International Journal of
Dairy Technology

SDT Society of Dairy Technology

doi: 10.1111/1471-0307.12926

REVIEW

Application of novel technologies to reach net-zero greenhouse gas emissions in the fresh pasteurised milk supply chain: A review

CAPUCINE GRANDSIR, NATALIA FALAGÁN and M. CARMEN ALAMAR*
Plant Science Laboratory, Cranfield University, Cranfield MK43 0AL UK

This review assesses the potential of three novel technologies (3-nitrooxypropanol, ultraviolet C light cold pasteurisation and biochar) to reduce the carbon footprint produced by the fresh milk supply chain at global level. In addition to the adoption of these technologies: (i) new policies should enhance the development and implementation of international standards to optimise the quality and safety of such technologies whilst facilitating their traceability; (ii) dairy firms and technology start-ups should benefit from worldwide emissions trading systems to limit technology implementation costs; and (iii) consumers could participate in the net-zero challenge by adopting easy-to-apply sustainable practices, thus reducing their milk carbon footprint.

Keywords Enteric methane, Waste, 3-NOP, UV-C light, Biochar, Greenhouse gas emissions.

*Author for correspondence. E-mail: m.d.alamargavidia@cranfield.ac.uk

INTRODUCTION

The milk supply chain involves more than 6 billion consumers worldwide, which are expected to grow by 1.7% by 2028 (FAO 2019) and its revenue to reach US$ 393 billion by 2026 (Statista 2018). This increasing demand calls for a more efficient and sustainable system to supply milk, avoiding a further increase in its already high carbon footprint (3.2 kg of carbon dioxide equivalent [CO_2eq]). These figures make milk the second most polluting drink in the world after coffee (Poore and Nemecek 2018). When looking at the European bovine milk supply chain, the highest emission mitigation potential stands at the farm stage, where enteric fermentation (EF) producing methane (CH_4) equals to 43% of bovine milk carbon footprint (Flysjö 2012). Methane is 86 times more potent at warming than CO_2 (during the first 20 years' after being released) and has a shorter lifespan (Jackson *et al*. 2019). Over the past decade, feed additives have been considered a promising methanogenesis inhibitor technology to reduce greenhouse gas (GHG) emissions from EF. These technologies include active molecules like 3-nitrooxypropanol (3-NOP) and nitrates (Hristov *et al*. 2015; Honan *et al*. 2021; Meale *et al*. 2021; Melgar *et al*. 2021; Schilde *et al*. 2021).

Bovine milk waste mitigation at both retail and consumer stages can further reduce up to 18% of the upstream bovine milk GHG emissions (Flysjö 2012). Nonthermal pasteurisation technologies such as high-pressure pasteurisation and ultraviolet C (UV-C) light treatment (Zhang *et al*. 2019; Shabbir *et al*. 2021) have also been shown to limit energy consumption and extend milk shelf life (Choudhary *et al*. 2011; Koutchma and Francisco 2017; Koca *et al*. 2018). Additionally, greenhouse gas removal (GGR) technologies (Santos *et al*. 2012; Lomax *et al*. 2015; Asibor *et al*. 2021) have been considered as a solution to remove the remaining GHGs from the atmosphere and reach net-zero emissions (Smith *et al*. 2016; Fawzy *et al*. 2021; Hu *et al*. 2021). However, most of the published literature focusses on specific stages during the supply chain and/or specific technical aspects of the technologies used to remove or reduce GHG emissions, without considering the feasibility of their implementation. The study herein aimed to review and provide critical insight into these novel technologies and their implementation potential (*viz*. technical and economical) for the fresh pasteurised bovine milk supply chain to reach net-zero GHG emissions. A case study on the United Kingdom (UK) was provided to illustrate the potential of these technologies.

METHODS

Collection of secondary data was performed using the following keywords in Google scholar, Scopus and Google: GHG mitigation technology or removal technology; feed additive; cold pasteurisation or nonthermal pasteurisation; GGR or greenhouse gas removal; bovine milk; and dairy. A total of 123 entries out of 314, including peer-reviewed journal papers and strategic and statistics reports from governments and official dairy organisations dated from 2010 to 2022 were selected based on these keywords. The gaps found in the literature were filled out by the collection of primary data. Three companies, including start-ups in the dairy technology sector, were contacted to perform a survey on key literature missing points. The specific questions were the following: (i) are you working on an EU or UK regulation approval for your technology? If so, how long do you believe this would take to be approved? (ii) are you based in the UK? (iii) what are the main constraints you are facing to scale up your technology process? (iv) would you have an approximate cost per litre of milk using your technology?

The assessment for technology implementation was performed following the methodology developed by Black *et al*. (2021), who evaluated the likelihood of adoption of similar green technologies in the industry considering the following: (i) the technology readiness level (TRL); (ii) the CO_2eq mitigation potential; (iii) the cost-effectiveness; (iv) the implementation barriers including technical, regulatory and financial aspects; and (v) the implementation time.

Recommendations were finally made in the form of a road map, which included different stages in the development of the technologies (TRL 1 to 9). These recommendations aimed to guide stakeholders on how to address technical, financial and regulatory barriers for technology implementation. The stakeholders considered were part of both the public (*viz*. international and UK governments, international and national standard setters, and researchers) and the private sector (*viz*. farmers, dairy firms, technology start-ups and consumers).

METHANE MITIGATION TECHNOLOGIES

One consequence of ruminants' enteric fermentation is the methanogenesis reaction that results in the production of CH_4 from CO_2 and hydrogen (H_2), which is facilitated by methanogenic archaea. During the last stage of methanogenesis, methyl-coenzyme M reductase (MCR) reduces methyl-coenzyme M with coenzyme B, producing CH_4 as a by-product, which is further released to the atmosphere when the animal burps (Duin *et al*. 2016). Moreover, methanogenesis competes with the production of propionate (a source of energy for cattle); both processes use H_2 as substrate; therefore, the more $\mathbf{H_2}$ is used for methanogenesis, the less propionate is produced. This competition can result in up to 12% loss in cattle energy intake, limiting optimal milk productivity (Beauchemin *et al*. 2009).

Feed additives have been primarily used to increase the productivity of dairy cattle (Honan *et al*. 2021). However, given the raising concern about climate change and GHG emissions, it is key to investigate whether feed additives can be used to reduce enteric CH_4 emissions (FAO 2010; Flysjö 2012; Sejian *et al*. 2015). Lipids, tannins and essential oils (*e.g*. carvacrol and thymol in oregano and thyme) can transform the rumen environment reducing CH_4 production up to 9%, 54% and 40%, respectively, when administrated to the bovine's diet. However, these results depend on the type of feed involved; their action is not specific and thus can have a negative impact on beneficial microorganisms; and large amounts are required to be effective (more than 20 g/kg of dry matter intake [DMI]) (Honan *et al*. 2021).

Methanogenesis inhibitors, such as nitrate and halogens, directly target the CH_4 inhibition pathway to reduce CH_4 production (Honan *et al*. 2021). They have also been shown to decrease the CH_4 production by 50% and 95%, respectively; however, nitrates can lead to toxic effects on ruminants' health whilst the methanogenesis recovery rate using halogens after 4–5 weeks of treatment can reach 62% (Knight *et al*. 2011; Latham *et al*. 2019). Contrarily, 3-NOP, a molecule that inhibits the MCR enzyme *via* oxidation, has been shown to reduce CH_4 production up to 19% and 42% when only 0.01 g/kg and 0.2 g/kg DMI were supplemented to dairy cattle, respectively (Jayanegara *et al*. 2018). That said, it is estimated that only 0.06 g/kg DMI can reduce the CH_4 emissions by 30% (Rooke *et al*. 2016). Additionally, 3-NOP can improve dairy cattle energy intake; Jayanegara *et al*. (2018) demonstrated that a higher H_2 availability resulted in more propionate being produced and therefore more energy (Jayanegara *et al*. 2018). Moreover, since the concentration of 3-NOP required in the rumen is so low, so they are the concentrations of nitrate, nitrite and 1,3 propanediol (Hristov *et al*. 2015); therefore, 3-NOP does not negatively affect the cattle health (Duin *et al*. 2016).

The 3-NOP technology was internationally patented in 2012 (Duval and Kindermann 2012). Since then, its potential to inhibit methanogenesis has been researched and demonstrated extensively *in silico* (Duin *et al*. 2016) and *in vivo* trials (Reynolds *et al*. 2014; Hristov *et al*. 2015; Jayanegara *et al*. 2018; Melgar *et al*. 2021). Its implementation has also been recommended by independent environmental organisations (*e.g*. Committee on Climate Change and WWF) to help governments tackling climate change (Lampkin *et al.* 2019; Committee on Climate Change 2019b). It has now reached a high level of maturity (TRL 7–8), and the Dutch company DSM Nutritional Products Ltd. has already trademarked the supplement under the name Bovaer®. DSM received full approval in Chile and Brazil and a positive opinion from the European Food Safety Authority (EFSA) in 2021. Bovaer® finally received full regulatory approval by the European Commission Standing Committee in April 2022 (EFSA 2022), before Bovaer®'s large-scale production plant in Darly, Scotland, is operational by 2025 (DSM 2021).

Lampkin *et al.* (2019) predicted that the implementation of 3-NOP as a feed additive would incur in a financial impact on farms with an approximate cost of $US 115 per t$CO_2$eq removed (Committee on Climate Change 2019a, 2019b). However, the cost of 3-NOP is difficult to predict since it is not yet commercialised. That said, the additive has also been proven to increase milk fat and protein content providing performance benefits to the industry (Lopes *et al.* 2016; Melgar *et al.* 2020, 2021). These nutritional benefits, in addition to the financial support the farmers will get, could compensate for the potential cost of 3-NOP, as soon as it is regulated and commercialised.

A limitation of 3-NOP, however, is that it needs to be constantly present in the rumen to efficiently reduce enteric methane emissions since the inhibition of the methanogenesis is a reversible process (Duin *et al.* 2016). Thus, the technology is currently not feasible for a grazing system where dairy cattle do not have constant access to the additive during spring and summer. The majority of farms in the world send dairy cattle to pasture, with 87% and 95% of British and Australian farms, respectively, using this outdoor system (FAO 2014; DEFRA 2019a). Further research is thus required to efficiently supplement dairy cattle with 3-NOP whilst pasturing (Black *et al.* 2021).

MILK WASTE MITIGATION TECHNOLOGIES

In developed countries, the highest volume of milk waste occurs at retail and consumer stages (Gross 2018) equalling to *ca.* 25 Mt CO_2eq/year of avoidable upstream GHG emissions (Porter and Reay 2016). Thermal technologies like high-temperature short-time (HTST) are widely used to inactivate milk pathogens and have been shown to extend shelf life up to 11 days (WRAP 2018). However, even after a thermal processing treatment, fresh milk remains highly perishable and can be spoiled prematurely before the expiring date (WRAP 2018; Martin *et al.* 2021). Thermal treatments involve large amounts of energy due to high temperatures (up to 72°C for 15 seconds for HTST) and subsequent cooling, both contributing to milk carbon footprint (0.12 kg CO_2eq/kg of milk [Tomasula and Nutter 2011]). Additionally, thermal treatments can alter milk nutritional and organoleptic quality (Bousbia *et al.*, 2021; Shabbir *et al.* 2021; Neoκleous *et al.* 2022).

Nonthermal technologies such as high-pressure processing (HPP), electrical field pasteurisation and UV-C light can be used as alternative technologies to extend milk's shelf life. These technologies inactivate milk pathogens at ambient temperature without subsequent cooling (Zhang *et al.* 2019), which is seen as more sustainable because they avoid energy consumption from heating (Evrendilek 2014; Shabbir *et al.* 2021; Zhang *et al.* 2021). High-pressure processing inactivates a comparable amount of spoilage and pathogenic microorganisms as HTST (Evrendilek 2014; Liu *et al.* 2020) but pressure requirements, ranging from 200 and 600 MPa, result in whey protein denaturation (Evrendilek 2014; Nunes 2019; Liu *et al.* 2020; Shabbir *et al.* 2021) and a higher capital investment compared with HTST (Goyal *et al.* 2013; Pendyala *et al.* 2021). Electric field pasteurisation consumes 63% less energy than HTST and can increase milk shelf life up to 15 days (Al-Hilphy *et al.* 2021), but it is still an expensive option compared with thermal technologies (Alirezalu *et al.* 2020). UV-C light pasteurisation is a technology that exposes milk to a shortwave light ranging from 200 nm to 280 nm to inactivate pathogenic microorganisms' genetic materials, with 253.7 nm providing the highest germinal effect (Gayán *et al.* 2014; Koca *et al.* 2018). When compared to other thermal and nonthermal technologies, UV-C light has been reported to be 1.3 and 14 times less costly than HTST and HPP, respectively (Abdul Karim Shah *et al.* 2016; Pendyala *et al.* 2021); whilst, at the same time, it extended milk shelf life up to 14 days (Koutchma and Barnes 2013), maintained protein and vitamin A levels, increased vitamin D3 content (enhancing functional properties) and maintained the colour, flavour and viscosity of the final product (Delorme *et al.* 2020).

The UV-C light technology is used worldwide by the dairy industry to clean food contact surfaces and packaging materials. It is also used to disinfect water used in milk processing steps and the air of the milk production area (Koca *et al.* 2018). Start-ups in Europe and Asia, including Lyras A/S in Denmark (Lyras 2020) and AseptoRay Ltd. in Israel (Aseptoray n.d.), are working on scaling up UV-C light milk treatment yet are still facing some limitations. The Lyras S/A company has been seeking Danish and EU approval since 2020 and expects to get it before the end of 2023 (Nielsen N Z, personal communication). The EFSA in both the European Union and the UK approved the use of UV-C light as a complement to thermal treatment under the novel food regulation (EC) No 258/97 (EFSA 2016). However, its application as a sole method is still in development and under regulation, mostly based on microbiological and technical reasons, even if its efficacity has been widely discussed and approved in laboratory research (TRL 6–7) (Cappozzo *et al.* 2015; Crook *et al.* 2015; Koutchma 2019; Delorme *et al.* 2020).

The UV-C light treatment application is challenging on liquids with high turbidity like milk (Shabbir *et al*. 2021) because it has a high absorption coefficient ($\alpha = 300\ cm^{-1}$) compared with drinking water ($\alpha = 0.1\ cm^{-1}$), meaning that UV-C light cannot penetrate the liquid in-depth and some pathogens are not directly exposed to the radiation (Datta and Tomasula 2015). Furthermore, UV-C light treatment efficiency relies on multiple parameters, which vary according to the raw milk characteristics. These parameters, which need to be adjusted and optimised depending on milk viscosity, turbidity, colour and initial microorganisms load, are as follows: UV dose (J/m^2), intensity (W/m^2), wavelength (nm) and light source (pulsed or continuous) (Koca *et al*. 2018; Delorme *et al*. 2020). For instance, Gram-positive bacteria are more resistant than Gram-negative bacteria and, therefore, would need a higher radiation level to be inactivated (Delorme *et al*. 2020). However, higher radiation levels may lead to quality and sensory alterations such as off-flavours due to lipid and vitamin oxidations, a change in texture because of protein denaturation and a reduction in vitamin C content (Orlowska *et al*. 2012).

The financial limitations of the implementation of UV-C light rest on the price of the final product, which can significantly vary between low-quality milk (*i.e.* high initial microorganism load) and high-quality milk (*i.e.* low initial microorganism load) (Nielsen, personal communication). However, the technology has lower energy, equipment investment and operational costs than standard pasteurisation (Table 1). It can save 90% energy and 60% water (Askew 2021), whilst equipment costs are 33% to 50% lower than HTST (Abdul Karim Shah *et al*. 2016) and can be implemented at any stage of the process with minimum disruption in the plant (Priyadarshini *et al*. 2018; Delorme *et al*. 2020).

Table 1 Energy consumption and milk flow rate to reach 5 log10 cfu/mL maximum imposed by the EU regulation, and infrastructure cost comparison between UV-C light nonthermal pasteurisation and HTST thermal pasteurisation.

	UV-C light	HTST
Energy consumption (kWh/m^3)	3.87[a]	211.7[b]
Milk flow rate (L/h)	26 000[a]	10 000[b]
Infrastructure cost ($US)	10 000–15 000[c]	20 000–30 000[c]

[a]Iversen (2021) – using Lyras S/A turbulent UV-C light CPS system.
[b]Modi and Prajapat (2014).
[c]Abdul Karim Shah *et al*. (2016).

GREENHOUSE GAS REMOVAL TECHNOLOGIES

The Committee on Climate Change (2019a, 2019b) advised that net-zero targets could not be met on time by only using technologies to reduce emissions (*viz*., 3-NOP and UV-C light). Industry also need to implement additional novel technologies focussed on removing residual GHGs from the atmosphere (greenhouse gas removals [GGRs]) (Lomax *et al*. 2015; Fawzy *et al*. 2020). Natural GGRs, including afforestation and forest management, habitat reforestation and soil carbon sequestration, are already fully developed and being implemented worldwide (TRL 9) (Asibor *et al*. 2021), so they are not under the scope of this study. Engineered GGRs, including bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced weathering, magnesium silicate or oxide in cement, wood as a construction material, and biochar, have the specificity to be at an early development stage (TRL < 7) (Asibor *et al*. 2021). They also have a greater potential to remove CO_2eq, but most of them are much more expensive than natural GGRs. For instance, DACCS currently costs between $US 600 and 1000 per t$CO_2$eq removed compared to $US 0–0.8 for afforestation (Asibor *et al*. 2021).

Biochar, a pyrolysis process by-product of burning biomass under anaerobic conditions, is one of the less expensive engineered options ($US 90–120 per CO_2eq removed). It is also the most relevant technology to be implemented into the dairy industry because of its circularity potential (Fawzy *et al*. 2021; Hu *et al*. 2021). The biomass used can come from waste including dairy manure, thereby contributing to solving waste management issues (Cao and Harris 2010; Li and Jiang 2017). Whilst biochar can also be used as a methanogenesis inhibitor like 3-NOP (Honan *et al*. 2021), and as a fertiliser to enhance soil fertility and crop resilience (Sohi 2012), its highest potential is at sequestrating carbon (C) and absorbing CH_4 and N_2O with a global estimated sequestration potential standing between 0.3 and 2 Gt CO_2eq/year (Fawzy *et al*. 2021). Biochar contains high amounts of C aromatic compounds, and the more stable these compounds are (this stability is defined by a resistance to thermochemical and biological decomposition for over 100 to 1000 years [Rees *et al*. 2020]), the more potential there is to sequestrate C and absorb GHGs (Blanco-Canqui 2021).

The biochar technology is now being scaled up to pilot plants and large-scale trials (TRL 5–6) (The Royal Society 2018; Tian *et al*. 2019; Vivid Economics for BEIS 2019; Asibor *et al*. 2021). However, start-ups, including CarboCulture in Northern Europe (CarboCulture 2021), bio365 in the USA (bio365 2022) and InRim in Australia (InRim 2022), are currently struggling to scale up the pyrolysis process because biochar's yield and stability depend on multiple parameters including biomass (*e.g.* lignin and mineral content, particle size) and pyrolysis variables (*e.g.* temperature, heating rate, reaction residence time, pressure and pyrolysis reactor type; Leng and Huang 2018; Fawzy *et al*. 2021). Studies have shown that feedstock with high lignin content, large particle size and processed with pyrolysis temperature exciding 500°C increase biochar stability as well as its capacity to sequestrate C and reduce N_2O and CH_4 (Ippolito *et al*. 2020; Li *et al*. 2020); yet high temperature most likely decreases biochar yield (Leng and Huang 2018; Tisserant and Cherubini 2019). Biochar stability is also soil-specific and influenced by the parameters of the soil it is applied to, such as temperature, pH, moisture, mineral content and C/N ratio (Zhu *et al*. 2015; Tisserant and Cherubini 2019). Biochar could also harm soils by decreasing surface albedo or modifying soil bio-ecosystems. These effects are still undefined in the long term, and real-time applications on fields are lacking (Meyer *et al*. 2012; Blanco-Canqui 2021). Large-scale deployment is also limited by the availability of biomass and land requirements (The Royal Society 2018) and especially biomass from agro-industrial waste whose supply is seasonal and competes with other sectors such as animal feed, energy production and even other GGRs like BECCS (The Royal Society 2018; Tisserant and Cherubini 2019). We suggest promoting crops growing on dedicated land to ensure an annual supply for biochar production; however, this land would be competing with the land used to grow food intended for human and animal consumption. This variability of supply, as well as feedstock origins and production types, will impact the price of biochar (Shackley *et al*. 2011). The highest production prices are found in developed countries like the USA and UK, where costs are US\$ 8.85 kg^{-1} and US\$ 13.48 kg^{-1}, respectively, compared to US\$ 0.09 kg^{-1} in the Philippines (Ahmed *et al*. 2016), where feedstock from waste is more accessible and less expensive than virgin feedstock (Roberts *et al*. 2010).

Biochar's production and application are not yet regulated by international and European legislation (Meyer *et al*. 2017). Standardisation is a prerequisite in the development of a large-scale trade of biochar; and as such, there is a need to define optimal and harmonised production methods, as well as biomass characteristics, whilst avoiding side effects on health and the environment (van Laer *et al*. 2015). Given the lack of legislation, voluntary standards were created to bridge this regulatory gap. The International Biochar Initiative (IBI), in the USA, and the European Biochar Certificate (EBC) are the most used standards in the world. There are also country-specific standards like the Biochar Quality Mandate (BQM) in the UK, which aim to promote good industry practices to enable producers to provide quality and safe biochar to their customers. These standards add credibility to the biochar market system and could be adopted into regulations to ensure the quality and safety of the product at an industrial scale (The Royal Society 2018).

CASE STUDY: MITIGATION POTENTIAL IN THE UK MILK SUPPLY CHAIN

The UK is the third-largest producer of milk in Europe with more than 6.8 billion kg produced annually for liquid consumption (DEFRA 2019b; Uberoi 2020), accounting for approximately 8.53 $MtCO_2eq$/year (Table 2).

Enteric fermentation represents 63% of emissions at the farm (Flysjö 2012; Magowan 2021), which is equivalent to 3.71 $MtCO_2eq$/year for liquid milk. Also, 90% of total UK agriculture CH_4 emissions come from the ruminant digestion process (DEFRA 2019b). Providing 3-NOP, with a 30% methane abatement potential, the UK's bovine herds could hence save up to 1.1 $MtCO_2eq$/year (*ca*. 13% of total liquid milk *CF*). In Scotland, Lampkin *et al*. (2019) showed that implementing 3-NOP on 80% of Scottish dairy cattle and 10% of Scottish beef cattle could reduce 0.27 $MtCO_2eq$/year of enteric methane emissions by 2045. Another study predicts that emissions could be reduced by 2.06 $MtCO_2eq$/year and 1.56 $MtCO_2eq$/year if 100% or 70% of UK dairy and beef cattle were supplemented with 3-NOP, respectively, by 2050 (Eory *et al*. 2020).

Downstream of the UK's milk supply chain, approximately 4% of milk is wasted at the retail and consumer stages; HTST being used at 93% in the country (Lewis and Deeth 2009; Flysjö 2012; Porter and Reay 2016). Avoiding milk waste could save up to *ca*. 0.20 $MtCO_2eq$ of upstream emissions per year (Porter and Reay 2016). However, milk not being consumed on time represents 54% of this total milk waste so *ca*. 0.11 $MtCO_2eq$/year would be prevented by extending milk shelf life with UV-C light (WRAP 2018). Moreover, UV-C light pasteurisation is 90% less energy-intensive than HTST (Askew 2021), which emits *ca*. 0.20 $MtCO_2eq$/year because of energy consumption (Cooper *et al*. 2019). The use of cold pasteurisation alone would additionally save up to 0.180 $MtCO_2eq$/year (90% of 0.20 $MtCO_2eq$/year), given a total of 0.29 $MtCO_2eq$/year being avoided (0.11 $MtCO_2eq$/year from preventing waste added to 0.18 $MtCO_2eq$/year from UV-C light energy savings). Emissions savings from nonthermal pasteurisation thus represent *ca*. 3% of the total UK's liquid milk *CF*.

To offset the UK's liquid milk carbon footprint, the pyrolysis process implemented at an industrial scale in the UK could produce biochar with the potential to remove 2.7 to 3.4 tCO_2eq/year per t applied, yet it depends on the type of feedstock used (Hammond *et al*. 2011). This would result in a removal potential of 6 to 41 $MtCO_2eq$/year limited by the available biomass in the UK including dedicated grown crops and feedstock from agro-industrial waste (Smith *et al*. 2016). These data are variable among studies assessing biochar environmental impact because of the different life cycle assessment (LCA) methodology parameters chosen (*e.g*. land requirements and production capacities) (Terlouw *et al*. 2021). The Royal Society (2018) estimated that biochar removing 5 $MtCO_2eq$/year is a more plausible scenario because it can only be deployed in a quarter of the 6 Mha of arable land in the UK. GHGs removed with biochar could thus represent *ca*. 59% of total liquid milk supply chain emissions with an industrial-scale implementation time

Table 2 Estimation of carbon footprint ($MtCO_2eq$ per 6.77 billion kg) of UK liquid milk production in the UK in 2020 from farm to consumers. Adapted from Flysjö (2012).[a]

Supply chain stages	Farm	Dairy (processing)	Packaging	Transport	Retail and consumer	Total
$MtCO_2eq$ per 6.768 billion kg of liquid milk produced annually[b]	5.89	0.34	0.27	0.47	1.56	8.53
% of Total	69	4	3	6	18	100

[a]Flysjö (2012) has identified sources of emissions from the UK milk supply chain using Arla Foods' milk production as a model. Arla Foods produces *ca*. 3.3 billion kg of raw milk per year in the UK (about half of all the UK milk production), making its milk supply chain broadly representative of the UK's supply chain (Arla Foods 2020).

[b]Estimates were carried out by multiplying the average carbon footprint of whole, semiskimmed and skimmed milk found in Flysjö (2012) by the amount of kg of milk produced in the UK in 2020.

estimation in the UK ranging between 2025 and 2030 (The Royal Society 2018; Vivid Economics for BEIS 2019).

If the three technologies were adopted at 100% of their CO_2eq potential by the time they are commercialised in the UK, a combined use could offset up to 75% of the milk *CF* which does not reach the net-zero target (Table 3). Even with implementation and full deployment of the technologies before 2050, the positive effects on climate change would take more than 20 years to have an impact, as emphasised in the sixth assessment report for the intergovernmental panel on climate change (IPCC 2021).

RECOMMENDATIONS TO DEVELOP, IMPLEMENT AND DEPLOY TECHNOLOGIES INTO THE MILK SUPPLY CHAIN

Technologies development (TRL 1 to 6)

The development of innovative methods to supplement dairy cattle with the 3-NOP molecule in a grazing system needs further research. The implementation could be based on a slow 3-NOP chemical release into the rumen, through boluses or encapsulations (Rooke *et al*. 2016; Granja-Salcedo *et al*. 2019) in order to ensure the continuous presence of the molecule in the cattle's digestion system. Also, it would be beneficial to design feeding systems that allow a shorter period between each 3-NOP administration (DSM 2019), mainly during spring and summer seasons.

In terms of full inactivation of microorganisms, further research is needed to implement UV-C light treatment for opaque liquids like milk. We suggest integrating turbulent flow with the pasteurisation system to pressure milk at high speed into a coiled tube reactor and therefore enabling a more renewable surface of the liquid in contact with radiations to allow greater microbial load reduction (Datta and Tomasula 2015). Other techniques such as the laminar flow, involving the injection of the liquid through a thin film on a surface irradiated with UV-C light (Datta and Tomasula 2015), should be further investigated.

Additional mitigation technologies, not necessarily targeting EF or milk waste, can help reach the net-zero targets. Efficient manure management like manure nutrient and density sensing, soil mapping (Trojan 2021), sustainable feed production such as algae-based animal feed (Tzachor 2019) and/or energy-efficient transportation of liquid milk using intermodal rail-road transportation (Cannas *et al*. 2020) are some examples with potential benefits in terms of emission control.

Governments could boost these initiatives by organising and funding research and development (R&D) programmes (Pourhashem *et al*. 2019) that aim to find multiple alternative mitigation technologies whilst solving current technical issues that hinder higher TRLs adoption. The £25 million Innovate UK SMART Grants addressed to any business or entity carrying R&D activities (UKRI 2021a) and the Transforming Food Production programme (UKRI 2021b) are examples of existing government R&D funding schemes. The latter has already enabled the development of nine innovative projects including a precision technology for dairy farmers to make informed decisions regarding the efficiency, productivity and sustainability of their farm. The French Government also recently deployed €428 million [$US 451 million] to support a 5-year R&D and innovation scheme for the agro-ecological transition through the fourth Investment for the Future Programme (Ministry of Agriculture 2021).

Technologies implementation (TRL 6 to 9)

Reduce the technology cost

A powerful financial tool to overcome large financial investments of the presented technologies is the carbon market (Calel 2013; Platt *et al*. 2018). It is a system where allowances, equal to 1 t of CO_2eq emitted, are traded between industrial plant businesses so they do not exceed the emissions cap imposed by governments at the risk of being fined (OECD n.d.). If the industrial plant exceeds the emission

Table 3 Summary of the technology maturity, adoption feasibility and implementation time.

Technologies	TRL	CO_2eq mitigation potential (Mt/year)	UK's milk chain carbon footprint mitigation potential (% total)	Cost-effectiveness ($US tCO_2eq^{-1})	Implementation barriers	Implementation time
3-NOP	7–8[a]	1.11[b]	13	115[c]	Grazing system; high cost	2025 (in the UK – currently available in Chile, Brazil and the EU)[c]
UV-C light	6–7[a]	0.29[d]	3	Not available	Lack of regulations approval; milk turbidity; process standardisation.	2023 (in the EU)[e]
Biochar	5–6[f,g]	5[g]	59	90–120[h]	No unified quality and safety regulation; biomass supply; land requirements; biochar yield and stability variability; soil specificity; high cost.	2025–2030[f,g]

[a]Technology readiness level (TRL) represents the level of maturity of technology and is estimated regarding the level of literature available online. From TRL 4, it exists more than 10 research papers validating the technology application in a laboratory. From TRL 5 to 6, companies including start-ups are developing the technology from pilot to large scale. At TRL 7, the technology is under regulatory bodies revision. At TRL 8, technology has been approved and is commercialised at TRL 9.

[b]3-Nitrooxypropanol (3-NOP) is a methanogenesis inhibitor. Its CO_2eq mitigation potential in the liquid milk supply chain is calculated on the assumption that it reduces 30% of a total enteric methane emission of 3.71Mt CO_2eq/year (DSM 2019; Lampkin *et al*. 2019; Eory *et al*. 2020).

[c]Committee on Climate Change (2019a, 2019b).

[d]Ultraviolet C (UV-C) light is used as a nonthermal pasteurisation treatment of milk. Its CO_2eq mitigation potential is calculated on the assumption that 0.2 $MtCO_2$eq/year would be avoided if waste does not occur at the retail and consumer stage (Porter and Reay 2016). Waste is 54% because of underuse of milk before the expiring date (WRAP 2018) so 0.11 $MtCO_2$eq/year would be avoided by extending milk shelf life using UV-C light. Moreover, UV-C light treatment requires 90% less energy than HTST thermal treatment so replacing HTST with UV-C light will additionally save up to 0.18 $MtCO_2$eq/year.

[e]Nielsen, personal communication.

[f]Vivid Economics for BEIS (2019).

[g]The Royal Society (2018).

[h]Asibor *et al*. (2021).

cap, the business can buy allowances from other businesses or it can purchase offset carbon credits (Thisted and Thisted 2020). An example of offset carbon credits designed for the dairy industry is 'CowCredits' developed by the start-up Mootral, a producer of methanogenesis inhibitors in the UK (Mootral 2021). These credits enable the start-up to distribute their product to farmers for free (Palmer 2021), and the same model could be applied to the 3-NOP technology. Another example of offsetting carbon credit is the carbon storage credit suggested by Platt *et al*. (2018) to finance GGRs, including pyrolysis process scale-up where biochar producers could receive carbon storage credits when using bio-oil and/ or biogas, co-products of biochar, as a source of energy for their plants. The carbon credits value needs to be high enough for the system to be feasible as the industrial plant business would prefer to directly invest in its own low-emissions technologies instead of buying credits (Thisted and Thisted 2020). Nonthermal pasteurisation including UV-C light treatment is an example of energy-efficient technology that dairies can invest in, for further plant implementation.

The EU emissions trading system (ETS) remains one of the largest in the world surrounded by other well-established ETSs among developed countries like the USA, Switzerland, the UK and South Korea. China recently launched its national ETS in July 2021 as a developing country and surpassed the EU ETS performances in 2022 (Liao and Yao 2022).

Define international process standards

A common implementation barrier to the three above-discussed technologies is that their action potential is highly dependent on different production and application parameters. International process standards need to be defined by the International Organisation for Standardisation (ISO) in collaboration with national standard bodies (*viz*., the British Standard Institute) and government agriculture departments to ensure the optimisation of the technologies for GHG emissions mitigation, their safety and compliance to regulations. The existing voluntary standards for biochar (*e.g.* BQM, EBC and IBI) can be used as a basis to define these international process standards and harmonise biochar production, facilitate the accounting of biochar CO_2eq removal potential and easily monitor its impact at a large scale (The Royal Society 2018; Pourhashem *et al*. 2019).

The immediate integration of early-stage technologies into funding policies can also rapidly highlight the impact of technologies parameters on relevant environments and can help to optimise and standardise production and application parameters (Lomax *et al*. 2015). Farmers are recommended to engage in existing early implementation governmental funding such as the sustainable farming incentive scheme (SFI), starting mid-2022, and the farming investment fund (FIF), taking place from December 2021 to 2026 in the UK. The SFI is intended to make tests and trials at small and pilot scales for sustainable land management practices (DEFRA 2021). The application of biochar into the soil can be largely promoted throughout this programme. The FIF aims to encourage and refund farmers using equipment and technologies from a defined list to increase the sustainability of their farms (Jones 2021). Farmers can participate in the elaboration of the list promoting the application of biochar and/or 3-NOP to help to define process standards. Agritech start-ups can also take part in the European innovation and technology (EIT) Food programme, called Test Farm. The programme is held every year to standardise and validate start-ups' technologies on-farm, as well as receive visibility, network and funding (EIT Food 2022).

Technologies deployment (TRL >9)

Continuous monitoring

Once novel technologies are commercialised, continuous monitoring of their impact on the environment and on human and animal health is unavoidable. For example, the standard dose of 3-NOP is set at 0.06 g/kg of DMI daily fed to dairy cattle; this has the potential to reduce 30% of methane production (Rooke *et al*. 2016) and has no side effects on animal health (Duin *et al*. 2016). However, there is still a risk that archaea enzymes become resistant to 3-NOP, which would reverse the methanogenesis inhibition process or that unexpected animal or consumer health issues appear in the long term (Jayanegara *et al*. 2018). Biochar application might lead to a decrease in surface albedo because it is a black material absorbing the light, which could generate surface energy imbalance and negate some of the positive impacts of biochar. Other biochar effects could be soil acidification and toxicity to humans and ecosystems because of black carbon particles (Tisserant and Cherubini 2019). The continuous monitoring challenge can be tackled with technologies to prevent potential long-term mitigation technologies reversible effects and health-related issues. These technologies include cattle wearing biosensors to monitor their heart rate and temperature (Knight 2020) and rapid near-infrared spectroscopy (Kusumo *et al*. 2018) and nuclear magnetic resonance technology (Söderqvist 2019) for soil carbon storage measurements.

Labelling

Consumer acceptance plays a major role in the adoption and deployment of a novel technology (Priyadarshini *et al*. 2018). They are more and more concerned about the quality and safety of products they consume; a behaviour that has been intensified with the COVID-19 outbreak (BSI 2021). Biotechnologies involving irradiations like UV-C light, or metabolism modification like 3-NOP, can be perceived as higher safety risks for users (Siegrist and Hartmann 2020). Moreover, recent consumer awareness of the climate crisis has also increased the demand for sustainable products with a lower *CF* (Golembiewski *et al*. 2015). A recommendation for novel technologies acceptance is to increase communication to consumers through labels related to product safety and sustainability (Golembiewski *et al*. 2015). Governments could impose mandatory safety labels, like the health mark in the EU and the UK (FSA 2021), on UV-treated milk to reassure the consumer that the product is safe for consumption. Dairy firms and technology companies could also use voluntary labels informing consumers about the *CF* of the product they consume. Examples of existing labels are the UK and Australian Carbon Trust labels, which compare the product *CF* to the market-dominant product *CF* based on the GHG protocol standard. In Asia, Japan launched its national carbon label adapted from ISO 14025 and providing a carbon emissions numerical value (Liu *et al*. 2015). Consumers with environmental concerns are willing to pay more for *CF* easy-to-read labelled foods (Rondoni and Grasso 2021) with the possibility to compare *CF* (Hartikainen *et al*. 2014); however, results depend on gender, age and educational background. In addition to the extra cost of labelled products, label implementation can take a long time; therefore, the benefit of consumer awareness and price premium needs to offset the cost and time taken by the firm to get the label. The success of these *CF* labels towards an eco-friendly consumption behaviour could bring about governments' intention to make it mandatory and to unify global carbon accounting labelling methods.

Additional sustainable consumption opportunities

Consumers are recommended to adopt sustainable milk consumption practices to complete the mitigation technologies action. They could prefer to buy locally produced milk to reduce transport emissions and the use of fossil fuel. The dairy plant of origin code can be found on the identification mark on the milk bottle in the EU, UK and USA (FSA 2021). At home, examples of simple actions to avoid milk waste are not only to freeze the milk which could save up to *ca*. 10 000 t and £5 million per year in the UK [$US 6 million] but also to decrease fridge temperature from 6.6°C to less than 5°C to save more than 50 000 t and more than £25 million per year [$US 31 million] (WRAP 2018). However, this would require more energy consumption and thus additional CO_2 emissions.

Finally, consumers can choose to balance their diet with both plant-based drinks and bovine milk. Plant-based drinks, especially oat and soy drinks emit three times less GHGs, require *ca*. ten times less land and *ca*. 12 times less water than milk (Poore and Nemecek 2018). However, these trendy drinks [their market value was $US 9.8 billion in 2017 and is expected to reach US$ 19.7 billion in 2023 (Statista 2018)] are nutritionally inferior to milk. The protein content is on average 48% lower than bovine milk, and the mineral and nutrient content and bioavailability (absorption level) tend to be inferior (Chalupa-Krebzdak *et al*. 2018).

CONCLUSIONS

The implementation of three novel technologies that will contribute to reach the net-zero GHG emissions in the fresh pasteurised milk supplied chain has been assessed. The use of 3-NOP, a feed additive, has a strong methane mitigation potential with no visible negative effects on the cattle health when 0.06 g is daily supplemented to 1 kg of DMI. UV-C light has been selected as a sustainable milk waste mitigation technology, which extends milk shelf life by decreasing the microorganism content whilst maintaining and enhancing quality and nutritional attributes, respectively. It is a cheaper option than HTST and can be implemented at any point in the milk processing line. Additionally, the highest potential of biochar made from wasted biomass sits on its carbon sequestration capacity when applied in culture fields. However, a collaborative and active involvement among government, industry and academia is key to ensure the full deployment of such technologies into the milk supply chain by 2025–2030. New national and international policies can help incentivise research and financially support farmers and other stakeholders to promote the use of novel technologies for a more productive and sustainable chain. Global voluntary standards can be used as a first step into legislation development whilst ensuring the quality and safety of technologies like biochar and UV-C light pasteurisation, which depend on multiple parameters. Dairy firms and technology start-ups can benefit from worldwide ETS systems to limit the implementation costs, whilst consumers could take part in the net-zero challenge by adopting easy-to-apply sustainable practices. Finally, additional technology alternatives to both reduce emissions and remove GHGs, including manure nutrient, density sensing, soil mapping, algae-based animal feed and intermodal rail-road transportation, should complement the 3-NOP action, UV-C light pasteurisation and biochar adoption. The final goal is to avoid a climate change catastrophe starting by reducing milk's *CF* which is one of the highest among beverages produced and consumed worldwide.

ACKNOWLEDGEMENTS

We thank Dr Siobhan Gardiner and Ashleigh Arton from Deloitte LLP for their support during the project.

AUTHOR CONTRIBUTIONS

Capucine Grandsir: Conceptualization; formal analysis; writing – original draft. **Natalia Falagan:** Conceptualization; supervision; writing – review and editing. **M. Carmen Alamar** Conceptualization; funding acquisition; supervision; writing – review and editing.

CONFLICT OF INTEREST

The authors have no conflict of interest that would bias the collection, analysis, reporting or publishing the research in the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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