Science Summary: Biochar-based Products for Ruminal Feed Supplements

Key Points

- This summary document provides a brief overview of three classes of carbonised, solid materials which have been trialed as feed supplements for ruminant livestock. These three broad classes are biochars, activated carbons, and biochar-mineral supplements.
- Within each of the three classes a wide range of compositions, structures, and properties can be achieved through the selection of inputs and altering the (usually thermal) processing steps used to create the feed supplement product.
- The international scientific literature features published results for a range of studies involving either live animal (*in vivo*) trials or laboratory (*in vitro*) fermentations using ruminal fluid extracted from animals.
- Results between different studies (and sometimes within studies) are highly variable. Such results range from a cluster of trials showing no significant effect to a few trials reporting reductions between 40% and 78%.
- Carbon-Kai research and development to date has developed Carbon Coated Minerals (CCM) formulations — a new generation beyond biochar — and trialed these against the types of activated carbon and biochars which are expected to have high performance.
- Calf feeding trials were undertaken with early Carbon-Kai formulations and these indicated growth rate improvements. Methane emissions were not measured in those calf trials.
- The most promising Carbon-Kai formulation shows methane reductions typically in the range of 11.5–47.6% relative to the controls (a few trials have suggested higher reductions could be possible, though these outliers need to be repeatable). These are indicative results used to guide formulation development rather than definitive real-world values — but they compare favorably with the best results reported in the international scientific literature for biochar-mineral supplements.
- Formulation development is ongoing and continuing to improve performance. The current focus is scaling up production of the leading Carbon-Kai formulation to the quantities needed for live animal trials.
- Larger animal trials, under New Zealand conditions and with sufficient statistical power, will be needed to assess the size of potential benefits.

Product-types, Properties, and Published Performance

The following brief literature review will cover three broad types of carbon-rich (or carbonaceous) materials which have been trialed as a stockfeed supplement. A particular focus will be on trials that have investigated reducing methane production during ruminal digestion. Some of these materials will be conductive "black carbons" with large surface areas. However, for each of the three broad types the properties will depend on processing parameters (such as the manufacturing temperatures used in the pyrolysis/carbonisation process).

Biochars

Biochars represent a range of carbon-rich, solid materials usually made from the thermal conversion of biomass feedstocks such as wood and other plant matter. The physical and chemical characteristics of a biochar largely depend on the type of biomass (wood, crop residues, grasses) and the intensity of the thermal treatment used to char (pyrolyse and/or carbonise) the biomass material.

The addition of charcoals and activated charcoals into animal feed has a long history dating back thousands of years. Charcoals and biochars have been promoted as a remedy for digestive system issues in livestock and as a feed additive to increase the efficiency of producing meat and milk[1]. Various biochars have been added to goat, sheep, and cattle diets (typically at rates between 0.5% and 2% of diet dry weight or DMI) in studies which demonstrate improved weight gain and feed conversion efficiencies[2]. Some of these studies have also reported methane emission reductions of between ~6% and ~78%. However, caution should be taken with some of these studies due to the measurement approaches used and/or mixtures of supplements simultaneously applied in the feed trials.

Various *in vitro* studies of biochars being added to the laboratory fermentation of ruminal fluid have reported significant decreases in methane production (25% reduction with biochar @ 0.5% DMI[3], 7.6% reduction with biochar @ 3% DMI[4], 23% reduction with biochar @ 2% DMI[5], and a 5% reduction in another study[6]).

No significant effect on methane production from the additions of various biochars has also been reported in other *in vitro* studies of ruminal fermentation (though some of these studies report numerical reductions in methane production up to 17% which were not considered statistically significant)[7].

Biochars blended with urea or nitrate have been reported to reduce methane production in ruminal digestion (25.9%-49% reduction *in vitro*[8] and 41% reduction *in vivo*[9]).

However, there are also some studies which have reported no statistically significant effects on methane reduction due to feeding biochars to cattle[10]. Though not considered statistically significant, one of those studies (Winders et al. 2019) reported that methane production was numerically decreased with biochar addition (reductions between 9.5% and 18.4% with biochar @ 0.8% DMI).

Activated Carbons

There is some degree of overlap in terms of structure and physical properties between biochars produced at higher temperatures and activated carbons. Activated carbons tend to have higher surface areas (over 1000 square metres per gram) compared to biochars produced at higher temperatures (around 300 square metres per gram).

Activated carbons are typically made from coconut shells, wood, or coal. Biochars can be converted into activated carbons through an additional "activation" step that typically burns off around 2/3 of the carbon to increase the products surface area per gram. This additional thermal processing step, and the loss of considerable solid carbon into gases, makes activated carbon more expensive.

An activated carbon (from a steam-activated biochar) resulted in a 22.6% reduction in methane production *in vivo* (as mmol of CH_4 per gram of digested organic material), though this was just below the level deemed statistically significant[11].

An Australian study on dairy cows reported that the addition of activated carbon (at 0.5% of diet dry matter) could reduce methane emissions measured in the milking shed by 33.8%. Significant increases in average milk protein (+2.63%) and milk fat (+6.32%) and a non-significant increase in milk production (+3.43%) were also reported[12]. Earlier *in vitro* trials as part of this project (the same activated carbon @ 0.5% and 2.0% of DMI) reported methane reductions in the 40-69% range[13]. Adding activated carbon to dairy cattle feed increases in milk fat content, counteracting the negative effects of low-quality corn silage according USA study (benefits attributed to the activated carbon sorbing fungal toxins in low-quality feed)[14].

Activated carbons have also been reported to both accelerate methanogenesis and reduce overall methane yield during anaerobic digestion of sewage, as well as functioning to promote direct interspecies electron transfer in fermentations[15].

Biochar-Mineral Complexes (BMCs) and Carbon-Coated Minerals (CCMs)

This broad range of potential products are created through combining biomass and various minerals prior to a thermal treatment step (usually pyrolysis and carbonisation). Adding specific minerals into the formulations allows the texture, elemental composition, and surface chemistry of the product to be customised[16].

A few *in vitro* studies of biochar-mineral formulations have reported mixed results or no significant effects[17]. A recently published *in vitro* study reported that a biochar-mineral supplement reduced methane production (19.03% reduction with supplement @ 4% DMI and 29.32% reduction with supplement @ 6% DMI)[18]. Formulations vary across those studies, with different combinations of minerals used.

Australian cattle trials (*in vivo*) with two different biochar-mineral formulations have reported methane reductions (9.5% reduction with biochar @ ~0.6% DMI and 12% reduction with biochar @ ~2.4% DMI for the better performing formulation) when feeding steers in methane collection chambers. However, a second trial on heifers with a change of diet, environment, and methane monitoring equipment produced no statistically significant effects on recorded methane emissions[19].

Outside of agriculture, biochar-mineral complexes have shown promise for enhancing the rates of oxidative treatment of water pollutants[20] and as part of an engineered *"Redox-Active Conductive Carrier"* to enhance the anaerobic digestion of sewage sludges[21]. These are examples of the utility of iron-containing biochars in catalyzing both purely chemical reactions and enhancing the metabolisms of microbial communities. These appear to be catalytic effects, which depending on the bio/chemical circumstances may provide mechanisms for increasing or decreasing methane emissions in ruminal digestive systems.

CARBON-KAI Research & Development

The research and development pathway for Carbon-Kai has involved the following:

- Avoiding the poorly performing types of thermal treatments, formulations, and dosing rates based on available scientific publications.
- Being informed by unpublished trial results from discussions with consultants and contacts from around the world.
- Producing formulations using abundant feedstocks available in New Zealand.
- Trialing post-carbonsation processes and blends (prioritising sustainable, low hazard, practical, and economical options).
- Customising surface texture, surface chemistry, and sorption performance.
- Avoiding the use of nitrate or urea. Alternative electron acceptors will not cause elevated non-protein-nitrogen (nitrate/nitrite/urea) levels in milk, blood, and meat.
- Using *in vitro* fermentation to trial new formulations against some of the best performing carbon materials in the international literature in order to select promising formulations for future animal trials in New Zealand.
- Using *in vitro* fermentation to trial formulations with ruminal fluid from different cattle types (bulls, cows, and steers) and fermenting common New Zealand feeds (ryegrass & clover and grain-based calf meal).

When produced at certain temperatures biochars provide large surface areas of conductive carbon. Additives and further processing can be used to tailor surface chemistry and redox functionality. Biochar-mineral supplements can enable microbes to readily access electron acceptors. This mechanism, along with sorption capacity, provides the theoretical basis for using biochar-mineral supplements to enhance metabolic processes.

Careful design of Carbon-Kai's Carbon Coated Minerals (CCM) formulations will be important for altering the rumen specifically to reduce unwanted outcomes.

Biochars (or pyrogenic carbon in the case of natural wildfires) are known for enhancing anaerobic microbial activity through facilitating direct electron transfer. Additions of even low levels of conductive biochar can reduce methane production by 13-24% in incubated peatland soils. The authors of that peatland soil study attributed the methane suppression to *"redox cycling, capacitive, and conductive electron transfer mechanisms"* enabled by the pyrogenic carbon (char or biochar)[22]. More recently, similar ideas have been advanced about how biochars can impact ruminal methanogenesis though conductivity, capacitance, and electrochemistry[23].

The most promising Carbon-Kai formulation is typically showing methane reductions in the range of 11.5–47.6% relative to the controls (a few trials have suggested higher reductions could be possible, though such extreme reductions need to be repeatable). These are indicative results to guide formulation development rather than definitive real-world values. Importantly, these results compare favourably with the best published performance of biochar-mineral supplements in the international literature and have been achieved at low inclusion rates using New Zealand feedstocks. Formulation development is actively continuing, with performance improving as the product is refined.

Calf feeding trials were undertaken with early Carbon-Kai formulations, indicating growth rate improvements. Methane emissions were not measured in those calf trials.

Animal trials with sufficient statistical power will be required to assess the size of potential benefits under New Zealand conditions. This would go beyond just the common feeds used in New Zealand, to also use specific breeds commonly raised in this country. The microbiome of cattle has been found to be dependent on breed, in cases where animals from both breeds are fed the same diet in the same environment[24].

The Need for Further Animal Trials

The Carbon-Kai research and development programme has to date been conducted primarily through *in vitro* laboratory fermentation trials. While this approach is a relatively fast and cost-effective method for screening formulations and guiding product development, it has inherent limitations. Laboratory fermentation using extracted ruminal fluid does not fully replicate the complexity of a live animal's digestive system, including variations in feed intake, rumen physiology, microbial community dynamics, and whole-animal metabolism. It is therefore not possible to determine from *in vitro* results alone the precise magnitude of real-world methane reductions. Further live animal trials also provide opportunity to quantify productivity gains, drenching reductions, or animal health outcomes that a Carbon-Kai supplement would deliver in commercial farming situations.

Progressing to live animal (*in vivo*) trials is the critical next step. Well-designed animal trials, conducted under New Zealand conditions, are needed to:

- Confirm and quantify methane emission reductions in ruminant animals, using validated measurement methods (such as respiration chambers or the SF6 tracer technique) with sufficient statistical power to reliably detect effects.
- Assess productivity impacts including milk yield and composition, live-weight gain, and feed conversion efficiency under typical New Zealand farming regimes and the common diets.
- Evaluate the supplement with the breeds most commonly farmed in New Zealand. Rumen microbiome composition can differ significantly between cattle breeds even when fed identical diets in the same environment, meaning breed-specific trials are important for generating locally applicable evidence.
- Investigate and address potential sources of variability in the impacts of feeding biochar-based supplements to ruminants (as seen in overseas trials). Performance impacts should be predicable and specific situations where the supplement provides greater or lesser impacts should be identified (this could include factors such as diet, animal life-cycle stage, microbiome composition, or health conditions).
- Assess animal health and welfare outcomes over an extended feeding period, including any effects on rumen health, blood chemistry, and meat or milk quality.
- Generate robust, independently-verifiable data that will be required for regulatory approval pathways, market credibility with farmers and processors, and potential integration into New Zealand’s emissions reporting frameworks.

A current priority for Carbon-Kai is producing sufficient quantities of the leading formulation to support these larger trials. Proposed trials would be designed in collaboration with appropriate scientific institutions and conducted to the standards required for peer-reviewed publication and regulatory submission. The promising results achieved through laboratory screening to date, and scientific publications which point to plausible modes-of-action, provide a well-founded rationale for investing in this next phase of evidence collection.

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