Use of feed additives for reducing greenhouse gas emissions from dairy farms

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Abstract

This review analyses methane emissions from dairy farms due to enteric fermentations and use of different feed additives as a strategy to control them. CH4 is a product that forms during the fermentation of food in the rumen of ruminants and on average represents a 7% loss of the energy ingested by the animal. CH4 is also a potent greenhouse gas. Various approaches have been studied in many countries with the aim of reducing methane emissions of digestive origin like the use of biotechnologies to modify the microbial ecosystem. This include selection of rumen micro-organisms through the elimination of protozoa or the inoculation of exogenous bacterial strains, vaccination against methanogenic micro-organisms, etc. or use of new food additives like plant extracts, organic acids, etc. and are theoretically promising paths. Their application is however still not known because trials are being performed mainly in vitro. This article focuses on reducing methanogenesis by adjusting the composition of the feed distributed to animals.

Introduction

Methane is a potent greenhouse gas which absorbs the sun’s heat and warms the atmosphere. Thus, if the concentration of heat absorbing gas like methane increases, the atmosphere will warm up resulting in global warming. The global warming potential (GWP) of methane is 25 times higher than that of CO2, and hence methane significantly contributes to enhanced greenhouse effect. According to NOAA reports in 2011, methane levels rose in 2010 for the fourth consecutive year after remaining nearly constant for the preceding 10 years, up to 1799 parts per billion. Methane concentration was measured 1794 ppb in 2009, and 1714 ppb in 1990. One of the environmental threats our planet faces today is the potential for long-term changes in the earth’s climate and temperature patterns known as global climate change. Average global temperature have risen considerably and the IPCC predicts increases in global average surface temperature to be 1.8-4°C by 2100. The average artcic temperature in 2012 was about 14.6°C, which is 0.6°C warmer than the mid-20th century baseline. The average global temperature has risen about 0.8°C since 1880, according to the new analysis. These temperature rises are much greater than those seen during the last century, when average temperature rose only 0.06°C per decade. Since the mid-1970s, however, the rate of increase in temperature rise has tripled. The IPPC’s report warns that climate change could lead to impacts on have tremendous impact on environment, animals and humans that are abrupt or irreversible.

Contribution of ruminants to greenhouse gas

The rising concentration of methane is correlated to increasing populations and currently about 70% of methane production arises from anthropogenic sources and the remainder from natural sources. Agriculture is considered to be responsible for about two-thirds of the anthropogenic sources. Biological generation in anaerobic environments (natural and man-made wetlands, enteric fermentation and anaerobic waste processing) is the major source of methane. Agricultural sources derived from enteric fermentation (81-92 million tonnes), paddy rice production (60-100 million tonnes), biomass burning (40 million tonnes) and animal wastes (25 million tonnes) are the major sources responsible for methane production. At a global scale, livestock farming contributes to 30-50% of total greenhouse gas emissions. India has a livestock wealth of 272.1 million cattle, 159.8 million buffaloes, 71.6 million sheep, 140.6 millions goats and 13.1 million other ruminants which produce large amount of methane as a part of their normal digestive process. This constitutes about 20% of the world’s ruminants population. Thus, in order to improve the greenhouse gas balance of farming, methane reduction by ruminants is of great concern. It would have a rapid effect on the environment as the life span of methane in atmosphere is 12 years as compared to 100-200 years of CO2 and N2O, respectively. Decreasing methane emissions from these sources by 10 to 15% would stabilise atmospheric methane at its present level and is a realistic objective. Hence, enormous efforts are being made across the world to find methods that are effective, safe and sustainable.

Ruminal fermentation and the production of methane

Methane is produced as a result of anaerobic fermentation in the rumen and the hindgut. Enzymes present in the rumen hydrolyze the dietary organic matter to aminoacids and simple sugars. The rumen is an ideal habitat for a large and diverse microbial population. The main functions of this group is to degrade plant polymers which cannot be digested by the host enzymes. The feed material is fermented to volatile fatty acids (VFA), carbon dioxide and methane. These VFAs pass through the rumen wall into the circulatory system and are oxidised in the liver, supplying a major part of the energy needs of the host. Volatile fatty acids may also be directly utilised by the host as building blocks for synthesis of cell material. Fermentation is also coupled to microbial growth and the microbial cell protein synthesised forms the major source of protein for the animal. The gases produced are waste products of the fermentation and are mainly removed from the rumen by eructation. A small proportion of methane is absorbed in the blood and is eliminated through the lungs.

Both methanogenic bacteria and protozoa are involved in methane production in rumen. Virtually all of the bacteria attached to protozoa are methanogens. These bacteria are responsible for between 0.25 and 0.37% of the total methane produced. Besides protozoa, a number of other organisms are also involved...
in ruminal fermentation and methane produc-
tion. Rumen methanogenic archaeabacteria uti-
lize hydrogen and carbon dioxide or for-
mate, acetate, methylamine and methanol for
production of methane. The involvement of
these bacteria in inter-species hydrogen trans-
fer (maintaining low partial pressure of hy-
drogen within the rumen) is an important inter-
action which alters the fermentation balance
and results in a shift of the overall fermenta-
tion from less-reduced to more-reduced end-
products.

Mitigation of methane emis-
sions

Generally speaking, the level of methane
production from the rumen is inversely related
to the quantity (energy value) and quality (di-
gestibility) of the feed an animal consumes.
As the amount of feed consumed increases,
the energy available for conversion to methane
also increases. There is a relationship between
methane emissions and feed digestibility.
Therefore, if the efficacy with which the
animal digests its feed is increased, the
amount of energy released in the form of
methane gas by rumin can be reduced. From
about 5-15% of the digestible energy in feed is
lost as methane gas. So, if we could reduce the
amount of methane produced by cattle, we
could significantly reduce the amount of feed
they need and also protect the environment
from the hazards of greenhouse effect.

The most promising approach for reducing
methane emissions from livestock is by
improving the productivity and efficiency of
livestock production. Increasing animal pro-
ductivity will generally reduce methane emis-
sions per kg of product (milk or meat).
Because of the improvement in production
efficiency, a greater proportion of the energy
in the animal feed is directed towards produc-
tion of useful products and hence methane
emissions per unit product is reduced. This
will also lead to a reduction in herd size to
produce the given level of product. In the de-
veloped countries of the world, ruminant livestock
are kept in well managed production systems
and generally fed diets that are very high in
digestibility and nutrients. The result is very
efficient production (milk or meat) relative to
the amount of methane emitted. Unfortunately, ruminants in developing coun-
tries are kept on diets that are low in both
digestibility and nutrient content. This leads
not only to greatly increased methane emis-
sions, but also very diminished productivity
relative to the animals’ genetic potential. This
inefficient productivity has global implica-
tions.

However, establishing conditions under
which rumen fermentation will be optimised
requires an understanding of the nutrient
requirements of the mixed microbial popula-
tion. Growth of rumen microbes is influenced
by chemical, physiological and nutritional
components. The major chemical and physi-
ological modifiers of rumen fermentation are
rumen pH and turnover rate and both of these
are affected by diet and other nutritionally
related characteristics such as level of intake,
feeding strategies, forage length and quality
and forage:concentrate ratios. Recent research
has suggested that interventions in early life
of the animal can trigger differential microbial
rumen colonization and development, which
may result in differential rumen CH₄ produc-
tion. This interesting concept may offer new
opportunities for mitigating CH₄ emission in
ruminants but needs to be further tested and
verified. Since methane represents a loss of
energy from the rumen and therefore an
unproductive use of dietary energy, scientists
have been looking for ways to suppress its pro-
duction.

Forage selection and processing

Reduction in methane emissions have been
observed through forage selection. The work of McCaughey et al. have shown that
the difference in the carbohydrate fraction of
forages such as grass silage, maize silage,
legumes or whole crop wheat silage gives rise
to difference in productivity. Hence, it is
important to select forage species that result
in reduced methane production. Gridding and
pelleting of forages can markedly decrease
methane production. At high intakes methane
loss/unit of diet can be reduced 20-40%.
Similarly, the work carried out by van Gastelen
et al. show that replacing Grass silage with
Corn Silage in a common forage-based diet for
dairy cattle offers an effective strategy to
dereduce enteric CH₄ production by 8% without
negatively affecting dairy cow performance.
The study undertaken by Lett et al. indicated
a 13 and 6% reduction in CH₄ per unit of
milk out when feeding a 25:75 grass
silage:corn silage diet compared with a 75:25
grain silage:corn silage diet. Independent
studies carried out by several group of workers
demonstrated that comparative high reduction
in enteric methane emissions can be achieved
by increasing the forage quality combined with
the management of stocking rates and rota-
tional grazing strategies.

Nitrates and sulphates

Both nitrates and sulphates may serve as a
terminals electron acceptor and therefore may
behave as an alternate hydrogen sink, thereby
reducing the amount of methane produced
under anaerobic conditions. The nitrate and
sulphite along with CO₂ are the hydrogen accep-
tors in the rumen. Conversion of nitrate to
sulphite and finally to ammonia is carried out by
rumen bacteria.

Leng provided a comprehensive review of
the earlier literature on nitrates. Recent
research with sheep and cattle has shown
promising results with nitrates decreasing CH₄
production by up to 50%. Asanuma et al. investigated the effects of dietary nitrate addi-
tion on ruminal fermentation characteristics
and microbial populations in goats. As the
result of nitrate feeding, a decrease in the total
concentration of ruminal volatile fatty acids
and the populations of methanogens, protozoa
and fungi was noted. Stoichiometric calcula-
tions by Hegarty show that to reduce
methane emissions by 50%, about 0.75 moles
of sulphate or nitrate ingestion per day is
required. However, since sulphate and nitrate
are toxic to ruminants at approximately 0.1
moles/day and 0.25 moles/day respectively,
they cannot be fed safely at levels required to
reduce methane emission.

Organic acids

Within the rumen, methane represents a
terminal hydrogen sink. Propionate production
represents an alternative hydrogen sink in
normal rumen fermentation, provided suffi-
cient precursors are available. The main pre-
cursors to propionate within this cycle are
pyruvate, oxaloacetate, malate, fumarate, and
succinate, or alternatively directly from pyru-
vate to propionate via the acrylate pathway
(high concentrate diets). Any of these organic
acids may promote alternative metabolic path-
ways to dispose of reducing power and hence
reduce methane production. Existing research
shows this to be a very promising approach.
Workers in the UK and Spain have studied in
vitro the effect of different concentrations of
fumarate in the rumen fermentation.

Callaway and Martin have considered the
effect of fumarate and malate on rumen fer-
mentation in vitro. Their results indicated that
malate addition not only acted as an alterna-
tive hydrogen sink, like fumarate, but also
buffers the ruminal contents by a dual mecha-
nism of reducing lactate accumulation and
increasing carbon dioxide production. It is
essential, particularly with high concentrate
diets that the disposal of ruminal lactate is
efficient to avoid a severe decline in rumen
pH. Martin found malate and fumarate, as
direct metabolic precursors of propionate,
reduce methane production when fed in a pure
form or in high malate forages. It decreases methane emissions by directing hydrogen into succinate rather than into methane. Asanuma et al.27 observed that the addition of fumarate to rumen utilizers both hydrogen as well as formate, which are the substrates for the methane formation. Malate has similar effects on fermentation as fumarate.28

The option of the use of the organic acids as daily supplements to reduce methane would only be practicably available to livestock receiving supplementary concentrates in a controlled manner. If concentrations of these organic acids in forages could be increased then the option would be available to all ruminant livestock.

Bacteriocins and ionophores

Bacteriocins are naturally occurring bacterial products with a bacteriocidal activity. They are effective as they directly inhibit methanogens and redirect H₂ to other reductive rumen bacteria such as propionate-producers acetogens. Callaway et al.29 have shown that nisin – a food additive, reduces methanogenesis by 36%. However, the organisms developed resistance quickly. This problem can be overcome by the use of bacteriocin of rumen origin. They have a potential as a new generation of rumen modifiers.30 Lee et al.31 found that semipurified bacteriocin i.e. Bovicin HCS inhibits 50% of methane production in vitro and methanogens did not show any adaptation to these bacteriocins. Ionophores are antibiotics produced by bacteria. Ionophores increases the proportion of gram positive bacteria in the rumen, resulting in a shift in fermentation acids from acetate and butyrate to propionate, and hence decreases the methane production.32 Menosins has been the most studied ionophore and it is routinely used in beef production and more recently in dairy cattle nutrition in many countries. There have been a number of experiments with menosins as a rumen modifier in various production systems, where CH₄ production was studied as a main objective either from a mitigation or from an energy loss perspective.33 34 Although some studies reported a long-term mitigating effect of menosin on CH₄ production, overall the effect of the ionophore on methane production appears to be inconsistent, transient and short-lived indicating that microbial adaptation occurs.

Tannins

In plants, tannins exist as polyphenols of varying molecular size and complexity and are of two types: hydrolysable and condensed tannins. The condensed tannins also called as proanthocyanidins, has a characteristic influence on proteins and carbohydrates. Tannins have both bacteriocidal and bacteriostatic effect and can also inactive ruminal enzymes. Tannins suppress methanogenesis directly through their antimethanogenic and defaunation property.35 Tannins, as feed supplements or as tanniferous plants have a potential for reducing CH₄ emission by up to 20%,36 37 Patra et al.38 has observed that there is a decrease in vitro methane production with methanol extract of harada (Terminalia chebula) at the level of 0.25/30 mL of incubation medium. He also observed a complete inhibition at double this level. Sources containing both hydrolysable and condensed tannins were shown to be more potent than those containing only hydrolysable tannins.41 According to Goel and Makkar,42 the antimethanogenic effect of tannins depends on the dietary concentration and is positively related to the number of hydroxyl groups in their structure. These authors concluded that hydrolysable tannins tend to act by directly inhibiting rumen methanogens whereas the effect of condensed tannins on CH₄ production is more through inhibition of fiber digestion.

Saponins

Saponins are complex compounds that are composed of a saccharide attached to a steroid or triterpene and have a soapy character due to their surfactant properties. Several studies with saponins reported decreased CH₄ production from about 6 to 27% by reducing the protozoa population.42 Saponins cause defaunation through their binding with sterols present on the protozoal surface.

Singal et al.43 found that 5 herbal products such as pulp powder of reetha (Sapindus mukorossi), shikakai (Acacia concinna), mahuja (Madhuca indica) cake, albezia leaves (Albizia lebbek) and yucca (Yucca schiagerea) reduces methane production in vitro. Inhibition of methane production upto 96% was reported with the ethanol and methanol extracts of soap nut (Sapindus mukorossi).44 Lila et al.45 studied the effect of different concentrations of sarsaponin wherein 60% of methane reduction was observed as the concentration increased from 1.2 to 3.2 g/L fermentation medium.

Studies from China have reported decreased CH₄ in ruminants treated with tea triterpenoid saponins but also substantial changes in microbial populations, including a reduction in protozoal counts.46 Combination of saponin and nitrate may have practical application in mitigating methane emission from ruminants. In a study, Quillaja saponin and nitrate in combination at low dose inhibited methanogenesis substantially while increasing feed degradability.47

Use of probiotics

Direct-fed microbials (DFM), in one form or another, are commonly used as supplements in animal production. The most widely used microbial feed additives (live cells and growth medium) are based on Saccharomyces cerevisiae (SC) and Aspergillus oryzae (AO). Their effect on rumen fermentation and animal productivity are wide ranging and this has been reviewed by several authors.48 49

Work carried out by Chaucheyras et al.50 suggest that live yeast cells can stimulate the use of hydrogen by aceticogenic strains of ruminal bacteria there by enhancing the formation of acetate and decreasing the formation of methane. However, the effects of yeast are strain dependent.51 The other effects observed include shift in fermentation towards butyrate or propionate or reduction in protozoal numbers. These effects are variable and short-term, diminishing 2-4 hour after feeding. Other DFM interventions of ruminal fermentation include inoculation with lactate-producing and lactate utilizing bacteria to promote more desirable intestinal microflora and stabilize pH and promote rumen health, respectively.52 There have also been other attempts to inoculate the rumen with fungi (Candida kefyr) and lactic acid bacteria (Lactococcus lactis) along with nitrate supplementation to control methanogenesis, but no consistent animal data have been reported.53

Use of prebiotics

The prebiotics or oligosaccharides are non-digestible carbohydrates normally used in the non ruminants for better gut health and feed utilization. They are used in rumen manipulation along with nitrates, probiotics and yeast to have reduced methane production. The increase in cellulosic rumen bacteria is provided by using prebiotic compounds such as mannan-oligosaccharide (MOS), fructo-oligosaccharide (FOS), galacto-oligosaccharide.54 Mwenya et al.55 showed that they enhances propionate production by stimulating Selenomonas, Succinimonomas and Megasure with inhibition of acetate producers such as Ruminococcus and Butyriovibrio. The administration of galacto-oligosaccharides have brought about reduction of methane production up to 11%.
Fats and oils

Oils offer a practical approach to reducing methane in situations where animals can be given daily feed supplements, but excess oil is detrimental to fiber digestion and animal production. Both dietary oil and essential oil acts as modifiers of rumen fermentation.

Dietary oils

Dietary oils like coconut oil, sunflower oil, mustard oil, horseradish oil have been found to reduce methane production in ruminants. Dietary fat seems a promising nutritional alternative to depress ruminal methanogenesis without affecting other ruminal parameters. Some of the possible mechanisms by which lipid supplementation reduces methane: reducing fiber digestion (mainly in long chain fatty acids); suppression of methanogens and suppression of rumen protozoa and to a limited extent through biohydrogenation of unsaturated FA thereby serving as a hydrogen sink.

Machmuleur et al. observed coconut oil as more effective inhibitor followed by rape seed, sunflower seed, and linseed oil. Coconut oil comprises medium chain fatty acids. Coconut oil control rumen methanogens by changing the metabolic activity and composition. A decrease in protozoa numbers has been as identified as explanation for the reduction in methane emission after the inclusion of coconut oil in the diet. Ruminal ciliate protozoa rely on hydrogen producing fermentation process that is inhibited by a high concentration of hydrogen. They share a symbiotic relationship with ruminal methanogens which allows an interspecies hydrogen transfer, thereby lowering the concentration of hydrogen for the ciliate protozoa. Therefore, less hydrogen is available for formation of methane after defaunation.

Dong et al. compared canola oil to coconut oil and demonstrated coconut oil as more effective methane inhibitor. Kongmuna et al. reported that supplementation of coconut with garlic powder improved in vitro ruminal fluid fermentation in terms of the VFA profile, reduced methane losses and reduced protozoal population. The inclusion of sunflower oil to the diet of cattle resulted in 22% decrease of methane emissions. The addition of canola oil at 0%, 3.5% or 7% to the diets of sheep reduced the number of rumen protozoa by 88-97%.

However, fats and oils may pose numerous negative impacts to the animals. Dietary oil supplementation caused lower fiber digestibility. Jordan et al. estimated that feeding copra meal containing coconut oil to animals takes a longer time to reach a common carcass weight and decrease the effects on total methane emissions. Many factors need to be considered such as the type of oil, the form of the oil (whole crushed oilseeds vs. pure oils), and handling issues e.g. coconut oil has a melting point of 25°C. High cost and the negative impact on milk fatty acid composition and overall milk fat content would need to be carefully studied. Recent strategies, based on processed linseed, turned out to be very promising in both respects.

Essential oils

Essential oils (EO) are blends of secondary metabolites obtained from the plant volatile fraction by steam distillation. They have characteristic aroma or essence. They have a very diverse composition, nature, and activities. The most important active compounds are included in 2 chemical groups: terpenoids (monoterpenoids and sesquiterpenoids) and phenylpropanoids. These 2 groups originate from different precursors of the primary metabolism and are synthesized through separate metabolic pathways.

These compounds are as antiseptics and antimicrobials. Due to the hydrophobic nature of the cyclic hydrocarbons; they interact with cell membranes and accumulate in the lipidic bilayer of bacteria, occupying a space between the chains of fatty acids. This interaction causes conformational changes in the membrane structure, resulting in its fluidification and expansion. The loss of membrane stability results in the leakage of ions across the cell membrane, which causes a decrease in the transmembrane ionic gradient. In most cases, bacteria can counterbalance these effects by using ionic pumps and cell death does not occur, but large amounts of energy are diverted to this function and bacterial growth is slowed down, resulting in changes in the fermentation profile.

Several studies have documented reduction in methane production by EOs. Supplementation of ruminant diets with EOs can alter microbial populations, digestion and fermentation of diets, proteolysis, and methanogenesis in the rumen.

In vitro studies demonstrated that garlic oil reduced the emission of CH4. The active diallyldisulfide and allylmethacrylan were responsible for most of its effects. According to Anki and Mirelan23 its antimicrobial activity is due to the organo-sulphur compounds, particularly allicin. The anti-methanogenic effect of garlic is due to direct inhibition of Archaea microorganisms in the rumen. have unique membrane lipids that contain glycerol linked to long-chain isoprenoid alcohols essential for the stability of the cell membrane. The synthesis of the isoprenoid units in methanogenic Archaea is catalyzed by the enzyme hydroxyl methyl glutaryl coenzyme A (HMG-CoA) reductase. Gebhardt and Beck57 found that garlic oil is a strong inhibitor of HMG-CoA reductase and hence the synthesis of the isoprenoid unit is inhibited, the membrane becomes unstable, and the cells die.

Castillejos et al. reported the effects of Thyme (Thymus spp.) and oregano (Origanum spp.) oils on methane production. The active component thymol is a monoterpen with strong antimicrobial activity against a wide range of gram-positive and negative bacteria. Thymol affects the energy metabolism of 2 relevant rumen bacteria grown in pure culture: Streptococcus bovis and Selenomonas ruminantium. It reduces methane concentrations as well as total volatile fatty acid production due to inhibition of microbial metabolism. It causes loss of integrity of the cell membrane and a reduction in the uptake of glucose. The effects of thymol are diet and pH dependent. Therefore, it is important to define the conditions under which these additives are used to modify rumen microbial fermentation in the desired direction.

Five essential oils (EOs), namely, clove oil (CLO), eucalyptus oil (EVO), garlic oil (GIO), origanum oil (ORO), and peppermint oil (PEO), were tested in vitro for their effect on methane production. The CLO contains eugenol (phenyl propanoid), EVO contains cineole (bicyclic monoterpinoid), GAO contains alliin and allicin (organosulfur compounds), ORO contains thymol (monoter-
pinenol monocyclic phenol), and PEO contains menthol (monoterpinoid monocyclic non-phenol). This study demonstrated that all the EOs significantly reduced methane production with increasing doses. However, different EOs vary in their potencies in modulating rumen microbial populations and fermentation. Further, a single EO may not effectively and practically mitigate methane emission from ruminants unless used at low doses in combinations with other antimethanogenic compounds.

Conclusions

The experimental results obtained with inhibition of methanogenesis in the rumen indicate that there exists a large number of chemicals, bacteriocins, antibiotics and plant secondary compounds like oils, tannins, saponins, etc which have the potential to modify the rumen microbial fermentation. However, each one of them is accompanied with one or the other drawback like simultaneous adverse effect on the other biochemical reactions in the rumen, toxic effect on the health, retention of some of the chemicals in the livestock product, etc.

The rumens microbes specially the methanogens get adapted to some of these feed additives and initial adverse effect observed on inhibition of methanogenesis are lost. In addition to these, most of the feed additives tested in vitro and found effective in inhibiting methanogenesis, have not been tested in vivo and therefore, their exact potential for practical use is still not known.

The use of any method for methane reduction can only be justified if there is a beneficial effect larger than the cost of the product. This ratio will depend on the cost of feed additive, the dose required and the resulting improvement in the animal performance. Generally, the techniques are economically non-adaptable due to their high cost and lower performance in the form of methane emission.

The most promising approach is one involving immunization against strains of both rumen protozoa and rumen methanogens, offering up to 70% reduction in methane emissions. This is at an early stage of development and the longevity of the immunization is required to be established. If successful, this approach could be applied to all ruminants in all member states. The use of propionate precursors and direct fed microbial offer alternative approaches which may allow up to 25% reductions in methane emissions and would be available to all livestock receiving daily supplements.

In the last two decades a lot of strategies to mitigate methane production in ruminants have been researched upon. There are numerous possibilities associated with this and most of which require substantial amounts of research and development so as to apply multiple technologies to mitigate greenhouse gas emission. However, strategies that can succeed at farm level should be more practical and involve no additional inputs. The potential of plant extracts in mitigating methane emission in ruminants is one such strategy that can be readily adopted as an on-farm practice. Since ruminants are so important to mankind as they convert rich fibrous biomass of the world into high quality protein sources i.e. meat and milk for human consumption, more considerations should be given to total farm greenhouse gas emissions, and not just methane emissions from enteric fermentation when investigating the issues.

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