Dietary plant bioactives for poultry health and productivity

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Dietary plant bioactives for poultry health and productivity

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Abstract
1. Plants and their biologically active chemical constituents, sometimes called secondary metabolites or bioactives, present numerous opportunities for the improvement of livestock production by inclusion in the diet.
2. Many such plant derived materials have well established therapeutic values in man; however, their potential as feed additives in animal production, particularly of poultry, remains largely unexploited.
3. There is increasing evidence indicating that they can be efficient in controlling diseases, and plant bioactives may also influence production parameters such as feed efficiency and product quality.
4. It has been reported that they may even replicate some of the effects of antibiotic growth promoters, which were banned from use in Europe from 2006.
5. This review assesses the status of plant bioactives in poultry production and their mode of action on avian physiology, particularly in the digestive tract.

INTRODUCTION

Interest in plants, plant extracts and derived phytochemicals (botanicals) as components of livestock feedstuffs has increased during the last decade. Much of the impetus for revisiting the plant kingdom to look for new, useful additives that can enhance health and productivity results from concerns about the safety and sustainability of antibiotic growth promoters. If transmissible antibiotic resistance factors result from the use of growth-promoting antimicrobials (GPA) in animal production, the efficacy of similar antibiotics in therapy for human diseases may be compromised. Hence, the EU introduced a ban on GPA in 2006. Other nations may follow. Before the ban, poultry production had a high dependence on GPA to control intestinal pathogens such as Escherichia coli, Clostridium perfringens and coccidial infection. Since then, improved management has compensated for some of the production-benefit losses, but not all. Consumer pressure also plays a part in the move to more "naturally" produced foods (Rickard, 2004). The increasing demand for organically produced foods also drives the search for alternative feed additives (Griggs and Jacob, 2005).

Botanicals should not be considered only as replacements for GPA, however. They have useful properties not shared by GPA. Herbs, spices and their extracts can stimulate feed intake and endogenous secretions (Wenk, 2003). Many botanicals have antioxidant activities that can improve the oxidative stability of poultry meat and eggs, increasing their shelf life. They may stimulate immunity directly, improving birds' resistance to disease. They also have the potential to modify cholesterol metabolism, leading to a product with...
healthier implications for human production. Even reproduction may be improved by increasing semen quality (Durape, 2007).

A final consideration, indeed the most important of all, is that many plants and phytochemicals have adverse effects on animals when ingested. Acamovic and Brooker (2005) remind us: “The effects depend to a great extent on the chemistry of the compounds, their concentration in the diet and the amount consumed, and are further dependent on the health status of the animals. Traditionally, most studies of the effects of these compounds on animals have focused on their adverse effects and how to alleviate them. However, recent public concern about the use of synthetic compounds in animal diets to enhance performance and health and welfare issues, coupled with changes in regulations on the use of synthetic medicaments, has stimulated interest and research in the use and effects of phytochemicals in the diets of farmed animals. Phytochemicals vary in their chemistry but can be divided into hydrophilic and hydrophobic compounds, of which a wide variety of polyphenolic and terpenoid compounds, as well as alkaloids, carbohydrates and non-protein amino acids, invoke special interest”.

The use of botanicals in human and animal health undoubtedly has potential value—many widely used therapeutic drugs originate from the plant kingdom—but the use of botanicals in animal production is less well established. It is important to provide a good description of each plant, its active phytochemicals and their molecular mode of action against microorganisms or their interaction with the host. Given the vastness and diversity of the plant kingdom, variations between cultivars, variation in applications, and many other factors, such a complete description will never be attainable. Nevertheless, it might reasonably be expected that botanicals in common use or intended for widespread application should have a body of efficacy, safety and mechanistic information to enable users to assess and understand the biological activity of the botanical in question. The aim of this review was to report on the status of the botanicals field in poultry in relation to these benchmark criteria.

The review itself was prompted by two main drivers. One was the EC Framework 7 Specific Support Action, contract 43077, FEED-SEG, a consortium whose broad objective is “to disseminate state-of-the-art research results in feed quality topics... (and to)... develop strategies and recommendations for European policies (e.g. research, health, agriculture)”. The second was the publication of an excellent review for botanicals and ruminants (Rochfort et al., 2008). The challenge that we as authors of this article accepted was to attempt to replicate the review of Rochfort et al. (2008), with poultry rather than ruminants as the subject group of animals. Poultry production encompasses broilers, layers and breeders from different species—chicken, turkey, and duck principally. Much less is known about the ostrich (Vispo and Karasov 1996), in spite of its growing commercial importance. This review focusses on plant bioactives, poultry production and its underlying science, and does not repeat the comprehensive sections in the Rochfort et al. (2008) review on social and regulatory issues, to which the reader is referred.

**THE STATUS OF PLANT BIOACTIVES AS FEED ADDITIVES**

Generally speaking, feed additives are considered as being applied in the feed by the farmer to healthy animals not only for nutritional purposes but also additional functionality on a long-term basis (possibly along the entire production period of the respective species), in contrast to veterinary drugs used only to treat health problems under control of a veterinarian, applied for a limited period only. As per definition from Regulation (EC) No. 1831/2003, “feed additives are substances or preparations—other than feed material or premixtures—which are intentionally added to feed or water in order to

- favourably affect the characteristics of feed, as e.g. flavouring or antioxidant,
- affect the characteristics of animal products regarding microbial load, shelf life or taste,
- affect the environmental consequences of especially large-scale livestock production e.g. by reduction of ammonia excretion or methane production,
- favourably influence animal production, performance or welfare by affecting the gastrointestinal microbiota and the digestibility of feeding stuffs, or—have a coccidiostatic or histomonostatic effect”.

Thus, this review, for the most part (as benefits to productivity are inevitably linked with the control of disease) concentrates on plant bioactives as feed additives rather than therapeutics. Valuable effects on, for example, fowl typhoid (Waihenya et al., 2002a) would not normally be covered.

Presently, herbal products are used by the feed industry predominantly as sensory additives, flavouring and appetising substances. Although an understanding of their mode of action would be a prerequisite for their optimal application in terms of efficacy, a full understanding of these aspects in animals is not yet achieved. For example, aromatic compounds and essential oils (EO) act along the animal digestive tract...
to improve appetite, bacterial modulation, and are able to induce a number of benefits on well being (Kamel, 2001). The antimicrobial properties of EOs and extracts can be dose-dependently bacteriostatic and/or bactericidal. In addition, several investigations have shown an antioxidative effect or changes in digestive physiology and digestion at weaning (Zabielski et al., 1999), the microbiology of the gut (Jensen, 1998) and the implementation of test models in poultry (Hess, 2002). Another complication is that plant bioactive compounds occur in nature as complex mixtures rather than as single compounds, and synergy between individual components may be an important feature of their action.

Plant bioactives are often proposed as possible replacements for AGP. Their efficacy in achieving the same effects remains open to question, but an undoubted advantage of plant bioactives over GPA is that resistance is less likely to become a problem than with conventional synthetic compounds.

It must also be remembered that plants contain many poisonous compounds, including some of the most toxic known to man. Some plant extracts may therefore be detrimental for poultry and by numerous mechanisms may decrease body weight, feed intake (FI) and feed conversion ratio (FCR) and digestibility. They can also influence mortality, muscular conditions and in some instances can be neurotoxic.

**Figure. Structures, estimated range and numbers of plant secondary metabolites (re-drawn from Acamovic and Brooker (2005), with permission).**

**BIOACTIVE COMPOUNDS AND THEIR EFFECTS ON PRODUCTION**

**Production efficiency and incidence of disease**

Numerous feeding trials have been performed with plant extracts, aromatic herbs and EOs additives, to investigate production parameters...
Table 1. Performance effects of plant material and plant extracts used as feed additives in poultry nutrition

<table>
<thead>
<tr>
<th>Plant species/extract</th>
<th>Dose</th>
<th>Performance effect</th>
<th>No effect</th>
<th>Detrimental</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesculus hippocastanum</td>
<td>0–10 mg/g body</td>
<td>Depression</td>
<td>Muscular incoordination paralysis</td>
<td>Williams and Olsen (1984)</td>
<td></td>
</tr>
<tr>
<td>Alfalfa extract</td>
<td>0.06%</td>
<td>Thymus and spleen weight</td>
<td>FI</td>
<td>Abdominal fat weight</td>
<td>Dong et al. (2007)</td>
</tr>
<tr>
<td>Aloe secundiflora extract</td>
<td>–</td>
<td>Reduced mortality in Newcastle disease infection, Increase of interleukin 6</td>
<td>Antibody levels</td>
<td>–</td>
<td>Waihenya et al. (2002a,b)</td>
</tr>
<tr>
<td>Artichoke water extract</td>
<td>5% DM</td>
<td>Humoral immune response</td>
<td>–</td>
<td>–</td>
<td>Stoev et al. (2000)</td>
</tr>
<tr>
<td>Balanites aegyptiaca saponins</td>
<td>5–250 mg/kg/day</td>
<td>Total cholesterol</td>
<td>Body weight</td>
<td>Nakhla et al. (1992)</td>
<td></td>
</tr>
<tr>
<td>Calendula officinalis extract</td>
<td>Drinking water</td>
<td>Mean weight</td>
<td>FCR</td>
<td>Immune response</td>
<td>Barbour et al. (2004)</td>
</tr>
<tr>
<td>Cassia obtusifolia</td>
<td>2% body weight</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Hebert and Flory (1983)</td>
</tr>
<tr>
<td>Cassia occidentalis</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Graziano et al. (1983)</td>
</tr>
<tr>
<td>Citrus extract</td>
<td>10–1000 g/t</td>
<td>Live weight</td>
<td>FI</td>
<td>Metabolisable energy</td>
<td>Juin et al. (2003)</td>
</tr>
<tr>
<td>Colchicinia momordica extract</td>
<td>5–80 µg/dose</td>
<td>Antibody level</td>
<td>–</td>
<td>–</td>
<td>Rajput et al. (2007)</td>
</tr>
<tr>
<td>EO (thymol, cinnamaldehyde, commercial preparation)</td>
<td>100 ppm</td>
<td>Daily weight gain</td>
<td>FI</td>
<td>–</td>
<td>Lee et al. (2003)</td>
</tr>
<tr>
<td>Field bean tannin hulls</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Digestibility</td>
<td>Flores et al. (1994)</td>
</tr>
<tr>
<td>Garlic extract</td>
<td>3.8% garlic paste</td>
<td>Cholesterol level</td>
<td>–</td>
<td>–</td>
<td>Qureshi et al. (1983)</td>
</tr>
<tr>
<td>Grape seed extract</td>
<td>2.50–5.18%</td>
<td>Protein and fat intake</td>
<td>–</td>
<td>Weight gain</td>
<td>Lau and King (2003)</td>
</tr>
<tr>
<td>Hemp seed meal</td>
<td>–</td>
<td>Concentration of palmitic and higher linoleic acids in eggs</td>
<td>Egg production</td>
<td>–</td>
<td>Silversides and Lefrancois (2005)</td>
</tr>
</tbody>
</table>
| *Note:* FI = Feed intake; FCR = Feed conversion ratio; TMEn = True metabolisable energy.
<table>
<thead>
<tr>
<th>Plant Extract/Herb</th>
<th>Dose</th>
<th>Parameter(s)</th>
<th>Response</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various herbs (thyme, oregano, marjoram, rosemary, yarrow) and their EO</td>
<td>10 g/kg</td>
<td>Performance, Intestinal microflora, Endogenous sialic acid secretion</td>
<td>Apparent metabolisable energy, Digestibility</td>
<td>Cross et al. (2007)</td>
</tr>
<tr>
<td>Labiatow extract (sage, thyme, rosemary)</td>
<td>5000 ppm</td>
<td>Apparent faecal digestibility CP digestibility</td>
<td>–</td>
<td>Hernandez et al. (2004)</td>
</tr>
<tr>
<td>Lentinus edodes T. fuciformis</td>
<td>0.5–4 g/kg</td>
<td>Ether extract digestibility Body weight gain FCR FI</td>
<td>Weight of organs Relative weights of organs and GIT –</td>
<td>Guo et al. (2004b)</td>
</tr>
<tr>
<td>Linseed meal</td>
<td>20% 50–250 mg/kg meal</td>
<td>Selenium toxicity Body weight Growth rate FI</td>
<td>–</td>
<td>Jensen and Chang (1976)</td>
</tr>
<tr>
<td>Mangifera indica seed meal</td>
<td>50–250 mg/kg meal</td>
<td>Body weight, Feed efficiency Organ weights</td>
<td>Deep sleep in young chicken</td>
<td>Sherry et al. (1982)</td>
</tr>
<tr>
<td>Myristica fragrance</td>
<td>–</td>
<td>–</td>
<td>Increased number of sleeping chicks</td>
<td>Sherry and Hunter (1979)</td>
</tr>
<tr>
<td>Nepeta cataria</td>
<td>25–1000 mg/kg</td>
<td>–</td>
<td>–</td>
<td>Hernandez et al. (2004)</td>
</tr>
<tr>
<td>Oregano, cinnamon and pepper essential oils</td>
<td>200 ppm</td>
<td>–</td>
<td>–</td>
<td>Hernandez et al. (2004)</td>
</tr>
<tr>
<td>Oregano essential oil Plant extracts containing 5% carvacrol, 3% cinnamaldehyde, 2% capsaicum oleoresin</td>
<td>50–100 mg/kg 100 mg/kg</td>
<td>FCR Growth Villi-related protective activity – Malondialdehyde in tissue</td>
<td>–Bootsoglou et al. (2002) –Jamroz et al. (2005)</td>
<td></td>
</tr>
<tr>
<td>Plant extracts containing capsaicin, cinnamaldehyde and carvacrol</td>
<td>100 mg/kg</td>
<td>Breast muscle proportion Ileal digestibility of nutrients –</td>
<td>–Bootsoglou et al. (2002) –Jamroz et al. (2005)</td>
<td></td>
</tr>
<tr>
<td>Rosemary extract</td>
<td>500–1000 mg/kg</td>
<td>Lipid oxidation parameters –</td>
<td>–</td>
<td>Galobart et al. (2001)</td>
</tr>
<tr>
<td>Rye extract</td>
<td>–</td>
<td>–</td>
<td>Weight gain</td>
<td>Day and Thomas (1980)</td>
</tr>
<tr>
<td>Saccharum officinarum</td>
<td>500 mg/kg/day</td>
<td>Phagocytic activity of peripheral blood leucocyte Antibody response Immuno-stimulating activity</td>
<td>–</td>
<td>Hikosaka et al. (2007)</td>
</tr>
</tbody>
</table>

(Continued).
<table>
<thead>
<tr>
<th>Plant species/extract</th>
<th>Dose</th>
<th>Performance effect</th>
<th>Detrimental</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Senna occidentalis</em> seeds</td>
<td>40—80 ppm sylimarin</td>
<td>Extensive axonal damage</td>
<td>Neurotoxic</td>
<td>Calore <em>et al.</em> (1998)</td>
</tr>
<tr>
<td><em>Silybum marianum</em> fruit extract</td>
<td>-</td>
<td>Decrease of slaughtering yields</td>
<td>-</td>
<td>Schiavone <em>et al.</em> (2007)</td>
</tr>
<tr>
<td><em>Synclisia scabrida</em> extracts</td>
<td>-</td>
<td>Reduction of lipid content in meat</td>
<td>Hepatoprotection</td>
<td>Sokomba <em>et al.</em> (1986)</td>
</tr>
<tr>
<td><em>Vicia faba</em> tannin extract</td>
<td>8—16 g/kg</td>
<td>Apomorphine-induced stereotype behaviour</td>
<td>-</td>
<td>Ortíz <em>et al.</em> (1994)</td>
</tr>
<tr>
<td><em>Vicia faba</em> proanthocyanidin extract</td>
<td>30 g/kg</td>
<td>Pseudomonas and Staphylococcus infection</td>
<td>Mortality</td>
<td>Yuste <em>et al.</em> (1992)</td>
</tr>
<tr>
<td><em>Yucca schidigera</em> extract</td>
<td>0.2% extract</td>
<td>Feed intake</td>
<td>Digestive enzyme</td>
<td>Preston <em>et al.</em> (1999)</td>
</tr>
</tbody>
</table>

**Table 1. Continued.**

CP, crude protein; DM, dry matter; EO, essential oil; FI, feed intake; FCR, feed conversion ratio; TMEs, true metabolisable energy.
such as feed intake, weight gain and feed conversion rate (Table 1; see also Windisch et al., 2008). Comparison of these data has often been very difficult, however, as different experiments were performed with different and widely ranged doses. Some authors reported the dose in mg per body weight, some in percentage in the feedstuff, while the others calculated based on the concentration of active principles. In many cases FI and FCR have been influenced by plant extracts. However, in a number of cases FI and FCR were not changed but the extracts still had positive effects on body weight, body weight gain, organ weight and/or energy utilisation. This results from the strong link between productivity and health. Plant extracts may stimulate the immune system (extracts from alfalfa, artichoke, Saccharum officinarum, Table 1 and elsewhere in this review), suppression of harmful microorganisms (Pseudomonas, Staphylococcus, E. coli, Eimeria spp., C. perfringens, Mycoplasma gallisepticum), stimulation of beneficial microbes such as Lactobacillus spp. (extracts containing capsaicin, cinnamonaldehyde and carvacrol), the regulation of the activity of some enzymes (e.g. lipase), protection of gut villi and bacterial adhesion parameters. Plant extracts may also influence the post-mortem quality of meat, especially cholesterol concentration, lipids content, oxidative stability, as well as the quality of eggs, although sometimes better quality was accompanied by reduced weight gain (grape seed extract). An important parameter that can influence growth performance is the protection given by plant extracts against some toxins that can be found in feedstuffs, e.g. ochratoxin A and selenium.

An extract of sugar cane, which was the residue after removing glucose, fructose and sucrose from sugar cane juice was fed at the dose of 0.5 g/kg/d (El-Abasy et al., 2002; Yamauchi et al., 2006) to broilers. A higher body weight gain, gain in body weight/day and lower feed conversion ratio were observed under this treatment, but, like many similar studies, the phytochemical(s) responsible were not identified. Besides some alterations in intestinal histology (higher values of villus height, villus area, epithelial cell area and cell mitosis) promoting growth and showing immunostimulating effects were observed. Chinese herbs were shown to be effective feed additives replacing antibiotics in Pekin meat duck diets (Wang and Zhou, 2007), and a similar conclusion was drawn by Jamroz and Kamel (2002) who observed improvements in daily gain and feed conversion ratio in poultry fed on a diet supplemented with plant extracts. Plant extracts from milk thistle (90 and 180 mg/kg feed), yarrow (900 and 1800 mg/kg), garlic (8230 and 16460 mg/kg), oregano, juniper (450 and 6000 mg/kg) and horseradish (450 and 6000 mg/kg) showed beneficial effects on male broiler chickens (Lewis et al., 2003). Based on feed conversion efficiency (FCE), two extracts e.g. yarrow and garlic were indicated as promising. Garlic (1 g/kg feed) and thyme (1 g/kg feed) were also most promising herb feed additive in the research performed using 5 commercial feeds supplemented with NorSpice® powders (Demir et al., 2003). Two additional commercial phyto-genic feed additives XTRACT™ containing carvacrol (5%), cinnamaldehyde (3%) and Capsicum oleoresin (2%) as well as Sangrovit® containing ground roots of Sanguinaria canadensis rich in the alkaloids sanguinarin and chelerythrin had no effect on chicken growth performance, nutrient utilisation or threonine efficiency, but slightly improved daily gain (+3.7%) and feed conversion ratio (+1.7%).

Dietary supplementation of an EO mixture Herbsromix® (oregano herb (Origanum onites), laurel leaf (Laurus nobilis), sage leaf (Salvia fruticosa), fennel fruit (Foeniculum vulgare), myrtle leaf (Myrtus communis) and citrus peel (rich in limonene) to broilers significantly improved feed conversion rate above that of the control group (Alcicek et al., 2004; Cabukt et al., 2006a). In laying hens, cracked-broken egg rate was decreased with the dietary supplement of EO (Cabukt et al., 2006b). Supplying Oregano EO reduced daily feed intake of broilers compared to control animals. Enrichment with EO significantly improved feed efficiency in broilers (Halle et al., 2008). Most studies have shown no significant difference in feed intake caused by herbal or EO additives, but growth was often enhanced and FCR rate improved. Since poultry are known to adjust feed intake strongly according to the demand of energy, FCR is therefore a very sensitive parameter in responses to growth promoters. Published results are, however, contradictory. Lee et al. (2003a) fed broilers with 200 mg/kg feedingstuff carvacrol or thymol. Carvacrol reduced feed intake, weight gain and feed conversion rate, whereas thymol showed no effect. Addition of oregano herb in quantities of 2–20 g/kg feed or oregano oil (100–1000 mg/kg feed) resulted, in contrast, in all cases in better performance of broiler chicks (Halle et al., 2004), whilst another trial of the same group (Westendarp et al., 2006) using carvacrol, p-cymene and γ-terpinene as pure substances in approximate 50 (carvacrol) or 25 (terpinene, p-cymene) mg/kg had almost no effect. Recently, Haselmeyer (2007) studied the effect of thymol in 4 concentrations from 0.1 to 1.0% as a feed additive in broilers. No significant difference in performance was obtained over the whole growing period (35 d). Turkeys fed with 1.25–3.75 g/kg dried oregano leaves showed, in contrast,
a clearly improved feed conversion rate (Bampidis et al., 2005). Adding 60 mg/kg carvacrol-rich thyme oil to the diet resulted in significantly higher body weight gain and better feed efficiency as well as decreased abdominal fat weight in quails (Denli et al., 2004). A dietary supplementation of oregano EO (300 mg/kg) showed a positive effect on performance of broiler chickens experimentally infected with Eimeria tenella (Giannenas et al., 2003).

In conclusion, the number of trials on the effects of plant extracts on performance in poultry is large. Recently, Windisch et al. (2008) also evaluated some of the available studies in broilers, turkeys and quails and concluded that a majority of the studies showed a reduction in FI due to the use of dietary plant extracts, a largely unchanged body weight gain and as a result an improvement in FCR. However, for each response parameter (feed intake, body weight gain and feed conversion ratio) differences in the quantitative response were found in different studies. Whether such a general statement is valid is doubtful, as each plant extract or phytogenic plant compound will most likely have a different mode of action and result in different types of effects on animal performance. A number of studies have also shown no response or a positive effect on feed intake and/or body weight gain. In addition, the experimental conditions in which the compounds are tested may greatly influence the outcome of the evaluation, e.g. the nature of the negative control treatment, experimental conditions with regard to health status of the birds and/or challenges imposed to the birds during evaluation of the feed additives, or the concentration of the compounds tested. Moreover, it can be assumed that there will be a publication bias in this area, meaning that products or studies showing no or negative effects have less chance of being published in a refereed journal.

**Product quality**

Many plants or plant extracts contain bioactive compounds that improve the quality of poultry products, including both meat and eggs. The main quality indices of interest are organoleptic properties, storage stability and the “healthiness” of the product for consumption by man. Although including herbs in the diet might be expected to influence taste in particular, there seem to be surprisingly few structured reports on the influence of phytochemicals on the organoleptic qualities of poultry products (Rizza et al., 2008; Windisch et al., 2008). Thus, the quality aspects reviewed here will cover predominantly the effects on stability and healthiness.

**Antioxidants**

Many plants and phytochemicals, including EO plants and EO, are known for their antioxidative properties based mainly on phenolic compounds in the oil or in other phytochemical fractions. Some non-phenolic substances may show a remarkable antioxidative potential. Such substances contribute to antioxidative benefits in three respects. Firstly, they may protect feed components from oxidative damage, substituting partly the use of α-tocopheryl acetate and related compounds as feed additives or preservatives respectively. They may also affect oxidative metabolism in the animal: examples will be given below. Finally, oxidative stability to a large extent determines the shelf life of fat, meat and eggs (Botsoglou et al., 1997; Govaris et al., 2005), and many plant bioactive feed additives have been shown to benefit storage quality.

The dietary supply of thyme oil or thymol to ageing rats showed a beneficial effect on the antioxidative enzymes superoxide dismutase and glutathione peroxidase as well as on polyunsaturated fatty acid composition in various tissues (Youdim and Deans, 1999). Animals receiving these supplements had higher enzyme levels and higher concentrations of polyunsaturated fatty acids in phospholipids of the brain than the untreated control (Youdim and Deans, 2000). Oregano EO added in doses of 50–100 mg/kg to the diet of chickens exerted an antioxidant effect in the animal tissues (Botsoglou et al., 2002). Such antioxidant effects would be expected to improve the health of poultry livestock as they do in other animals, including man.

Storage quality is generally linked to the oxidation of fats. Dietary thyme improved the oxidative stability of eggs (Botsoglou et al., 1997; Liu et al., 2009); although thymol is the EO compound most associated with biological effects in thyme, other components also appeared to be involved (Botsoglou et al., 1997). Saffron (Crocus sativus L.; Botsoglou et al., 2005), oregano (Radwan et al., 2009), rosemary (Lopez-Bote et al., 1998; Florou-Paneri et al., 2006; Radwan et al., 2009), sage (Lopez-Bote et al., 1998), turmeric (Curcuma longa; Radwan et al., 2009), tea catechins (Yilmaz, 2006), mulberry leaf, Japanese honeysuckle and goldthread (Liu et al., 2009) had similar benefits to the oxidative stability of eggs. The effects of rosemary were not seen in another study (Galobart et al., 2001). Also with rosemary and sage extracts, the concentration of total cholesterol oxidation products (COPS) was reduced, and a similar trend was observed in microsomal fraction isolates in which the rate of metmyoglobin/
hydrogen peroxide-catalysed lipid peroxidation was lower in birds receiving these plant extracts in comparison with the control fed on basal diet only (Lopez-Bote et al., 1998). Thus, many plants can improve the oxidative stability aspect of product quality, although the phytochemicals responsible have not been identified.

Lipid metabolism

Fatty acid and cholesterol metabolism in the bird is influenced by many plants and phytochemicals, leading to improvements in the fatty acid composition and particularly cholesterol content of meat and eggs. Garlic is probably the best characterised plant to lower the cholesterol content of poultry meat (Konjufka et al., 1997; Lim et al., 2006) and eggs (Chowdhury et al., 2002; Mottaghitalab and Taraz, 2004; Yalcín et al., 2006, 2007). Other plants and herbs have also been reported to be beneficial in this respect, including green tea (Uuganbayar et al., 2005) of which Chinese green tea was best (Uuganbayar et al., 2006), and mixed herbs (Poltołowicz and Wezyk, 2001). The mechanism whereby garlic decreases cholesterol involves lower serum concentrations of cholesterol (Horton et al., 1991; Chowdhury et al., 2002; Mottaghitalab and Taraz, 2004; Lim et al., 2006; Yalcın et al., 2006), which then presumably limits the cholesterol available to be taken up into muscle and eggs. The results of Santoso et al. (2005) suggest that Sauropus androgynus (Katuk) extract acts in a similar manner to garlic. Broiler chicks fed on Codonopsis lanceolata root (a plant used in Korean cuisine) showed decreased serum levels of triglyceride, total cholesterol and low density lipoprotein cholesterol compared to the control group, and decreased triglycerides and total cholesterol levels in liver and breast muscle. The effect appeared to be linked to biliary cholesterol excretion being increased by 15%. Whether this is a common mechanism of product-cholesterol-lowering plants is not yet clear. The pattern of fatty acids in the abdominal fat of chicken was also altered by oregano oil (Wald, 2002), and dietary carvacrol lowered plasma triglycerides (Lee et al., 2003a). Yolk colour is also a quality trait that is influenced by plant additives. Green tea decreased the yellowness of the yolk (Uuganbayar et al., 2005), as did mixed herbs (Poltołowicz and Wezyk, 2001), while other dietary ingredients/additives, including alfalfa concentrate, tomato powder and marigold extract increased the colour intensity of yolk (Karadas et al., 2006). These natural additives would be preferred over some synthetic pigments that have been fed to poultry for many years but which are now less acceptable to consumers (Karadas et al., 2006).

BIOACTIVE COMPOUNDS AND THE GASTROINTESTINAL ENVIRONMENT

Normal flora

Most of the gut microbiological analysis of poultry used in food production has been done in the broiler chicken. The two main sites of microbial activity are the crop and the caecum (Smith, 1965), although microbe-host interactions elsewhere in the digestive tract may have important consequences for health (Lan et al., 2005). Before the advent of molecular community profiling techniques, cultivation-based analysis indicated that the anterior part of the tract (crop, gizzard, small intestine) was dominated by facultative bacteria, principally Lactobacillus spp., while the caecum contained mainly strict anaerobes (Fuller, 1984). Numbers were high, up to 1011 per g of digesta. More recently, terminal restriction fragment length polymorphism (T-RFLP) analysis, also based on 16S gene sequence analysis, indicated that the bacterial communities at different parts of the gut were different, except when comparing jejunum and duodenum (Torok et al., 2008). Lu et al. (2003) confirmed this difference when comparing 16S rRNA gene libraries from the ileum and caecum. The former contained nearly 70% Lactobacillus spp., while the latter had only 8% Lactobacillus and was dominated by Clostridiaceae-related species. Fuller (1984) estimated that there may be more than 200 species in the avian gut. Gong et al. (2002a) and Zhu et al. (2002) found that many of the 16S rRNA sequences from caecal clone libraries were dissimilar to known bacteria. The library sequences obtained by Zhu et al. contained 40% related to Sporomusa or enteric bacteria related to γ-proteobacteria, such as E. coli, a result that was not replicated in the other molecular studies. Smaller numbers of bacteria colonise the small intestine, yet they represent a surprisingly diverse community (Knarreborg et al., 2002; van der Wielen et al., 2002). A specific community colonises the caecal mucosa, different from that inhabiting the lumen (Gong et al., 2002b). All sequence analysis studies report that there are large numbers of unknown bacteria present (Apajalahti et al., 2001; Gong et al., 2002a,b; Lu et al., 2003; Apajalahti et al., 2004). While some might assume that these bacteria might be unculturable (e.g. Apajalahti et al., 2004), there is no reason to suppose that they will be functionally different to known gut species and that they may eventually be cultured.

Both diet and age have a major influence on the composition of the gut bacterial community.
The first report of the effect of diet on the community by molecular techniques was that of Apajalahti et al., (2001), who used a G + C profiling method to demonstrate that diet had a major effect on gut composition. Even a relatively minor change in diet – the supplementation of a barley diet with glycosidases – resulted in 73% dissimilarity between bacterial communities in the ileum and 66% in the caecum (Torok et al., 2008). The changes seemed to occur across many species, with no individual bacterial species contributing more than 1 to 5% of the total. Lu et al. (2008) made the point that the broiler should be thought of as a young animal whose mature flora has not yet been achieved. The caecal and ileal communities were similar up to 14 d, diverging thereafter.

**Gut microbiota and productivity**

How useful or harmful are the resident gut bacteria to health and productivity? Some would consider that the most telling observations about the role of gut microorganisms in the health and productivity of poultry are (i) that gnotobiotic and caecotomised chicken and quail chicks grow better than their conventional counterparts (Fuller and Coates, 1983; Furuse and Yokota, 1984, 1985) and (ii) that antibiotics enhance growth efficiency in broiler production (Graham et al., 2007). Fuller (1984) concluded that, although bacterial glycosidases digested polysaccharides in the feed, there was no evidence of a net benefit to productivity from this activity. Indeed, he went so far as to say “In fact the net effect of the flora is harmful”, Vispo and Karasov (1996), on the other hand, argue that the retention in evolutionary terms of a caecum (1996), on the other hand, argue that the retention in evolutionary terms of a caecum is coccidiosis, caused mainly by *Eimeria* spp. (Kennedy, 2001). The disease is passed from bird to bird via droppings, which means that the problem is greatest in intensive units unless measures are taken to control oocyte numbers.

**Immunity**

The nutrient content of the diet has a major effect on immunity in poultry (Kidd, 2004), without reference to plant bioactives, but there is nonetheless growing published evidence for benefits to be obtained by incorporating plants rich in certain phytochemicals being beneficial for immune function in poultry (Świtkiewicz and Koreleski, 2007). Chinese herbs in particular seem to be cited as positive for immune effects, though other plants and extracts have been reported to be positive. We have not been able to find a systematic account of the precise phytochemicals that might be beneficial, so what follows is inevitably rather disjuncted: there does not appear to be a hypothesis linking the different plants. Immune function would be enhanced as a consequence of a more stable intestinal health favoured by feed additives, or by animals being less exposed to microbial toxins or other undesired metabolites, for example ammonia and biogenic amines. Consequently, additives like aromatic herbs or volatile oils may relieve the animals from immune defence stress during critical situations, raising the intestinal availability of essential nutrients for absorption and thus, assist the animal to grow better within its genetic potential.

Sometimes extracts of plants, not well characterised, have beneficial effect. Ethanol extracts of *Allium sativum* (garlic), *Glycyrrhiza glabra* (licorice), *Plantago major* (plantain) and *Hippophae rhamnoides* (sea buckthorn) all had some beneficial immunological effects on cellular
immunity in laying hens (Dorhoi et al., 2006). Polysavone, an extract of alfalfa, enhanced immunity in broilers (Dong et al., 2007). The phagocytic activity of peripheral blood leucocytes in chickens orally administered sugar cane extracts or a polyphenol-rich fraction of the sugar cane extract (500 mg/kg/day) for 3 consecutive days increased significantly, when compared with that of saline-administered control chickens (Hikosaka et al., 2007). Achyranthan, a low-molecular-weight Chinese herbal polysaccharide, showed immunostimulating effects in both growth assays and in vitro studies (Chen et al., 2003).

*Ligustrum lucidum* and *Schisandra chinensis* improved antioxidative metabolism and immunity of laying strain male chicks (Ma et al., 2007). Aniseseed (*Pimpinella anisum*) used at up to 4% inclusion in laying quail diets provided beneficial effects on immune responses, although 5% caused negative effects on feed intake and feed conversion ratio (Bayram et al., 2007). Similar effects were found in broiler chicks (Durrani et al., 2007).

**Coccidiosis**

Coccidiosis is the most important disease in poultry production (Cox, 1998) causing annual costs of more than $3 billion to the worldwide industry as estimated by Dalloul and Lilleyhoj (2006). Mortality, malabsorption of nutrients, impaired growth rates and rapid and effective transmission between animals are characteristic of the disease, which is caused by several species of *Eimeria*. Secondary bacterial infections are frequently observed and may further increase the severity of the disease. In-feed medication by anticoccidial drugs has provided good protection of flocks for decades. Emerging problems with parasite resistances and concerns about drug residues however have stimulated the search for alternatives. Concomitantly with the ban of antibiotic growth promoters in animal production, the European Union (EU) has put to question the use of coccidiostats from the year 2012 onwards. The decision will have high impact on poultry production within the EU and is expected to influence also other regions.

Coccidiosis vaccines are mostly used for breeder and layer chickens, but hardly at all for broilers (EC, 2008), which is the most numerous type of chicken. Six *Eimeria* species are considered economically relevant (Holdsworth et al., 2004), but immunity is highly species-specific and not all species and relevant strains are included in most commercial vaccines. To overcome these limitations, a lot of effort is put into new strategies for vaccine development (Dalloul and Lilleyhoj, 2006; Shirley et al., 2007).

A summary of reported anticoccidial effects of plants and plant extracts in poultry is given in Table 2.

**Proxidants**

Allen and Fetterer (2002) provided a comprehensive review on various feed ingredients and their influence on coccidiosis. Flaxseed, flaxseed oil and corn oil, which contain high amounts of polyunsaturated fatty acids (PUFA), reduced lesions caused by the chicken parasite *Eimeria tenella*, but not lesions caused by *Eimeria maxima* (Allen and Fetterer, 2002; Yang et al., 2006). Artemisinin, a naturally occurring antimalarial compound, significantly lowered lesions (Allen and Fetterer 2002) and reduced oocyst output (Arab et al., 2006) from *E. tenella* when given at low levels as a feed additive. The mechanisms of action of PUFA as well as artemisinin are assumed to involve induction of oxidative stress to the parasites. However, there might be practical difficulties in including sufficient amounts of PUFA for protection in the diets, also due to antioxidative ingredients which are usually included in feed, as studies by Allen et al. (2000) have shown. Furthermore, this mode of action seems to be effective against *E. tenella*, which is adapted to the specifically anaerobic conditions of the caeca, but not so much against other *Eimeria* species.

**Antioxidants**

Diet supplemented with γ-tocopherol, with the spice turmeric or curcumin, which all possess antioxidative properties, reduced small intestinal lesion scores and improved weight gains during *E. acervulina* and *E. maxima* infections (Allen and Fetterer, 2002). Antioxidative activity is also suggested as the mode of action of various South African plant species investigated by Naidoo et al. (2008). *Tulbaghia violacea* showed improved FCR and lowered oocyst output during a mixed *Eimeria* challenge. Green tea reduced oocyst shedding after an *E. maxima* infection, but no beneficial effects on weight gain were detected (Jang et al., 2007). Wang et al. (2008) reported beneficial effects of grape seed proanthocyanidins by counteracting weight loss, mortality and lesion scores and lowering oxidative stress in intestinal tissues. All these compounds may exert their anticoccidial activity by protecting infected tissues from oxidative damage and therefore reducing the severity of coccidiosis. Similar to compounds causing oxidative stress, the effect of antioxidants seems to be restricted to certain *Eimeria* species only, especially *E. acervulina* and *E. maxima* (Allen and Fetterer, 2002).
Table 2. Plants and plant extracts with anticoccidial activity

<table>
<thead>
<tr>
<th>Plant species/extract</th>
<th>Scientific name</th>
<th>Activity/Mode of action</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn oil</td>
<td><em>Zea mays</em></td>
<td><em>E. tenella</em> body weight, higher IgA, lower plasma carotenoids,</td>
<td>Yang et al. (2006)</td>
</tr>
<tr>
<td>Betaine e.g. from sugar beet</td>
<td><em>Betaine</em></td>
<td><em>E. tenella</em> body weight, higher IgA, lower plasma carotenoids,</td>
<td>Yang et al. (2006)</td>
</tr>
<tr>
<td>γ-Tocopherol e.g. from <em>Linum usitatissimum</em>, various seed oils</td>
<td><em>γ-Tocopherol</em></td>
<td><em>E. maxima</em> lesions, weight gain. <em>E. acervulina</em> (not <em>E. tenella</em>) Antioxidative</td>
<td>Allen et al. (2000), Allen and Fetterer (2002)</td>
</tr>
<tr>
<td>Betaine e.g. from sugar beet (Beta vulgaris ssp. vulgaris var. altissima)</td>
<td><em>Betaine</em></td>
<td><em>E. acervulina</em> (and <em>E. tenella</em>), but less effective invasion and development when used in combination with salinomycin. <em>E. maxima</em> weight gain (not <em>E. tenella, E. acervulina</em>)</td>
<td>Allen et al. (2000), Allen and Fetterer (2002)</td>
</tr>
<tr>
<td>China bark tree extract, Quinine</td>
<td><em>Cinchona succirubra</em></td>
<td><em>E. tenella, E. melangrimitis Sz</em> invasion in vitro</td>
<td>Christaki et al. (2004), Fayer (1971)</td>
</tr>
<tr>
<td>Olympus tea</td>
<td><em>Sideritis scardica</em></td>
<td><em>E. tenella</em> weight gain, diarrhoea, mortality, lesions, oocysts output</td>
<td>Florou-Paneri et al. (2004)</td>
</tr>
<tr>
<td>Grape seed proanthocyanidin extract, ethanol/water extract from pomace</td>
<td><em>Vitis vinifera</em></td>
<td><em>E. tenella</em> weight gain, mortality, lesion scores. <em>Eimeria</em> mix (Etens, Emax, Eace): FCR, lesions, OPG (exact inclusion rate unclear!)</td>
<td>Naidoo et al. (2008), Wang et al. (2008)</td>
</tr>
<tr>
<td>Sugar cane extract</td>
<td><em>Saccharum officinarum L.</em></td>
<td><em>E. tenella</em> body weight gain, oocyst output, lesions, antibody response. Small group sizes, no specification of extract.</td>
<td>El-Ahasy et al. (2003)</td>
</tr>
<tr>
<td>Wild garlic acetone/water extract from whole plant</td>
<td><em>Tulbaghia violacea</em></td>
<td><em>Eimeria</em> mix (Etens, Emax, Eace): FCR, OPG. Marasmine = S-(methylthiomethyl)cysteine sulfoxide), bis(methylthio)-methyl disulfide, and derivatives</td>
<td>Naidoo et al. (2008)</td>
</tr>
<tr>
<td>Green tea leaves Oriental plum, Japanese plum</td>
<td><em>Camellia sinensis</em></td>
<td><em>E. maxima</em> oocyst output</td>
<td>Jang et al. (2007)</td>
</tr>
<tr>
<td></td>
<td><em>Prunus salicina</em></td>
<td><em>E. acervulina</em> body weight gain, OPG, IFN-g and IL-15 (mRNAs) of IEL, spleen cell proliferation. Phenolics, antioxidants,</td>
<td>Lee et al. (2008)</td>
</tr>
</tbody>
</table>

**Essential oils**

Amelioration of coccidiosis was observed when supplementing commercial feed additives containing oregano EO (Giannenas et al., 2003; Batungbacal et al., 2007) or ground aerial parts of oregano (Giannenas et al., 2004). Both applications protected significantly from weight loss or improved feed efficiency and reduced oocyst output and lesion scores in a coccidiosis challenge. Improvement of the negative impact of coccidiosis was also reported for supplementation with Olympus tea (*Sideritis*...
scardica; Florou-Paneri et al., 2004). The EO constituents 1,8-cineole and camphor, from Artemisia annua protected weight gain and reduced E. tenella as well as E. acervulina lesions (Allen and Fetterer, 2002).

Various other plants/products

Youn and Noh (2001) tested 15 therapeutic plants against an E. tenella challenge and found a root decoction of Sophora flavescent to be most active in protecting weight gain and reducing mortality and bloody diarrhoea. Moreover, a sugar cane extract had protective effects when inoculated in the crop of chicken simultaneously with a challenge. Body weight gain, haemorrhages, oocyst output, lesion scores and antibody response were improved (El-Abasy et al., 2003). Betaine, an osmoprotectant ubiquitous among plants, enhanced the activity of anticoccidial drugs in some cases (Allen and Fetterer 2002; Fetterer et al., 2003), but failed to do so in others (Waldenstedt et al., 1999). Apparently, its effect is restricted to certain Eimeria species only.

Immunomodulation

Immunomodulatory effects are assumed to be responsible for protection by plum powder (Prunus salicina) against an E. acervulina challenge (Lee et al., 2008). Body weight gain, oocyst shedding, IFN-γ and IL-15 levels were significantly improved. Furthermore, Guo et al. (2004a,b) found enhanced cellular and humoral immune responses of E. tenella-infected chickens when supplementing a polysaccharide extract from Astragalus membranaceus, which may become particularly interesting when used in conjunction with vaccination.

Future perspectives

In summary, plants and products derived thereof have clearly shown the potential to alleviate coccidiosis and reduce its severity in several studies. Moreover they might play a role in counteracting subclinical infections and secondary bacterial infections associated with the disease. Most of the active plant materials could improve some, but not all of the relevant parameters in coccidiosis and variable effectiveness against the different Eimeria species was observed in some cases. To date, no alternative to anticoccidial drugs is yet known with comparable efficacy and economy of use in broiler production, and a recently published EC report strongly recommends to maintain the actual status of so-called “coccidiostatic drugs” as feed additives within the EU (EC, 2008). Nevertheless, plant products may have increasing significance in organic farming, whenever antibiotic-free rearing of animals is desired, as supporting agent for vaccination (adjuvants), or in combination with conventional anticoccidial drugs, especially in the light of possible bans or reduction of approved drugs in large economies like the EU. This should be a great incentive for stimulating research in the field of alternatives to conventional anticoccidial drugs in general and especially on the role of plants and plant products.

Difficulties in comparing research data arise from the use of different experimental models and different strains of Eimeria. Parasite strains are known to possess variable virulence and may cause variable severity of challenge in different experiments. An important effort to harmonise techniques in coccidiosis research and models for evaluation of drug efficacy against coccidiosis was taken in the course of the COST 89/820 programme and by Holdsworth et al. (2004). Guidelines for efficacy testing are also published by regulative authorities, e.g. the recently published EFSA “guidance for the preparation of dossiers for coccidiostats and histomonostats” (EFSA, 2008). Such guidelines should also be taken into consideration when alternatives to anticoccidial drugs are investigated in order to provide sound and comparable scientific results.

Necrotic enteritis

Necrotic enteritis (NE) is a disease in poultry causing high economic costs and seriously impairs animal welfare. Due to the ban on subtherapeutic antibiotic usage, NE has become increasingly prevalent in the EU. Demands for safer food have put pressure on the development of alternative management or dietary strategies to control this disease. C. perfringens, a Gram-positive, anaerobic, spore-forming toxigenic bacterium is found in soil, dust, faeces, feed and poultry litter and has been identified as the main causative agent causing NE in poultry (Branton et al., 1997; Annett et al., 2002; Dahiya et al., 2006; McDevitt et al., 2006). C. perfringens is principally a normal inhabitant of the chicken intestine but under certain circumstances it can begin to proliferate rapidly, accompanied by increased toxin production causing the intestinal mucosal necrosis characteristic of NE (Branton et al., 1997; Collier et al., 2003; Dahiya et al., 2005, 2006). However, even high doses of C. perfringens in the intestinal tract of broiler chickens do not always lead to the development of NE, as the gut flora of healthy birds can apparently prevent its pathogenicity (Fukata et al., 1991). Various predisposing factors, among them dietary composition and incidence of coccidiosis (Williams, 2005), may lead to over-proliferation of
C. perfringens, and the subsequent progression to disease is still poorly understood. Host specific virulence factors like production of α-toxin are assumed to play a role, and recent findings point towards the importance of the netB gene, necessary for the production of the respective toxins (NetB) (Keyburn et al., 2006; Chalmers et al., 2008; Timbermont et al., 2008). However, control of C. perfringens seems to be essential and dietary ingredients have a great influence on the incidence of NE in broiler chickens.

Reports of the effects of plants and their extracts on mainly avian C. perfringens are summarised in Table 3. Dahiya et al. (2006) reviewed the potential of plant-derived feed ingredients to control C. perfringens and NE. Numerous plants and plant products have been found to possess inherent antimicrobial activity against clostridia, although mostly their effects were only determined in vitro. Oregano, black pepper, cloves and the EO components carvacrol and eugenol possess antibacterial activity against clostridia as well as E. coli, Staphylococcus aureus and Salmonella pullorum. Furthermore, lemon myrtle (Wilkinson et al., 2003), Artemisia princetis var. orientalis (Cho et al., 2003), Hypericum scabrum (Sokmen et al., 1999) and Aristolochia paucinervis (Gadhi et al., 1999) displayed in vitro activity against C. perfringens and other bacteria.

Reports on in vivo investigations are scarce: according to Dahiya et al. (2006), supplementation of flaxseed may have benefits by modification of intestinal microbial colonisation. Linolenic acid, the main constituent of flaxseed fatty acids, may prevent the adhesion of bacteria to intestinal epithelial cells and mucus, whereas addition of pectin and guar gum to diets has reportedly eliminated NE from sick birds. Specific blends of EO components like thymol, carvacrol and eugenol (Mitsch et al., 2004) as well as astaxanthin from the microalgae, Haematococcus pluvialis, were found to be effective in controlling C. perfringens colonisation and proliferation in the gut of broilers (Waldenstedt et al., 2003). Finally, lupulone from hops, when administered in drinking water, inhibited proliferation of artificially inoculated C. perfringens in the chicken gastrointestinal tract (Siragusa et al., 2008).

Escherichia coli

Escherichia coli is the most common bacterial pathogen of poultry and responsible for significant losses in the world’s industry. Although our understanding of pathogenicity has increased in the past years, the virulence factors (genes) which lead to disease remain to be fully unravelled (La Ragione and Woodward 2002). For practical reasons, E. coli isolated from diseased chicken are termed avian pathogenic E. coli (APEC). Colisepticaemia or colibacillosis manifests itself most commonly as an infection of the respiratory tract, in rare cases also as enteritis. E. coli are common inhabitants of poultry intestinal microbiota, thus the gastrointestinal tract is seen as a possible reservoir for infection (Ewers et al., 2009) and incidence of the disease might be reduced by keeping intestinal E. coli numbers low.

Reports of the effects of plants and their extracts on APEC are summarised in Table 3. There are numerous studies on in vitro effectiveness of plant-derived extracts and compounds, as well as EO against (avian) E. coli (Smith-Palmer et al., 1998; Penalver et al., 2005b,c,d; Fisher and Phillips 2006; Horosova et al., 2006; Prakash, 2006; Geidam et al., 2007). EO containing a high percentage of phenolic components (e.g. carvacrol and thymol) show higher inhibitory capacity compared to the oils containing, for example, the monoterpenic alcohol linalool (Penalver et al., 2005a). However, literature supporting actual in vivo activity is scarce. An alternative strategy to suppress intestinal E. coli might involve preventing their adhesion to the intestinal mucosa. This may be achieved by feeding compounds which increase mucus production, thus reducing the possibility of bacterial adhesion to the intestinal epithelium. A mixture of carvacrol, cinnamaldehyde and capsaicin caused the release of large amounts of mucus on glandular stomach and wall of jejunum in chickens when incorporated into their diets (Jamroz et al., 2006). Becker and Galletti (2008) exploited the ability of E. coli to adhere to mannose receptors and mannose-containing analogues to find food and feed components with gut health-promoting effects. Out of 18 dietary components tested, artichoke and sesame seed extracts performed well in binding various E. coli strains. Sesame seed extract was also most effective in binding chicken Salmonella isolates.

Antiviral effects

Although a vast range of plants possess antiviral activity (Jassim and Naji, 2003), they are probably underexplored and underutilised for this purpose in poultry farming. Actually, the most important viral diseases are sought to be controlled by vaccination. A polyphenolic extract from Geranium sanguineum aerial roots and an extract of the red marine alga Ceramium rubrum showed excellent in vitro inhibition of human and chicken influenza A viruses (Serkedjieva and Hay, 1998). The very scarce animal trials comprise sulfated Astragalus polysaccharides...
<table>
<thead>
<tr>
<th>Plant species/extract</th>
<th>Scientific name</th>
<th>Activity/Mode of action</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaxseed, linolenic acid</td>
<td>Linum usitatissimum</td>
<td>Prevents adhesion of pathogenic bacteria</td>
<td>Dahiya et al. (2006)</td>
</tr>
<tr>
<td>Guar gum, pectin</td>
<td>Cyamopsis tetragonolobus</td>
<td>Unknown</td>
<td>Dahiya et al. (2006)</td>
</tr>
<tr>
<td>Thymol, carvacrol and eugenol</td>
<td></td>
<td>Inhibit C. perfringens colonisation and proliferation</td>
<td>Dahiya et al. (2006), Mitsch et al. (2004)</td>
</tr>
<tr>
<td>Turmeric, EO from rhizome</td>
<td>Curcuma longa</td>
<td>Inhibits C. perfringens</td>
<td>Dahiya et al. (2006)</td>
</tr>
<tr>
<td>Eugenol, EO from clove</td>
<td>Syzygium aromaticum</td>
<td>Inhibits C. perfringens</td>
<td>Dahiya et al. (2006)</td>
</tr>
<tr>
<td>Astaxanthin, from red algae</td>
<td>Haematococcus pluvialis</td>
<td>Inhibits C. perfringens caecal colonisation</td>
<td>Waldenstedt et al. (2003)</td>
</tr>
<tr>
<td>Lupulone, from hops</td>
<td>Humulus lupulus</td>
<td>Inhibits intestinal C. perfringens</td>
<td>Siragus et al. (2008)</td>
</tr>
<tr>
<td>Hypericum, acetone extract from aerial parts</td>
<td>Hypericum scabrum</td>
<td>Inhibits C. perfringens (in vitro)</td>
<td>Sokmen et al. (1999)</td>
</tr>
<tr>
<td>Arctostaphylos paucinervia, defatted chloroform extract of rhizome</td>
<td>Arctostaphylos paucinervia</td>
<td>Inhibits C. perfringens (in vitro)</td>
<td>Gadhi et al. (1999)</td>
</tr>
<tr>
<td>Oregano, EO</td>
<td>Origanum vulgare</td>
<td>Bactericidal effect</td>
<td>Horosova et al. (2006)</td>
</tr>
<tr>
<td>Agave, extract</td>
<td>Agave paca</td>
<td>Inhibits C. perfringens (in vitro)</td>
<td>Verastegui et al. (1996)</td>
</tr>
<tr>
<td>Paper daisy, petrolatum ether and ethanol extracts of flowers</td>
<td>Helichrysum sp.</td>
<td>Growth inhibition of various Helicobacter species</td>
<td>Aslan et al. (2007)</td>
</tr>
<tr>
<td>Plant extract + 5% carvacrol, 3% cinnamaldehyde, 2% capsicum oleoresin</td>
<td>Origanum vulgare, Cinnamomum cassia, Capsicum annum</td>
<td>Prevents adhesion of E. coli</td>
<td>Jamroz et al. (2006)</td>
</tr>
<tr>
<td>Shiitake, extract</td>
<td>Lentinus edodes</td>
<td>Increases the number of desirable bacteria in order to inhibit colonisation of invading pathogens</td>
<td>Guo et al. (2004c)</td>
</tr>
<tr>
<td>White jelly, herb polysaccharide extract</td>
<td>Tremella fuciformes</td>
<td>Increases the number of desirable bacteria in order to inhibit colonisation of invading pathogens</td>
<td>Guo et al. (2004c)</td>
</tr>
<tr>
<td>Huang Qi, herb polysaccharide extract</td>
<td>Astragalus membranaceus</td>
<td>Increases the number of desirable bacteria in order to inhibit colonisation of invading pathogens</td>
<td>Guo et al. (2004c)</td>
</tr>
<tr>
<td>Spanish origanum, EO</td>
<td>Cymbopogon capitatus</td>
<td>Antimicrobial activity</td>
<td>Penalver et al. (2005)</td>
</tr>
<tr>
<td>Thyme, EO</td>
<td>Thymus mastichina</td>
<td>Antimicrobial activity</td>
<td>Penalver et al. (2005)</td>
</tr>
<tr>
<td>Geranium, EO from steam distillation</td>
<td>Pelargonium sp.</td>
<td>Partly greater efficacy against E. coli than commercial thyme oil</td>
<td>Penalver et al. (2005)</td>
</tr>
<tr>
<td>Guava, aqueous extract</td>
<td>Psidium guajava</td>
<td>Prevents adhesion of E. coli</td>
<td>Geidam et al. (2005)</td>
</tr>
<tr>
<td>Sesame seed extract</td>
<td>Sesamum indicum</td>
<td>Adhesion of E. coli (in vitro)</td>
<td>Becker and Galletti (2008)</td>
</tr>
<tr>
<td>Betel pepper, aqueous extract</td>
<td>Piper betel</td>
<td>Inhibition zone in agar gel plates</td>
<td>Prakash (2006)</td>
</tr>
<tr>
<td>Senna, aqueous extract</td>
<td>Cassia auricuata</td>
<td>Inhibition zone in agar gel plates</td>
<td>Prakash (2006)</td>
</tr>
</tbody>
</table>

(Huang et al., 2008), Ocimum sanctum and leaf galls of Ficus racemosa (Kolte et al., 1999), which showed effects against infectious bursal disease (IBD) and Aloe secundiflora, which reduced mortality and severity of clinical signs during a Newcastle Disease infection (Waihenya et al., 2002b).

**Zoonotic infection**

Of major concern to consumers are the hazards presented by zoonotic infection from contaminated poultry meat. *Campylobacter* spp. is the greatest hazard in terms of numbers of infections and days lost through illness (Friedman et al.,
However, the infection is usually short-term and self-limiting. *Campylobacter jejuni* readily colonise the gastrointestinal tract (GIT) of poultry, without causing any disease in the host birds. The principal site of colonisation is the lower GIT, especially the caeca, large intestine and cloaca (Beery et al., 1988; Stern et al., 1988). *Campylobacters* do not adhere to the intestinal surface but are highly motile and rapidly track along intestinal mucus, preferentially within caecal and cloacal crypts (Beery et al., 1988). Commercial broiler flocks rarely start shedding *Campylobacter* before 2 weeks of age however, when shedding occurs, *Campylobacter* is spread rapidly throughout the flock (Corry and Atabay, 2001; Mead, 2002; Newell and Fearnly, 2003). Until now, the main approaches evaluated for handling the *Campylobacter* problem in practice include hygienic barriers, diagnostics at the flock level, competitive exclusion, decontamination and intervention efforts targeting the lower GIT (Hariharan et al., 2004). Despite major efforts, however, there are currently no really successful strategies for reduction or elimination of *C. jejuni* from the food chain. *Salmonella* infections in man that result from the consumption of poultry products are less numerous, but much more severe. Human infection by two common serovars, *S. enteritidis* and *S. typhimurium* usually occurs via food-borne transmission. Consumption of raw or undercooked contaminated eggs usually causes *S. enteritidis* infection, while *S. typhimurium* is transmitted by contaminated chicken meat (Babu and Raybourne, 2008). Dietary interventions, including fatty acid modifications, probiotic or prebiotic treatment have been investigated (Babu and Raybourne, 2008), but our understanding of conditions that lead to the proliferation of these zoonotic bacteria is patchy (Mead, 2004).

Antibiotic growth promoters, now banned in Europe but still permitted elsewhere, are so effective that their withdrawal has caused major difficulties in poultry production (Casewell et al., 2003). But how do they achieve that growth promotion? Is it due to the suppression of major pathogens like *C. perfringens*? Or sub-pathogenic species like *S. faecium*? Or is it due simply to a decreased bacterial load (Windisch et al., 2008), or perhaps due to the anti-inflammatory effects of AGP via the inhibition of production and excretion of catabolic mediators by intestinal inflammatory cells (Niewold, 2007)? Finding the answer to these questions is vital, because without that knowledge it will be difficult to select phytochemical replacements for AGP. Molecular ecological analysis described changes in the microbiota in response to bacitracin-virginiamycin (Lu et al., 2008), but other than a decreased community diversity in birds receiving the GPA, it was difficult to explain why production benefits should occur. Indeed, the decreased numbers of *Lactobacillus* contradicted the usual perception of these being beneficial bacteria, the basis of their use as probiotics (Fuller, 1989).

**SPECIFIC PLANT BIOACTIVES**

Acamovic and Brooker (2005) estimated that plants produced around 5100 different secondary compounds (Figure). One of the most common problems of research performed using plant extracts in poultry nutrition has been the poor characterisation of the plant material or extracts and their standardisation. In many cases, the identity or concentration of active principle has been generally unknown. Due to the possible variation in plant material under different environmental conditions, harvest time, drying and storage conditions, repetition of the experiments is generally impossible to identify them. This is probably why different results are obtained in independent experiments even when using the same plant species. Thus, the development of analytical methods and the proper standardisation of the material used for feeding is crucial if the benefit of the knowledge is to be maximised. Moreover, feeding experiments have often been performed using negative controls only. To be able to compare data from different experiments, the commonly accepted GPA might be recommended as a positive control. The effects of some of the most common categories of plant bioactives and their physiological mode of action are described in the following sections.

**Essential oils**

EO are steam-volatile or pressed-volatile (*e.g.* citrus extracts) extracts of plants, used traditionally by man for many centuries for the pleasant odour of their essence, their flavour, or their antiseptic and/or preservative properties. Although commonly thought of as being derived from herbs and spices, they are present to some degree in many plants for their protective role against bacterial, fungal or insect attack. They comprise mainly cyclic hydrocarbons (monoterpenes) and their alcohol, aldehyde or ester derivatives (Figure). EO appear as feed additives in the form of the EOs themselves, or as EO-rich plants, or as pure compounds, sometimes synthetic or “nature-identical”.

The number of papers published on the use of EO and especially those containing the phenolic compounds carvacrol and thymol has increased dramatically over the last few years. The majority report, however, on production parameters (feed uptake, feed conversion, weight...
gain) only. Comparatively little information is given on their mode of action, metabolism or generally on science based functionality due to the fact that many reports deal with results of commercial products, avoiding statements on pharmacological effects or health claims.

EO used as feed additives for broilers were shown to enhance activities of trypsin, of amylase in tissue homogenates of pancreas, as well as the jejunal chyme content (Lee et al., 2003b; Jang et al., 2004). A mixture of carvacrol, cinnamaldehyde and capsaicin also stimulated the intestinal secretion of mucus. Jamroz et al. (2006) stated that the increased release of large amounts of mucus and the creation of a thick layer of mucus on glandular stomach and jejunum wall in chicks fed with the above mixture could be responsible for the reduced adherence of pathogens (E. coli, C. perfringens and others) to the gut epithelium. This confirms – as already known from human nutrition physiology (Teuscher, 2003) and phytopharmacology (Hänssel and Sticher, 2004) – the mode of action of spices and EO on gut function, namely that it involves at least partly an irritation of the exposed tissues and leading to higher secretion of mucus and enzymes.

In general, antimicrobial activity of EO and EO compounds, whether bacteriostatic or bactericidal, or against other microorganisms like fungi, protozoa or food-borne pathogens, is well documented (Smith-Palmer et al., 1998, Dorman and Deans, 2000; Chao et al., 2000; Burt, 2004; Si et al., 2006). Most active in this respect are the phenolic compounds carvacrol, thymol and eugenol but also other substances, including phenylpropane, limonene, geraniol or citronellal, may be involved (Deans and Ritchie, 1987; Pauli, 1994).

The action of EO compounds as antimicrobials occurs via at least two separate mechanisms. The first is by rapidly depleting the intracellular ATP pool, through inhibiting ATP synthesis as a result of their effects on the transmembrane electrical potential. The leakage of ions such as potassium and phosphate out of the cell indicates clearly the membrane damage resulting in disturbances of the osmotic pressure of the cells (Ultee et al., 1999; Lambert et al., 2001; Veldhuizen et al. 2006). Furthermore, changes in the fatty acid composition of bacterial cell membranes have been observed at sublethal doses of several EO compounds (Di Pasqua et al., 2006). A second growth-inhibitory mechanism is that substances like carvacrol prevent the synthesis of flagellin, causing bacterial/cells to be aflagellate and therefore nonmotile. Such cells are significantly less able to adhere to epithelial cells, which renders bacteria non-infective (Burt et al., 2007), a mechanism similar to that known from acid galacturonides in the diet (Guggenbichler et al., 2004). The anti-flagellate activity of EOs obtained from fresh leaves of Cinnamomum aromaticum, Citrus limon pericarps and Allium sativum bulbs was investigated in vitro on Tetratrichomonas gallinarum and Histomonas meleagridis with positive results (Zenner et al., 2003).

As EOs comprise a large number of components, it is likely that their mode of action involves several targets in the bacterial cell. The hydrophobicity of EOs enables them to partition in the lipids of the cell membrane and mitochondria, rendering them permeable and leading to leakage of cell contents. Physical conditions that improve the action of EOs include low pH, low temperature and low oxygen levels. Synergism has been observed between carvacrol and its precursor p-cymene and between cinnamaldehyde and eugenol (Burt, 2004). Thus, extrapolating from the effects of single EO compounds to the effects of mixtures must be done with caution.

In vitro antimicrobial activities have been measured with a number of EOs and single compounds mainly against enteropathogenic strains of E. coli, Salmonella sp., C. perfringens and others. Using either the broth microdilution method or the agar diffusion test, EOs with a higher percentage of phenolic compounds showed the best inhibitory capacity in terms of MIC (minimum inhibitory concentration; Jugl-Chizzola et al., 2005; Penalver et al., 2005; Ben Arfa et al., 2006). The combination of oregano EO with fluoroquinolones, doxycycline, lincomycin, and maquindox florfenicol to treat infections caused by ESBL-producing E. coli were reported to lower, to a great extent, the effective dose of these antibiotics and thus minimise the side effects of antibiotics (Si et al., 2008). Differences have been observed, however, in the activities of plant species and plant parts on one side and the sensitivity of species and strains of the microorganisms on the other. This is due to the varying chemical composition of the used plant material (chemotype, morpho- and ontogenetic variation), a factor quite often neglected in microbiological or animal studies. The in vitro active concentrations exceeded furthermore in general the dietary doses accepted by the animals, which results in few studies being available so far demonstrating the efficacy of EO compounds against specific pathogens in vivo.

Some studies with poultry showed a clear reduction of C. perfringens in the jejunum and caecum of broilers fed with a mixture of EO components (Losada and Koehler, 2001; Mitsch et al., 2004). The same blend of components as well as oregano oil or crude drug was effective against Eimeria ssp. infections in broilers, thus
reducing the application of coccidiostats (Giannenas et al., 2003, 2004; Oviedo-Rondon et al., 2005, 2006). The components of Artemisia annua, camphor and 1,8-cineole, at 119 mg/kg, also protected weight gains, and reduced E. tenella lesion scores. Camphor decreased E. acervulina lesions (Allen et al., 1997, 1998). Carvacrol, cinnamaldehyde, oregano oil and thymol also inhibit C. perfringens spore germination and outgrowth in ground turkey during chilling. Cinnamaldehyde was significantly more effective than the other compounds at a lower concentration (0.5%) at the most abusive chilling rate evaluated (Juneja and Friedman, 2007). A study to test the efficiency of carvacrol, thymol, trans-cinnamaldehyde and tetrasodium pyrophosphate on the radiosensitisation of E. coli and Salmonella typhi in chicken breast demonstrated that these active compounds helped reduce significantly the numbers of E. coli and S. typhi (Lacroix et al., 2004). A combined administration of Lactobacillus fermentum and EOs of Origanum vulgare and Thymus vulgaris decreased the percentage of crop, caecum, liver and spleen colonisation by Salmonella enterica var. dusseldorf in chicks when compared to the control group without any treatment (Koscova et al., 2006). In a study to test the effects of the antibiotic avilamycin and anise oil supplementation on broilers’ body weight, including carcass characteristics and organoleptic analysis of meat, it was concluded that anise oil, at a dose of 400 mg/kg, can be used as an alternative to antibiotics for growth promotion in broiler diets (Simsek et al., 2007).

It is sometimes assumed or implied that effects of the inclusion of aromatic herbs in the diet will be caused by the terpenes that comprise their EO. Cross et al. (2007) demonstrated that this need not always be true: thyme and yarrow had different effects on broiler performance to their corresponding EO. With oregano, marjoram and rosemary, the effects were similar.

Two further antimicrobial benefits can theoretically be achieved by adding EO to animal feed: the reduction of feed microbial load and the improvement of the microbial hygiene of the carcase (Aksit et al., 2006). The number of reports in this area is, however, much too limited to draw conclusions.

Tannins

Tannins comprise a complex mixture of higher plant, water-soluble polyphenolic compounds of varying molecular masses that have the ability to react with proteins, polysaccharides and other macromolecules. They tend to be considered antinutritional, because they decrease the digestibility and metabolisable energy of feeds through direct interaction with proteins and carbohydrates from both exogenous and endogenous sources. In ruminants, tannins may be useful in limiting protein degradation in the rumen, thereby permitting more dietary amino acids to flow to the abomasum (McSweeney et al., 2001). In poultry, contrastingly, growth is suppressed by vegetable tannins (Ahmed et al., 1991). Amino acid absorption is compromised by tannins, especially of methionine, histidine and lysine (Mansoori and Acamovic, 2007). High tannin extracts did not alter the mortality of chickens, however they reduced the absorption of minerals such as calcium, magnesium, potassium, sodium and phosphorus from the feed (Hassan et al., 2003). In another experiment tannins extracted from Vicia faba seeds increased mortality, reduced body weight, feed intake and poorer feed conversion ratio (Ortiz et al., 1994) as well as decreased the digestibility of protein and the activity of digestive enzymes (Yuste et al., 1992). There do not seem to be reports of beneficial effects of tannins in poultry.

Saponins

Some research has been performed on the application of plant saponins to poultry production, the compounds being recognised as natural detergents. Extracts from two saponins-rich plants, Yucca schidigera and Quillaja saponaria (Cheeke, 2000; Yeo and Kim, 1997; Preston et al., 1999), had no clear effect on broiler chick performance. Some effects, like increased food intake, body weight gain and energy utilisation were reported in one experiment (Preston et al., 1999), while in another the feed intake was not affected when a 0.2% concentration of the extract was incorporated (Yeo and Kim, 1997). It should, however, be made clear that the claim that it is the saponins present in Yucca or Quillaja extracts that are responsible for their positive effects has not been justified. These extracts are simply condensed juice pressed from the trunk, in which saponins are one of the dominant groups of compounds present in this matrix. Polysaccharides are also abundant, and their influence on nutritional parameters cannot be neglected. Structurally undefined saponins (75 mg/kg/day) showed positive effects on growth and carcase quality (Miah et al., 2004), while Balanites aegyptica kernel saponins tended to reduce body weight in chicks (Nakhala et al., 1992).

Betaine

Although betaine is a generic description of a type of zwitterionic chemical compound, the
term used in poultry nutrition refers to a plant extract or a feed additive containing one particular betaine, namely trimethyl glycine. This review covers the effects of betaine only summarily, because a comprehensive review of betaine and poultry was published very recently (Metzler-Zebeli et al., 2009). Betaine is an osmoprotectant present in all plants and particularly abundant in sugar beet and its byproducts. Benefits from its use as a feed additive include the prevention of stress and inhibition of Eimeria parasitic infection, both presumably due to the ionic nature of the molecule. Its methyl groups are thought also partly to substitute other methyl group donors such as methionine and choline. Both modes of action lead to improved nutrient digestibility and growth performance.

**Other plant bioactives**

A large group of phytochemicals that are widely distributed in plants is phenolics. Among these, the flavonoids (Figure) are the group which has been indicated as possibly most beneficial for poultry performance. The addition to feed of 300 mg/kg of flavonoids (rutin, hesperidine, quercetin and naringenin) together with mannooligosaccharides (MOS) had a significant stimulatory effect on feed conversion ratio (Batista et al., 2007). Additionally there was lower meat oxidation both after refrigeration and freezing when birds were fed flavonoids + MOS, which may be attributed to antioxidant effect of flavonoids; quercetine and hesperidine are considered the strongest antioxidants of the flavonoid family (Burda and Oleszek, 2001). Extracts containing isoflavones significantly increased serum testosterone levels in male chickens and had no specific haematoprotective effect, but slightly decreased slaughter yields. The lipid content of breast and thigh was decreased and the resistance of muscles to oxidative stress increased under this treatment (Schiavone et al., 2007). Moreover it was shown that silimarin phytosome can provide protection against the negative effects of aflatoxin B1 in broiler chicks (Tedesco et al., 2004). Similarly, it protects against pollutants such as carbon monoxide, pesticides and herbicides, by breaking them down from potentially lethal substances into those that are less destructive to the human body. Polyphenol rich grape pomace (peels and seeds) added at the rate of 5–30 g/kg of diet reduced the lipid oxidation in meat during refrigerated storage and increased liver α-tocopherol concentration (Goni et al., 2007). Grape seed extract in the rate of 2.59–5.28% of the feed reduced post mortem development of thiobarbituric acid reactive substances in dark poultry meat but had also detrimental effect on the body weight gain (Lau et al., 2003).

Extracts from sage, thyme and rosemary (5000 mg/kg), rich in rosmarinic acid, another natural antioxidant, had no influence on feed intake and feed conversion, but from 14 to 21 d of age broilers grew faster and improved apparent whole tract and an improved ileal digestibility of nutrients was observed (Hernandez et al., 2004).

An alcohol extract of Propolis (honey bee glue) containing polyphenols used at the rate of 50–250 mg/kg diet significantly increased average weight gain, feed consumption and feed efficiency in broiler chicks. The mortality rate determined after 21 d of growth was decreased as compared to the control diet (Khojasteh and Shivazad, 2006).

**CURRENT RESEARCH PROJECTS**

The global trend to move away from in-feed antibiotics and coccidiostats has strengthened since 2006, when the use of GPA was banned within the EU member states. Therefore research groups and poultry industries worldwide are searching to develop alternatives. Some have performed clinical trials with herbal feed additives.

At present different herbal preparations in poultry feeding are examined for their antibacterial, antiparasitic, antioxidative and/or other health and performance promoting properties like feed intake, feed conversion, body weight, weight gain, growth performance, feed conversion ratio, gizzard function, gut development, nutrient digestibility, digestibility of organic matter and crude protein, gut microflora...
or content on metabolisable energy of feed mixture.

For example at this time in Austria some companies are working in these fields: Richter Pharma AG www.richter-pharma.at, Delacon Phytogenic Feed Additives www.delacon.com, Indian Herbs GmbH www.indianherbs.at and Biomin AG www.biomin.at. They are conducting clinical trials in feeding herbal additives to different poultry, e.g. laying hens, broilers and turkeys. In Australia, PRATU (Poultry Research and Teaching Unit, www.poultryhub.org) is involved in many aspects of poultry science including nutrition and physiology, health and welfare, disease, production and environment and they have funded research projects in all these sectors. There are also other research groups all over the world (both from universities, institutes and companies) as in Germany, United Kingdom, Poland, Finland, Spain, The Netherlands, Turkey, China, Taiwan, India, Pakistan, Ukraine, Lithuania, United States, Canada, Australia, and Brazil which are doing research in these fields of activity. Unfortunately details of these projects are for the most part not publicly available currently.

CONCLUSIONS

The banning of GPA was intended mainly to protect the human population from transmissible antibiotic resistance reaching human pathogens, rendering them refractory to treatment. The benefits of the ban extend to less stress on the environment in general, for example in terms of loss of microbial diversity in soils fertilised with manure from animals receiving GPA (Opalinski et al., 1998). The main downside of the ban was the problems it presented to livestock producers, significantly poultry producers. The examples presented here demonstrate that there is a strong basis for looking to the plant kingdom for solutions to the problems, and indeed for new opportunities to benefit poultry production.

Although this is a lengthy review, it is by no means comprehensive. Plants or their bioactives have production or health benefits across a wide range of effects other than those described here, including fertility (Cerolini et al., 2005), minimising lead concentrations in meat (Hanafy et al., 1994), and relief of heat stress (Rajmane and Sonawane, 1997). We hope that the present review sets a framework for identifying some plant bioactives that hold particular promise for future research and application.

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