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Oil cakes and their biotechnological applications – A review

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Abstract

Oil cakes have been in use for feed applications to poultry, fish and swine industry. Being rich in protein, some of these have also been considered ideal for food supplementation. However, with increasing emphasis on cost reduction of industrial processes and value addition to agro-industrial residues, oil cakes could be ideal source of proteinaceous nutrients and as support matrix for various biotechnological processes. Several oil cakes, in particular edible oil cakes offer potential benefits when utilized as substrate for bioprocesses. These have been utilized for fermentative production of enzymes, antibiotics, mushrooms, etc. Biotechnological applications of oil cakes also include their usages for vitamins and antioxidants production. This review discusses various applications of oil cakes in fermentation and biotechnological processes, their value addition by implementation in feed and energy source (for the production of biogas, bio-oil) as well.

Keywords: Oil cakes; Chemical composition; Biotechnological applications; Feed source; Biogas production; Biocontrol agent

1. Introduction

There has been an increased exploitation of organic residues from various sectors of agriculture and industries over the past few decades. Crop residues such as bran, husk, bagasse, and fruit seeds are utilised as a potential raw material in bioprocesses as they provide an excellent substratum for the growth of microorganism supplying the essential nutrients to them (Pandey and Soccol, 1998, 2000; Pandey, 1994; Pandey et al., 2000a,b,c,d, 1999a; Pandey, 1992). Their application in bioprocesses also offers advantages in bioremediation and biological detoxification of hazardous compounds. Their application in the field of fermentation technology has resulted in the production of bulk-chemicals and value-added products such as amino acid, enzymes, mushrooms, organic acids, single-cell protein (SCP), biologically active secondary metabolites, etc. (Pandey, 2003; Pandey et al., 1999a,b; Soccol et al., 2005; Nampoothiri et al., 2002; Vandenberghe et al., 2000). This review focuses on the various process related to the value-addition of oil cakes (residue obtained after oil extraction) by their utilisation in bioprocesses for the production of industrial bio-products. Biotechnological applications of sunflower oil cake (SuOC), sesame oil cake (SOC), soy bean cake (SBC), coconut oil cake (COC), mustard oil cake (MOC), palm kernel cake (PKC), groundnut oil cake (GOC), cottonseed cake (CSC), canola oil cake (CaOC), olive oil cake (OOC), rapeseed cake (RSC) is emphasised in detail.

Oil cakes/oil meals are by-products obtained after oil extraction from the seeds. Oil cakes are of two types, edible

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and non-edible. Edible oil cakes have a high nutritional value; especially have protein content ranging from 15% to 50% (www.seaofindia.com). Their composition varies depending on their variety, growing condition and extraction methods. Due to their rich protein content, they are used as animal feed, especially for ruminants and fish. Non-edible oil cakes such as castor cake, karanja cake, neem cake are used as organic nitrogenous fertilizers, due to their N P K content. Some of these oil cakes are found to increase the nitrogen uptake of the plant, as they retard the nitrification of soil. They also protect the plants from soil nematodes, insects, and parasites; thereby offer great resistance to infection (www.itdgpublishing.org.uk).

Annual growth in oil cake production is projected to average 2.3% annually over the decade to 2010. India is one of the world's leading oilseeds producers. Total production currently stands at over 25 million tonnes per annum while the exports account for over 4.3 million tonnes of oil cake – valued at US$ 800 million annually (www.seaofindia.com). SBC dominates the oil cake market, and its share of production is projected to rise from 64% in the base period, to 66% by 2010. Of the total oil meal production increase of 23 million tonnes, 17 million tonnes is from developing countries including India, Brazil and Argentina.

2. Chemical composition of oil cakes

The composition and nutritional availability of oil cakes widely vary based on the quality of the seed or nuts, method of oil extraction, storage parameters, etc. The chemical composition of the oil cakes was widely studied by many authors and some of them are given in Table 1. SBC has rich amino acid profile. It is an excellent source of amino acids such as tryptophan, threonine and lysine but is deficient in methionine. SuOC has about 27% crude protein while dehulled SuOC has high protein content of 40% and fibre of 10%. The chemical composition of undehulled SuOC was studied by Bautista et al. (1990) to evaluate its biotechnological potential. SuOC can be fractionated into three main components, a lignocellulosic fraction (LCF), a proteinaceous fraction (PF) and a soluble fraction (SF), which represented 23.2–25.3%, 55.4–57.6% and 17.1–21.4% of the dry weight, respectively. After removal of the PF, the remaining sub products (LCF and SF) have a high potential for use as fermentation sources. SuOC is high in methionine, but low in lysine and threonine. RSC and CaOC have protein content of 33% and good source of amino acids but are deficient in lysine. CSC has protein content of about 40% and fibre content of 11–13%, is deficient in lysine, methionine, threonine and tryptophan. COC contains high levels of residual oil composed of short chain saturated fatty acids, is deficient in amino acids such as lysine, methionine, threonine and histidine but high in arginine. PKC has the lowest protein content among all the other oil cakes and contains high levels of galactomannans. The amino acid profile is poor and is deficient in lysine, methionine and trytophan. SOC has protein content of about 35% and nutrient composition compares favourably with SBC. The protein content of different varieties ranges from 41% to 58%. It is an excellent source of methinoine, tryptophan and cysteine, still low in lysine and threonine. The amino acid composition of SOC complements SBC. The amino acid composition of some of the oil cakes is given in Table 2. The composition of OOC is generally different from the other oil cakes. It has low crude protein and high crude fibre content. A large proportion of the proteins (80–90%) are linked to the lingo-cellulose fraction. OOC fat is high in unsaturated C16 and C18 fatty acids, which constitutes 96% of the total fatty acids (Swick, 1999).

3. Biotechnological applications of oil cake

Oil cakes have been widely used for the production of industrial enzymes, antibiotics, biopesticides, vitamins and other biochemicals. They have also been commonly used as feed supplement. Table 3 shows some important applications of oil cakes.

3.1. Production of enzymes

There are several reports describing production of various enzymes using oil cakes as substrate in solid-state fermentation (SSF), or as supplement to the production medium. Oil cakes are ideally suited nutrient support in SSF rendering both carbon and nitrogen sources, and reported to be good substrate for enzyme production using fungal species. The enzyme production could be further enhanced by optimisation of physiological and biological conditions.

Table 1
Composition of oil cakes

Oil cake	Dry matter (%)	Crude protein (%)	Crude fibre (%)	Ash (%)	Calcium (%)	Phosphorus (%)	Ref.
CaOC	90	33.9	9.7	6.2	0.79	1.06	Ewing (1997)
COC	88.8	25.2	10.8	6.0	0.08	0.67	Gohl (1970)
CSC	94.3	40.3	15.7	6.8	0.31	0.11	Friesecke (1970)
GOC	92.6	49.5	5.3	4.5	0.11	0.74	Kuo (1967)
MOC	89.8	38.5	3.5	9.9	0.05	1.11	Kuo (1967)
OOC	85.2	6.3	40.0	4.2	–	–	Maymone et al. (1961)
PKC	90.8	18.6	37	4.5	0.31	0.85	Owusu-Domefeh et al. (1970)
SOC	83.2	35.6	7.6	11.8	2.45	1.11	Kuo (1967)
SBC	84.8	47.5	5.1	6.4	0.13	0.69	Kuo (1967)
SuOC	91	34.1	13.2	6.6	0.30	1.30	Brendon (1957)

Table 2
Amino acid composition (% of crude protein) of oil cakes

Amino acids	CaOC	COC	CSC	GOC	MOC	OOC	PKC	SOC	SBC	SuOC
Arg	2.12	11.0	11.1	11.0	6.4	2.40	13.9	12.8	7.4	9.1
Cys	–	0.9	1.5	0.9	2.5	–	1.9	2.1	1.6	1.8
Gly	1.75	4.2	4.5	6.0	4.9	3.10	4.8	5.3	4.5	5.6
His	1.13	2.1	2.6	2.5	2.6	0.70	2.5	2.9	2.4	2.8
Isoleu	1.41	3.0	3.2	3.0	3.8	2.30	3.8	3.6	4.6	4.2
Leu	2.39	6.0	5.9	6.1	6.3	4.20	6.4	7.5	7.8	6.9
Lys	2.02	2.5	4.1	3.6	5.4	0.70	3.7	2.9	6.1	3.5
Met	0.77	1.0	1.3	0.4	1.7	0.20	2.7	3.1	1.4	2.2
Phenylalanine	1.54	4.1	5.4	4.9	3.8	2.70	3.6	4.3	5.5	5.1
Threonine	1.50	3.0	3.2	2.8	4.0	2.80	3.5	3.2	3.8	3.4
Tryptophan	0.46	–	1.1	–	–	–	2.8	1.4	1.3	1.4
Tyrosine	1.05	3.1	2.7	3.7	2.7	0.60	2.7	3.9	3.5	1.4
Valine	1.71	5.8	4.5	3.7	4.7	3.30	5.7	4.0	5.2	5.8
Ref.	www.canola-council.org	Owusu-Domefeh et al. (1970)	Smith (1970)	Owusu-Domefeh et al. (1970)	Miller et al. (1962)	Rupic et al. (1999)	De Vuyst (1963)	De Vuyst (1963)	Fetuga et al. (1974)	De Vuyst (1963)

Table 3
Application of oilcakes in bioprocesses yielding industrial metabolites

Oil cake	Products	Microorganism	References
	Protease	*Bacillus horikoshii*	Joo et al. (2002)
	Protease	*B. clausi* I52	Joo et al. (2003)
	Protease	*Penicillium* sp.	Germano et al. (2003)
	Protease	*Bacillus* sp. I-312	Joo and Chang (2005)
	Protease	*A. oryzae* NRRL 1808	Sandhya et al. (2005)
	Phytase	*A. ficuum*	Bogar et al. (2003)
	δ-endotoxin	*B. thuringiensis* var *kurstaki* ATCC 33679	Vidyarthi et al. (2002)
	Lipase	*P. simplicissimum*	Di Luccio et al. (2004)
COC	α-amylase	*A. oryzae*	Ramachandran et al. (2004a)
	Glucoamylase	*A. niger*	Pandey et al. (1995)
	Lipase	*Candida rugosa*	Benjamin and Pandey (1996, 1997, 1998)
	Inulinase	*Staphylococcus* sp., *Kluyveromyces marxianus*	Selvakumar and Pandey (1999)
	Phytase	*Rhizopus oligosporus*	Sabu et al. (2002)
	Phytase	*M. racemosus*	Bogar et al. (2003)
	Phytase	*R. oryzae*	Ramachandran et al. (2005)
	Protease	*A. oryzae*	Sumantha et al. (2005)
SOC	Lipase	*P. chrysogenum* S_1	Ramakrishnan and Banerjee (1952)
	L-glutaminase	*Zygosaccharomyces rouxii*	Kashyap et al. (2002)
	Phytase	*Mucor racemosus*	Bogar et al. (2003); Roopesh et al. (2006)
	Phytase	*R. oryzae*	Ramachandran et al. (2005)
PKC	Mannanse Tannase	*A. niger*	Ong et al. (2004); Sabu et al. (2005, 2006)
	α-amylase	*A. oryzae*	Ramachandran et al. (2004b)
OOC	Mushroom	*Pleurotus eryngii*, *P. pulmunaris*	Zervakis et al. (1996)
	Lipase	*Rhizomucor pusillus*, *R. rhizopodiformis*	Cordova et al. (1998)
CSC	Glucoamylase	*Thermomucor indicae-seudaticae*	Kumar and Satyanarayana (2004)
	Mushroom	*P. sajor-caju*	Bano et al. (1993); Shashirekha et al. (2002)
	Cephamycin C	*Streptomyces clavuligerus*	Kota and Sridhar (1999)
MOC	Lactic acid	*Lactobacillus casei*	Tuli et al. (1985)
	Mushroom	*P. sajor-caju*	Bano et al. (1993); Shashirekha et al. (2002)
GOC	α-amylase	*A. oryzae*	Ramachandran et al. (2004)
CaOC	Phytase	*A. ficuum*	Ebune et al. (1995a,b)
SuOC	α-amylase	*B. licheniformis*	Haq et al. (2003)
	Cephamycin C	*S. clavuligerus*	Kota and Sridhar (1999); Sarada and Sridhar (1998)
	Clavulanic acid	*S. clavuligerus*	Sircar et al. (1998)
	Mushroom	*P. sajor-caju*	Bano et al. (1993); Shashirekha et al. (2002)

Lipase (Benjamin and Pandey, 1996), α-amylase (Ramachandran et al., 2004a,b), phytase (Sabu et al., 2002; Bogar et al., 2003; Ramachandran et al., 2005; Roopesh et al., 2006), protease (Sandhya et al., 2005; Sumantha et al., 2005) and glutaminase (Kashyap et al., 2002) are some of the enzymes produced using oil cakes as nutrient source.

Lipase production has been among the earliest reports describing use of oil cakes since 1950s using fungal strains of *Penicillium* sp., especially *P. chrysogenum* S_1 isolated from molds growing in sesame. The strains when grown in SOC medium containing 10% sesame oil showed an appreciable amount of lipolytic activity (Ramakrishnan and Banerjee, 1952). COC extract was evaluated for its efficacy as substrate for the production of lipase using *Candida rugosa*. Raw extract supported the growth with comparatively less lipase activity (Benjamin and Pandey, 1996). Lipase production was also studied with *Aspergillus niger* using gingelly oil cake (Kamini et al., 1998), OOC (Cordova et al., 1998). The thermostable fungal cultures of *Rhizomucor pusillus* and *Rhizopus rhizopodiformis* showed appreciable lipase activity (Cordova et al., 1998). Babassu oil cake was used for growth and lipase production in SSF by a Brazilian strain of *P. restrictum* (Gombert et al., 1999; Gutarra et al., 2005). Emtiazi et al. (2003) studied extracellular lipase production by *Pseudomonas* strain X using CSC. Maximum production of lipase was obtained on CSC (400 U/ml) in 50 h. Addition of olive oil to pre-culture induced maximum lipase production in 24 h. Sunflower oil induced lipase production by 540 U/ml and the maximum lipase activity was observed at 60 °C (1200 U/ml) and at pH 8 (Emtiazi et al., 2003). Another bacterial strain, *Bacillus mycoides* was identified as lipase producer on COC. The growth of the organism and lipase production was maximum after 72 h of incubation under shaking. Olive oil and beef extract were best carbon and nitrogen sources. Na^+ induced more lipase than K^+ and Mg^{2+} (Thomas et al., 2003). Production of lipases by *Penicillium simplicissimum* was studied in SSF using SBC as substrate (Di Luccio et al., 2004). The enriched samples from different oil seed cakes for the isolation of lipolytic fungi by tributyrin agar clearing method and subsequently by cultivating the selected isolates under submerged fermentation conditions and assaying for their extracellular lipase producing capabilities led to identification of a *Rhizopus* sp. designated as *Rhizopus* sp. BTS-24. Gingelly oil cake was used as a carbon source with optimal lipase production under the initial pH of 5.0, incubation time of 72 h, incubation temperature of 28 °C, volume of the medium to volume of the flask ratio of 1:5 and agitation speed of 100 rpm (Bapiraju et al., 2004).

Oil cakes such as COC, SOC, PKC, GOC, CSC and OOC were reported as substrates for phytase production in SSF using three strains of *Rhizopus* spp., namely *R. oligosporus* NRRL 5905, *R. oryzae* NRRL 1891 and *R. oryzae* NRRL 3562. Mixed substrate fermentation using COC and SOC resulted more than two-fold increase in phytase production under optimised conditions (64 U/gds phytase) in comparison to the use of COC and SOC individually (Ramachandran et al., 2005). Phytase production has also been reported with SOC and GOC with *Mucor racemosus* NRRL 1994. At optimised conditions phytase production reached 44.5 U/gds when combination of SOC and wheat bran was used which was almost 4-fold higher than that obtained from wheat bran (Roopesh et al., 2006). CaOC was studied for phytase production with *Aspergillus ficuum* in a SSF process. Lower concentrations of phosphorus favoured the production of the enzyme. Compared with the control, Tween-80 and sodium oleate increased the rates of phytase production and hydrolysis of phytic acid, while Triton X-100 had a negative effect on these processes (Ebune et al., 1995a). Similarly, effects of moisture content of media, inoculum age and homogenization on production of phytase and reduction of phytic acid content in CaOC by *A. ficuum* NRRL 3135 during static SSF were investigated. Optimum moisture content of media for these processes was 64%. Rate of phytase production increased with an increase in inoculum age between 2 and 5 days (Ebune et al., 1995b). COC was used for phytase production with *R. oligosporus* with maximum enzyme production (14.29 U/g of dry substrate) occurring at pH 5.3, 30 °C, and 54.5% moisture after 96 h of incubation. The addition of extra nutrients to the substrate resulted in inhibition of product formation (Sabu et al., 2002). Similarly, phytase production has also been reported using CaOC and COC along with wheat bran using three *Mucor* and eight *Rhizopus* strains. *M. racemosus* gave the highest activity (14.5 IU/g dry matter phytase activity) on COC. The optimised supplementation of COC with glucose, casein and $(NH_4)_2SO_4$ led to increase in phytase production to 26 U/g dry matter. Similarly, using optimised medium phytase, α-amylase and lipase production of *M. racemosus* was compared in solid-state fermentation and in shake flask (SF) fermentation (Bogar et al., 2003).

An extra-cellular alkaline protease was produced by a bacterial strain of *Bacillus* sp. AR-009 when grown on nug meal (a by product of oil extraction from *Guizotia abyssinica* seeds) as the sole nitrogen source. The enzyme had an optimum pH of 9.5–11.5 and was stable in the pH range of 5–12. Its optimum temperature was 55 °C in the absence of calcium and 65 °C in the presence of calcium (Gessesse, 1997). *Bacillus horikoshii* producing an extra-cellular alkaline protease showed maximum enzyme activity when grown in SBC (1.5%, w/v) and casein (1%, w/v) at pH 9.0 and 34 °C over 16–18 h incubation period. The enzyme had an optimum pH of around 9 and maintained its stability over a broad pH range between 5.5 and 12 (Joo et al., 2002). Similarly, an oxidative and SDS-stable alkaline protease was produced by *Bacillus clausii* and maximum activity was observed in a medium containing (g/l): SBC, 15; wheat flour, 10; liquid maltose, 25; K_2HPO_4, 4; Na_2HPO_4, 1; $MgSO_4 \cdot 7H_2O$, 0.1; Na_2CO_3, 6. The enzyme had an optimum pH of around 11 and optimum temperature of 60 °C. The alkaline protease showed extreme stability towards SDS and oxidizing agents but was inhibited by PMSF (Joo et al., 2003). Also, protease production by a wild strain of *Penicillium* sp. in SSF was reported using defatted SBC as carbon and nitrogen source and solid matrix for SSF (Germano et al., 2003). The suitability of several oil cakes such as COC, PKC, SOC, OOC were evaluated for neutral protease production along with several agro-industrial residues such as wheat bran, rice husk, rice bran, spent brewing grain (Sandhya et al., 2005). While, COC in combination with wheat bran was used for production of neutral metalloprotease by *A. oryzae* NRRL 2217 (Sumantha et al., 2005).

Ramachandran et al. (2004a) evaluated several oil cakes for the production of alpha amylase using *A. oryzae*. Best results (1827 IU alpha amylase/gds) were obtained when COC was used as a substrate in SSF. Mixed solid substrate fermentation resulted in improved enzyme titres and maximum amount of enzyme (9196 U/gds) was obtained when SSF was carried out using combination of wheat bran and GOC (Ramachandran et al., 2004b). COC was also used for production of glucoamylase enzyme by *A. niger* NCIM 1245 and under optimised conditions enzyme units as high as 194 IU/g dry fermented substrate were produced when fermentation was carried out for 96 h at 30 + 1 °C with an initial substrate pH and moisture of 4.5–4.7 and 65%, respectively. Addition of inorganic nitrogen enhanced the enzyme yields without affecting dry matter loss significantly (Pandey et al., 1995). A thermophilic mould *Thermomucor indicae-seudaticae* was used for the production of a thermostable and neutral glucoamylase in SSF. The mold produced the enzyme optimally at 40 °C and pH 7, when grown in a medium supplemented with 2% CSC (Kumar and Satyanarayana, 2004).

CaOC has been used as a substrate for xylanase production by *Trichoderma reesi*. The results suggested xylanase yields were better in CaOC than from Solka-floc, xylan or glucose. Maximum xylanase activity obtained from CaOC was 210 IU/ml in 9–12 days. The enzyme system produced using CaOC also contained a higher proportion of acetyl–xylan esterase, cellulase, and xylosidase activities. This system was more than or equally efficient as that produced using Solka-floc in hydrolysing CaOC, corn cobs, corn and wheat bran, straw, and larchwood xylan to fermentable sugars (Gattinger et al., 1990).

Selvakumar and Pandey (1999) used COC for the production of inulinase enzyme in SSF using *Staphylococcus* sp. RRL-1 and *Kluyveromyces marxianus*.

Federici et al. (1988) reported pectinolytic enzyme by *Cryptococcus albidus* var. *albidus* IMAT-4735 using suitably treated olive vegetation waters. Enzyme production was favoured by increasing concentrations of SuOC in the medium. The enzyme was characterized as an endopolygalacturonase with considerable potential technological interest.

Salinity tolerant yeast *Zygosaccharomyces rouxii* NRRL-Y 2547 was used for extra-cellular glutaminase production using wheat bran and SOC (Kashyap et al., 2002).

PKC has been reported for the production of tannase in SSF using *A. niger* ATCC 16620 (Sabu et al., 2005; Sabu et al., 2006). Palm oil cake and PKC have been utilized for various enzyme production by *A. niger* ATCC 6275 (Prasertsan et al., 1997; Ong et al., 2004).

3.2. Production of mushroom

The supplementation of oil cakes (MOC, SuOC, CSC, and SBC) with rice straw substrate colonized by the mushroom, *Pleurotus sajor-caju* increased the mushroom yields between 50% and 100%, compared to the unsupplemented substrate. Oil cake supplementation also affected an increase in the solubility of the rice straw substrate; there was an increase in the contents of free sugars and amino acids, and a decrease in cellulo–hemicellulosics (Bano et al., 1993). The effect of supplementing spent rice straw substrate with extra organic nitrogen (in the form of oil cakes) was studied for production of mushroom *Pleurotus sajor-caju*. Their chemistry and the increase in the in vitro dry matter digestibility of rice straw were also investigated. CSC proved to be better in enhancing the mushroom yields (up to 12 times to those of unsupplemented spent straw, than the other oil seed cakes. CSC supplemented mushrooms showed increased protein, fat and decreased carbohydrate contents. Also, there was a significant reduction in the spawn run period (Shashirekha et al., 2002).

OOC was tested for the cultivation of *Pleurotus* to colonize on olive press-cake supplemented with various dilutions of raw olive mill wastewater and cultural characters such as earliness, yield, biological efficiencies and quality of basidiomata were estimated (Zervakis et al., 1996).

3.3. Production of antibiotics and biopesticides

Oil cakes have also been reported for use in production of antibiotics and antimicrobials. Arun and Dharmalingam (1999) reported evaluation of alternative media constituents like carbon sources and buffers for the large-scale production of daunorubicin. *Streptomyces peucetius* cultivated on the media containing SOC as carbon source with HEPES or phosphate buffer showed good yield of the antibiotic, and the intermediates were also converted into the final product more efficiently. Use of SuOC, SBC and SOC has been reported for production of clavulanic acid (Sircar et al., 1998). Sarada and Sridhar (1998) used SuOC for the production of cephamycin C. The cephamycin production has also been reported in medium containing deoiled CSC along with SuOC (Kota and Sridhar, 1999). Bacitracin biosynthesis was reported in SSF using media containing defatted oil cakes (SBC, SuOC) by *Bacillus licheniformis* (Farzana et al., 2005). Vidyarthi et al. (2002) studied the growth and δ-endotoxin yield of *Bacillus thuringiensis* (Bt) subsp kurstaki in tryptic soy yeast extract (TSY) medium, SOC based commercial medium and waste water sludge medium. The viable spore count in sludge medium was comparable to that obtained in laboratory and commercial media.

3.4. Production of other biochemicals

Mould strains were used to grow on oil seeds in 1950s to synthesize thiamine (in Czapek liquid medium). It was also observed that GOC was a good medium for growth on a large scale (Srinivasan and Ramakrishnan, 1952). Tuli et al. (1985) observed that supplementation of Mg^{2+} (1 mM) and MOC (6%) in the whey permeate medium improved lactic acid production ability of the immobilized cells. The lactic acid conversion of substrate without supplementation was 90% (Tuli et al., 1985). *Bacillus circulans* strain YUS-2 was reported as strongest antioxidant-producer in fermentation of SOC. Two major strong antioxidants from fermented SOC were purified and identified as known sesaminol triglucoside and sesaminol diglucoside, however, their results also demonstrated that the fermentation process with *B. circulans* YUS-2 was highly effective to gain the extraction efficiency of the sesaminol glucosides (Ohtsuki et al., 2003).

4. Other applications

4.1. As growth supplement for nematodes

The media containing linseed oil-cake agar, mustard oil-cake agar, neem oil-cake agar, beef extract agar, Emerson agar and YPSS agar were used for growing an endoparasite of nematodes. In general, maximum radial growth of most of the isolates was recorded on linseed oil-cake agar medium, whereas neem oil-cake agar medium supported least growth of all the isolates of *C. anguillulae*. Linseed oil-cake agar medium also maintained the typical characters of the fungus and clear visibility of morphological details (Gupta et al., 2005).

4.2. Preparation of protein hydrolysate

Oil cakes such as SOC and MOC have also been used as substitutes for animal protein hydrolysates, used in the treatment of protein malnutrition. Growth experiments with rats indicated that the product was comparable to commercial casein (Krishnamurti, 1965). Amino acid profile of SOC and MOC (Table 2) shows them to be rich in leucine, phenylalanine, arginine and glycine. Also, dry matter analysis shows presence of high crude protein content indicating their suitability as protein supplements.

4.3. As feed source

The effect of feeding different levels of SOC on the intake and digestibility of crude protein, crude fibre, and crude fat in Awassi fattening lambs were studied and it was observed that SOC resulted in more daily gain and better feed conversion efficiency compared to control (Omar, 2002). GOC was replaced with MOC in feed to evaluate its effect on the growth performance of growing lambs. The study suggested GOC could completely be replaced with MOC without affecting feed intake, feed efficiency, nitrogen balance, mineral balance and growth performance of growing lambs (Anil Kumar et al., 2002). The influence of various level of PKC fermented by *Trichoderma harzianum* in ration on local duck physiological organs was studied and the results showed that 25% fermented PKC in ration had highly significant influence on liver, pancreas, kidney and heart (Yellita et al., 2001).

The efficiency of various alternative protein sources as partial or complete dietary replacements for fish meal has been evaluated in fish diets, such as RSC (Higgs et al., 1979). MOC, SOC and linseed cake were used as dietary protein sources for the common carp fingerlings (Hossain and Jauncey, 1989). Nevertheless, many of these ingredients have been used as dietary protein sources for other fish species, i.e. linseed cake (Hasan et al., 1989, 1991), MOC (Hasan et al., 1991) GOC (Wu and Jan, 1977; Jackson et al., 1982) and SOC (Hasan et al., 1991). MOC, SOC, COC were studied as a substitute for fish meal protein up to a maximum of 75% of the total protein content of the common carp fry. The histopathological examination of liver revealed higher levels of intracellular lipid deposition in fish fed diet containing MOC (Hasan et al., 1997).

4.4. As energy source

The effect of the incorporation of various wastes with castor cake in relation to biogas generation and digester microbiological activities have been studied and it was observed that with proper C:N ratio adjustments, various types of wastes along with castor cake, could profitably be employed for maximum microbiological activity and gas output (Lingaiah and Rajasekaran, 1986). Effect of particle size, temperature, loading rate and stirring on biogas production from oil-expelled castor cake was studied in 5-L capacity single-stage fermentors protected from light at 30 and 37 °C (Gollakota and Meher, 1988).

OOC combustion in a fluidized bed combustor was studied and cold-flow tests included investigations of the effects of particle-size distribution, fluidization velocity, and bed height (Abu-Qudais, 1996). Similarly, a bench scale model to prepare intact samples was designed and fabricated. Proximate analysis indicated that OOC has an excellent potential to be a renewable source of energy. Moreover, the calorific values of OOC and oil shale mixtures, to catalyse oil shale combustion, were also studied (Alkhamis and Kablan, 1999). Similarly, OOC co-firing with coal in a circulating fluidized bed and combustion experiment results suggested that OOC is good fuel that can be mixed with lignite coal for cleaner energy production in small-scale industries by using CFB (Atimtay and Topal, 2004).

Studies have also been conducted to investigate the effect of the water vapour on the structure of the products obtained by low temperature thermal destruction of CSC at atmospheric pressure. For structural analysis, the pyrolysis oils and aromatic and polar subfractions were conducted using FTIR and ^{1}H NMR spectra (Ozbay et al., 2001a). Also, the flash pyrolysis experiments of sunflower SuOC in a tubular transport reactor at atmospheric pressure under nitrogen atmosphere and chemical characterization of products showed that the oil obtained from SuOC can be used as a renewable fuel and chemical feedstock

(Yorgun et al., 2001). Similarly, the fixed-bed pyrolysis experiments on CSC to determine the possibility of being a potential source of renewable fuels and chemical feedstock, in two different reactors, namely a tubular and a Heinze retort were conducted and effect of pyrolysis atmosphere and pyrolysis temperature on the pyrolysis product yields and chemical composition were investigated. The maximum oil yield of 29.68% was obtained in N_2 atmosphere at a pyrolysis temperature of 550 °C with a heating rate of 7 °C min^{-1} in a tubular reactor (Ozbay et al., 2001b). The slow pyrolysis of SBC in a fixed-bed reactor under three different atmospheres for determining the effects of pyrolysis temperature and particle size, nitrogen and steam showed that the fractions were quite similar to currently utilized transport fuels (Putun et al., 2002). Similarly, SuOC pyrolysis experiments conducted in a fixed-bed tubular reactor and the effects of nitrogen flow rate and final pyrolysis temperature on the pyrolysis product yields and chemical compositions showed that the oil obtained from SuOC can be used as a renewable fuel and chemical feedstock. The production of bio-oil and bio char was also studied from RSC obtained by cold extraction pressing revealed that bio char obtained were carbon rich, with high heating value and relatively pollution-free potential solid bio fuel. The bio-oil product was presented as an environmentally friendly green bio fuel candidate (Ozçimen and Karaosmanoglu, 2004).

4.5. As bio-control agent

The efficacy of oil-seed cakes of neem, castor, mustard and duan against plant-parasitic nematodes and soil-inhabiting fungi infesting mungbean and the subsequent crop, chickpea were investigated. The population of plant-parasitic nematodes, *Meloidogyne incognita*, *Rotylenchulus reniformis*, *Tylenchorhynchus brassicae*, *Helicotylenchus indicus*, etc., and the frequency of the pathogenic fungi *Macrophomina phaseolina*, *Rhizoctonia solani*, *Phyllosticta phaseolina*, *Fusarium oxysporum* f. *ciceri*, etc., were significantly reduced by these treatments, but the frequency of saprophytic fungi was increased (Tiyagi and Mashkoor Alam, 1995).

Oil cakes in combination with *Bradyrhizobium* sp. and *Paecilomyces lilacinus* have been studied for control of root rot of mungbean (Ehteshamul-Haque et al., 1995). Khan and Saxena (1997) reported improvement in tomato plant growth with reduced nematode growth in neem cake amended soil. Similar study using some nematicides (aldicarb, carbofuran, ethoprop) along with oil cakes (linseed, mustard, neem) against *Pratylenchus thornei* infesting *Mentha citrata*, *M. piperita* and *M. spicata* in glasshouse experiments has been reported (Shukla and Haseeb, 1996). Also, use of oil cakes of neem, castor and mahua independently and in combination with a chemical nematicide (carbofuran 3G) for the management of *Pratylenchus delattrei* in crossandra under glass house conditions has been reported. Neem oil cake was effective compared to other oil cakes used and there was a synergistic effect when the neem cake was coupled with carbofuran 3G in the management of *P. delattrei* (Jothi et al., 2004).

Oil cakes in combination with 35% wheat bran, 20% MOC, 25% cow dung and 20% fine sand were reported for tubificid worms production in a culvert system under running water. New offspring appeared after 20 days from the start of the experiment, and 2.85 g raw materials produced 1.0 g of worms (Ahamed and Mollah, 1992).

5. Conclusions

Oil cakes are rich in fibre, protein and energy contents. They offer potential benefits when used as substrates in developing bioprocesses for the production of organic chemicals and biomolecules. Studies using them for the production of industrial enzymes have shown promising results. Mixed substrate fermentation has been more advantageous for such applications. While edible oil cakes are used as feed source and protein hydrolysate, some of the non-edible cakes find its application as biocontrol agents. Also, use of oil cakes offers good alternative to traditional applications by their exploitation in the production of environmentally friendly green bio fuel. Another key point to be noted is that the bioprocess utilising oil cakes is attractive due to relatively cheaper availability of the oil cakes throughout the year, making it even more favourable when economics is considered.

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