate eq.]	[kg CO_2 eq.]	[kg R11 eq.]	[kg Ethene eq.]	[MJ]	[MJ]	[m^3]
Mastercolor Plus										
Baseline	2.11E+00	3.22E-08	3.05E-04	9.18E-05	7.77E-02	2.75E-09	3.78E-05	2.57E-01	2.42E+00	8.70E-04
Scenario A	1.28E+00	3.01E-08	2.17E-04	7.65E-05	4.59E-02	2.63E-09	2.29E-05	1.84E-01	1.53E+00	6.54E-04
Scenario B	8.93E-01	3.05E-07	3.51E-04	1.48E-04	8.02E-02	4.54E-09	2.54E-05	1.02E-01	1.04E+00	6.49E-04
Acrylux										
Baseline	3.13E+00	4.78E-08	4.51E-04	1.36E-04	1.15E-01	4.07E-09	5.59E-05	3.81E-01	3.58E+00	1.29E-03
Scenario A	1.90E+00	4.46E-08	3.21E-04	1.13E-04	6.80E-02	3.89E-09	3.40E-05	2.72E-01	2.27E+00	9.69E-04
Scenario B	1.32E+00	4.50E-07	5.19E-04	2.19E-04	1.18E-01	6.70E-09	3.74E-05	1.50E-01	1.53E+00	9.57E-04

mix which, in 2017, was based on natural gas (47%), coal (11%), oil derivates (5%) and renewable energy (roughly 35%) (Canada Energy Regulator, 2020; ARERA, 2020). Moreover, comparing with LCAs performed for two paint products by Kougoulis et al. (2012), the carbon footprint was equal to 2.42 and 2.32 kg CO_2eq for the vinyl emulsion and alkyd emulsion respectively, much lower than our data, although the boundary and the FU are the same. The difference is due to many factors: i.e. analysis is endpoint whereas our study use the midpoint approach; the quantity of water present in the paint formulation is between 30 and 40% against 10−18% of our paints; the packaging phase is included only in our study; the distance for the transport is only 100 km, whereas the our study includes intercontinental transports by ship and road.

It must be pointed out that the reduction of environmental impacts owing to packaging and waste paints can become significant, totalling the quantity of paints packed annually both at the company- and, generally, country-level. Considering that Acrylux, for example, has a GWP of 7.6 kg CO_2eq/kg (Table 5) and bearing in mind that roughly 330 tonnes of paints were sold by the company, around 2,508 t CO_2eq can be counted per year. Considering the decrease of GWP occurring in scenarios A and B, at the company level savings become 1,230 t CO_2eq and 1,247t CO_2eq respectively. Nationwide, taking into account that 303,000 t (Table 2) of the same kind of paints were produced in Italy the results could positively affect the paint industry: savings of CO_2eq can be increased to 1,166,565 t CO_2eq, which could be comparable to the emissions of approximately 778,000 cars in a year (Transport and Environment, 2018). Furthermore, these savings positively affect the direct and indirect CO_2eq emissions of the chemical industry, which were 12 Mt, as mentioned in the introduction, reducing them by 9.4%.

The same calculation can be carried out for the packaging materials, so roughly 13,200 t of polypropylene and over 38,000 t of aluminium can be recovered. This is significant for recovering and recycling packaging materials to implement a further circularity of materials.

This highlights some limits of the present research. This study did not include the phases of collection of the waste paints, which could negatively affect the advantageous results achieved.

Furthermore, it could be difficult to currently implement the recycling of waste paints, as underlined by British Coatings Federation (2015b), because one of the most key obstacle is represented by legislation and material classification of end-of-waste according to the EU Waste Framework (European Commission, 2019).

The low incidence of packaging on the total impact indicators of paint can be underlined as a limit of this research as well.

The results of this LCA highlight the potential weakness of the production chain. Accordingly, they allow researchers to hypothesise some corrective measures both in the products and in the supply chain. However, to confirm the feasibility of these measures, a complementary analysis, like Life Cycle Costing, will be carried out in future research, both for paint and packaging. Particularly we stress that the best environmental performance of the scenario A must also be confirmed by economic evaluation.

Another issue of the research regards the exclusion of the use phases of paints, which could be investigated to assess VOCs and underline the better substitutes for these harmful emissions.

5. Sensitivity analysis

The results of sensitivity analysis in LCA studies are important because they can be used to confirm the hypotheses considered.

The authors have evaluated the incidence of the use of paint waste on the environment, in comparison with the baseline scenario. It has been reported only in the results for Mastercolor product because of the higher environmental impacts in comparison with Acrylux. To perform the sensitivity analysis, the paint waste has been increased by 5% (from 0% to 45%), evaluating for each indicator how much the variation influenced the result. As expected (Fig. 8), the decreasing of the environmental indicators is sensitive to the increasing of recycled waste paint, highlighting a constant diminishing for all the environmental indicators. On average, the intensity of decreasing for the environmental indicators is equal to approximately 5% for every 5% increase of waste paint use: the GWP indicator decreases of 5.48% more than the others. Notably, the peak reduction (about 10%) for the ADPE indicator occurs at both 15% and 35% to the increase in the percentage of waste paint.

The sensitivity analysis was also carried out for the packaging, evaluating the incidence of the increasing of polypropylene and

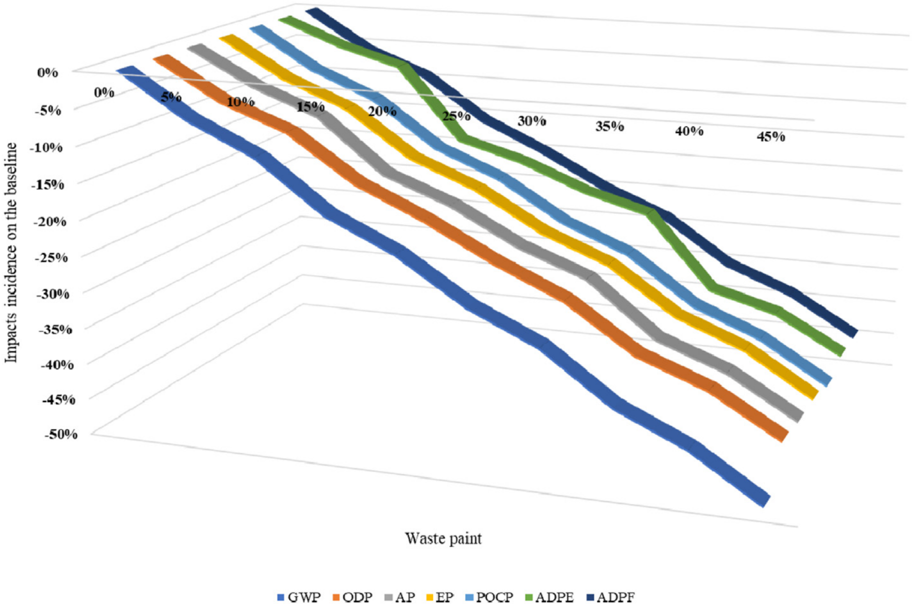

Fig. 8. Impacts incidence on baseline per percentage of waste paint used.

aluminium recycled packaging on the environmental indicators. Both packaging recycled materials were increased by 10% (from 0% to 50% and from 0% to 100% respectively). The results obtained confirm the expected rate of incidence of packaging on the total environmental indicators, but show a negligible influence, between 1 and 2% on the total for all impact categories, thus they were omitted.

6. Conclusions

The significant weight of paints sector in the chemical industry, both in Italy and the EU suggests increasing updated and detailed research and studies. From the perspective of a more sustainable development in the chemical industry, the use of LCA analyses has become an extremely useful tool. In light of this consideration, the environmental performance of three scenarios have been undertaken and the findings allowed the authors to identify the best among them. The baseline scenario investigated the current production cycle, which uses both virgin paint and primary polypropylene packaging. Regarding the comparison between the two paints investigated, Mastercolor Plus and Acrylux, the analysis was divided into three modules: module A1 (production and supply of raw materials) has the greatest impact on both products for all indicators and has shown a significant impact of silicone for both products and calcium carbonate and carboxymethyl, mainly for their production phase; module A2 (the ship and road transportation of raw materials to the manufacturing site) has underlined that the main impact is due to the transport of powders by ship and road, whereas resin transport affects manly the ADPE indicator in Acrylux, because the percentage of resins in the chemical formulation of this paint is high; module A3 (paint and packaging production process) reveals that packaging production has the highest environmental impact, followed by the electrical energy.

On the basis of the LCA results in the baseline scenario, the feasible measures to reduce the environmental impacts have been identified: the use of waste paints and packaging materials different from the virgin polypropylene allowed the reduction of raw materials, transport, and packaging impacts. The better performance was due to the use of waste paint, which reduced by roughly 48% on average the impact indicators. The sensitivity analysis undertaken for the use of waste paint confirmed the hypothesis of improvement. Potential enhancement in the packaging materials might be achieved by using recycled PP 50% (scenario A) for both products. Nevertheless, the contribution of packaging alternatives is negligible on all impact indicators.

Generally, in comparison to the baseline scenario, the environmental impacts of scenarios A and B have been reduced by 45.5% and 45.2% respectively. GWP was the best performing, decreasing by 50.3% in scenario A and by 49.8% in scenario B.

The sustainable options to measure the environmental performance of the paints have been identified according to a CE approach. In particular, the collection and recycling of waste paints that are currently incinerated or landfilled could implement a circularity in this burdened chemical sector.

The significant impact of some materials currently used in paints means there is a need for research into replacing these raw materials with innovative and natural materials: in particular, replacing chemical elements with bio-based products will be important for future research.

CRediT authorship contribution statement

Annarita Paiano: Conceptualization, Methodology, Writing – original draft, Supervision. **Teodoro Gallucci:** Conceptualization, Investigation, Data curation, Writing – original draft. **Andrea Pontrandolfo:** Visualization, Validation, Writing – original draft, Writing – review & editing. **Giovanni Lagioia:** Writing – review & editing. **Paolo Piccinno:** Data curation, Validation. **Amedeo Lacalamita:** Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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