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Review

Personalized Medicine of Omega-3 Fatty Acids in Depression Treatment in Obese and Metabolically Dysregulated Patients

Suet-Kei Wu ^{1,2,†}, Wei-Jen Chen ^{3,†}, Jane Pei-Cheng Chang ^{2,4,5}, Ta-Wei Guu ^{2,6}, Ming-Che Hsin ⁷, Chih-Kun Huang ⁷, David Mischoulon ⁸, Lucile Capuron ⁹ and Kuan-Pin Su ^{2,3,4,5,*}

¹ Graduate Institute of Nutrition, China Medical University, Taichung 404, Taiwan; wskei23@gmail.com

² Mind-Body Interface Research Center (MBI-Lab), China Medical University Hospital, Taichung 404, Taiwan; peko80@gmail.com (J.P.-C.C.); da20vid@gmail.com (T.-W.G.)

³ An-Nan Hospital, China Medical University, Tainan 709, Taiwan; yizingch@gmail.com

⁴ Department of Psychiatry, China Medical University Hospital, Taichung 404, Taiwan

⁵ College of Medicine, China Medical University, Taichung 404, Taiwan

⁶ Division of Psychiatry, Department of Internal Medicine, China Medical University Beigang Hospital, Yunlin, Taiwan

⁷ Body Science & Metabolic Disorders International Medical Centre (BMIMC), China Medical University & Hospital, Taichung 404, Taiwan; matthsin@gmail.com (M.-C.H.); dr.ckhuang@hotmail.com (C.-K.H.)

⁸ Depression Clinical and Research Program, Massachusetts General Hospital, Harvard Medical Scholl, Boston, MA, USA; dmischoulon@partners.org

⁹ University of Bordeaux, INRAE, Bordeaux INP, NutriNeuro, UMR 1286, Bordeaux, France; lucile.capuron@bordeaux.inra.fr

* Correspondence: cobol@cmu.edu.tw

† Equal contribution as first authors.

Abstract: The co-occurrence of depression and obesity has become a significant public health concern worldwide. Recent studies have shown that metabolic dysfunction, which is commonly observed in obese individuals and characterized by inflammation, insulin resistance, leptin resistance, and hypertension, is a critical risk factor for depression. This dysfunction may induce structural and functional changes in the brain, ultimately contributing to depression's development. Given that obesity and depression mutually increase each other's risk of development by 50-60%, there is a need for effective interventions that address both conditions. The comorbidity of depression with obesity and metabolic dysregulation is thought to be related to chronic low-grade inflammation, characterized by increased circulating levels of pro-inflammatory cytokines, and C-reactive protein (CRP). As pharmacotherapy fails in at least 30-40% of cases to adequately treat major depressive disorder, a nutritional approach is emerging as a promising alternative. Omega-3 polyunsaturated fatty acids (n-3 PUFAs) are a promising dietary intervention that can reduce inflammatory biomarkers, particularly in patients with high levels of inflammation, including pregnant women with gestational diabetes, patients with type 2 diabetes mellitus, and overweight individuals with major depressive disorder. Further effort directed to implement these strategies in clinical practice could contribute to improved outcomes in patients with depression and comorbid obesity and/or metabolic dysregulation.

Keywords: omega-3 polyunsaturated fatty acids (n-3 PUFAs); major depressive disorder (MDD); obesity; metabolic dysregulation; comorbidities

1. Introduction

Depression and obesity have emerged as significant public health concerns due to their increasing prevalence. Before 2020, depression impacted about 280 million people globally [1], but the COVID-19 pandemic has worsened the situation, leading to an increase of about 53.2 million new

cases of major depressive disorder (MDD) and an overall prevalence of 3152.9 cases per 100,000 population [2]. MDD can affect individuals of any age, ethnicity, causing severe individual and socioeconomic consequences [3,4]. Women have a higher risk of developing MDD compared to men [4,5] and adolescents, especially girls and young women, experience a significant increase in the prevalence of depression, self-harm, suicide, and overall [6]. MDD not only impacts mental health, but also has significant effects on physical health, functional abilities, workplace productivity, and economic burden [7–9]. The economic burden includes the costs of medical treatments, which may not always effectively manage depression or its complications [8,10].

Depression is notorious for being a risk factor for metabolic dysfunction associated with obesity, including inflammatory response, high blood pressure, impaired insulin sensitivity and impaired leptin sensitivity [11]. This association suggests a bidirectional relationship between depression and metabolic dysfunction, with each condition increasing the progressive risk of each other by 50-60% [12]. Metabolic abnormalities related to inflammation, commonly observed in individuals with obesity, may play a vital neurobiological role in the onset of depression beyond the influence obesity alone [13–15]. Obese adults have a 14-34% higher risk of clinically diagnosed MDD compared to non-obese controls, while obese adolescents have a 40% increased risk of developing depression [16–18]. The combined impact of MDD and obesity on quality of life is greater than their independent effects, suggesting a synergistic relationship between these conditions [19].

Current pharmacotherapy for MDD is often inadequate due to the heterogeneity of patients under the existing diagnostic system. As a result, there is a growing interest in nutritional approaches, such as omega-3 polyunsaturated fatty acids (n-3 PUFA) supplementation, as a potential alternative for treating MDD. A recent practice guideline published by Guu et al. (2019) recommends considering n-3 PUFAs as a possible therapeutic option for MDD based on their beneficial effects on inflammation and mood, and in lowering the likelihood of developing MDD in specific populations, including women with perinatal MDD, children, and the elderly [20–25]. Recent studies have also investigated the effect of n-3 PUFAs on individuals with high inflammation, including MDD patients (Mischoulon et al., 2022; Rapaport et al., 2016), patients with MDD and comorbid type 2 diabetes mellitus [24,26] or who are overweight/obese [27].

2. MDD, Stress and Neuropsychimmunity

MDD is a leading cause of global disability [28] and is diagnosed according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) criteria, with symptoms that may vary between individuals. One pathophysiological mechanism of MDD is attributed to the neuroendocrine theory of abnormal homeostasis of the hypothalamus-pituitary-adrenal (HPA) axis, characterized by excessive activation of the stress hormone cortisol [29]. Acute and severe forms of MDD have been associated with an increased cortisol response to stress, whereas mild or atypical types of MDD may not display the same cortisol response [30].

In addition to cortisol, adipokines such as leptin and adiponectin, have also been proposed to play significant roles in MDD. Leptin can activate PI3K/Akt and MAPK/Akt pathways that inhibit GSK3 β activities and elevate β -catenin signaling Akt signaling pathway [31], besides activate hypothalamic brain-derived neurotrophic factor (BDNF)-expressing neurons to induce neuroprotection [32]. Leptin levels are lower in male patients with MDD but higher in those with BMI \geq 25 and aged 40 and above [33]. Adiponectin has receptors in the brain and can cross the blood-brain barrier. Its pathways promote neurogenesis [34], spinogenesis, dendritic complexity [35] and synaptic plasticity modulation [36], suggesting it could result in antidepressant responses [37,38].

The neuroimmune hypothesis posits that inflammatory may have a role in MDD as evidenced by elevated levels of markers of inflammation and oxidative stress, including interleukin-6 (IL-6), interleukin-17 (IL-17), interleukin-21 (IL-21), interleukin-35 (IL-35), tumour necrosis factor-alpha (TNF- α), 8-hydroxy-2'-deoxyguanosine (8-OHdG), and F2-isoprostanes in individuals with MDD [39,40]. Clinical findings indicating that cytokine administration leads to the development of MDD in 40-50% of patients [41–44]. Furthermore, chronic neuroinflammation, specifically interleukin-1 β (IL-1 β) and interferon- α (IFN α) can result in structural, connectivity, and excitability changes in the

brain [45]. Notably, chronic systemic inflammation has been identified as a major contributor to neuropsychiatric symptoms in obese individuals, irrespective of depressive history [46].

The classical antidepressant hypothesis, known as the monoamine theory uses monoamine oxidase inhibitors (MAOIs) and selective serotonin reuptake inhibitors (SSRIs) to restore low monoamine levels in the brain [47], while serotonin and norepinephrine reuptake inhibitors (SNRIs) are also used to treat MDD [48] but individual response varies significantly. Long-term follow-up studies have identified a higher risk of weight gain in individuals prescribed antidepressants, highlighting the need for personalized treatment approaches that consider an individual's BMI or adiposity [49]. Studies have shown that different medications may be more effective for individuals with different levels of obesity, with escitalopram being more effective for individuals with normal BMI, venlafaxine for those with obesity class II and III, and bupropion-SSRIs for those with obesity class III (BMI \geq 40 kg/m²) [50,51]. However, morbid obesity (BMI \geq 40 kg/m²) may complicate the drug response outcomes [52], suggesting the need for personalized treatment approaches.

Despite advances in MDD treatment, approximately 30% failed to achieve adequate clinical response [53], while higher BMI has been associated with poorer treatment outcomes [54,55] and increased side effects leading to lower compliance [56,57]. These individual factors, including BMI and adiposity, highlight the need to improve tolerability and efficacy, with an understanding of the complex interplay between neuroendocrine, adipokine, and neuroimmune factors and the role of BMI in treatment response being crucial for advancing personalized therapeutic approaches in clinical practice.

3. The Interplay between Depression, Obesity and Metabolic Dysregulation

Obesity, characterized by excessive accumulation of adipose tissue in the body, which affects over one billion worldwide is a significant global health issue associated an increased risk of ischemic heart disease, type 2 diabetes, and certain cancers cases [58]. Body mass index (BMI) is commonly used to diagnose obesity. However, the application of international BMI criteria to Asian and Pacific populations has been controversial, leading to the development of regional criteria. This underscores the importance of considering population-specific factors, as body composition and adipose tissue distribution can vary across different ethnicities.

Obesity-induced inflammation, characterized by inflammatory processes in adipose tissue, has been linked to mood symptoms associated with obesity [59–61]. Chronic inflammation caused by enlarged adipocytes and disruption of adipose tissue function, triggering local and systemic inflammation [62], which is closely associated with metabolic syndrome and damage to various organ systems [63]. Furthermore, immune challenges can activate adipose tissue hypertrophy, inflammation, macrophage infiltration, and secretion of pro-inflammatory cytokines such as leptin, interleukin-6 (IL-6), tumor necrosis factor (TNF- α), and plasminogen activator inhibitor-1 (PAI-1) [64–66], leading to inflammation in the brain and potentially triggering depression [45].

Obesity and MDD share common mechanisms such as dysregulation of glucose and lipid metabolism, persistent inflammation, and excessive stimulation of the HPA axis (Lee et al., 2016; Milaneschi et al., 2019). Cortisol has been shown to increase appetite and promote the consumption of high-calorie foods, potentially contribute to weight gain and obesity development [17]. Chronic exposure to elevated cortisol levels can lead to structural changes in brain areas, such as the hippocampus, potentially contributing to cognitive deficits commonly seen in patients with MDD [67]. Furthermore, individuals with MDD have been found to exhibit altered cortisol circadian rhythms and blunted cortisol responses to stress, which may be related to HPA axis dysregulation and elevated cortisol levels [67]. Additionally, certain antidepressant medications used to treat MDD may exacerbate obesity through side effects related to weight gain and changes in appetite [68,69].

Leptin resistance is linked to obesity and its associated metabolic imbalances [70]. Adiponectin may have a protective role against the development of metabolic dysregulations [71–73]. Adiponectin levels may fluctuate in individuals with MDD and are influenced by factors such as gender [74] and depression severity [75]. Research has also found interleukin-6 (IL-6) increases and expression of adiponectin (ADIPOQ), declined in adipose tissue of depressed patients compared to non-depressed

individuals [76]. The severity of depression and adiponectin levels may be correlated, suggesting possible direct involvement in the pathogenesis of depression or the presence of coexisting metabolic disturbances [77].

In addition, the gut microbiota plays a significant role in regulating various physiological processes that affect both obesity and MDD [78]. An imbalance in the microbial community, known as gut dysbiosis, has been implicated as a significant factor in the development of both conditions. "Leaky gut" is associated with increased intestinal permeability has been linked to both inflammatory bowel disorder (IBD) and MDD, particularly in patients with lower levels of beneficial bacteria such as *Bifidobacterium* and *Lactobacillus* [79–81]. The abundance of *Bacteroidetes* and *Firmicutes* have been proposed as biomarkers of obesity and linked to IBD [80], their ratio is significantly elevated in individuals who were overweight or obese [82]. N-3 PUFAs derived from flaxseed [83] and fish oil [84] have been shown to lower the their populations. These anaerobic bacteria ferment fibre and produce short-chain fatty acids (SCFA), which are essential metabolites in maintain intestinal homeostasis, regulating immune function, and systemic effects on metabolism and cardiovascular health [85]. In addition, elevated intestinal fatty acid binding protein (I-FABP) levels have been observed in patients with recent suicide attempts and are positively correlated with the severity of depressive symptoms [86] while distinct blood microbiome and metabolomic signatures have been observed in depressed patients following antidepressants treatment [87].

4. Personalized Omega-3 Polyunsaturated Fatty Acids (n-3 PUFAs) Intervention in Depression

Low levels of n-3 PUFAs, including EPA and DHA, have been observed in depressed patients [88,89], particularly those who do not respond to antidepressant [90]. N-3 PUFAs have been identified as potential therapeutic agents for depression due to their numerous beneficial effects including anti-neuroinflammatory, anti-oxidative stress, anti-neurodegeneration and modulation of neurotransmitter system [91]. Furthermore, supplementation with these fatty acids in the form of fish oil has been found to be comparable to commonly used antidepressant drugs [92,93]. Therefore, supplementation of these fatty acids to maintain adequate level of n-3 PUFAs in the body is crucial.

Mehdi et al. demonstrated the use of omega-3 as adjunct therapy to reduce the severity of depression [5]. Current recommendations suggest using pure EPA or EPA-DHA combination as adjunctive therapy for depression, at 1-2 g/day for at least 8 weeks [23]. These findings suggests that supplementation of PUFAs, may be a potential alternative approach for managing MDD, notably in pregnant women [20,94–96], children and elderly. A recent meta-analysis demonstrated that n-3 PUFAs have a positive antidepressant effect in MDD patients, with an effect size of 0.4 [97]. It is noteworthy that greater dosage of at least 60% EPA in the intervention group and an increased likelihood of achieving a positive antidepressant response [97]. The effectiveness of EPA supplementation appears to be higher when taken at a dosage of 4 g/day [27,98]. Additionally, Tu et al. investigated the effectiveness of EPA and DHA efficacy using functional magnetic resonance imaging (fMRI), observing elevated brain activity in emotion perception and cognitive control regions [99]. However, the efficacy of n-3 PUFAs may vary depending on presence of comorbidities in depressed individuals [100], highlighting the need for personalized treatment strategies tailored to each patient's unique needs and symptoms.

Individual's biological characteristics and safety concerns should be considered when personalizing nutritional approaches for the management of MDD. Depressed patients often have co-existing inflammatory conditions, neurodegenerative diseases, or physiological deficits (see Table 1). N-3 PUFAs have shown effectiveness in improving depressive symptoms, especially in those with inflammation. For instance, depression is a common occurrence in patient with hepatitis C who receive interferon (IFN)- α therapy. However, it was found that EPA, but not DHA, significantly impact in reducing the occurrence of IFN- α depression among patient undergoing the therapy [101]. It also indicating that supplementation n-3 PUFAs highly effective in improving depression, with better clinical effect in pure EPA and EPA-major groups compared to DHA-major groups [102], particularly in individuals with high inflammatory status. Omega-3 indices were found to improve cognitive depressive symptoms in depressed patients with chronic heart failure [103]. Furthermore,

the effectiveness of n-3 PUFAs supplementation in depressed patient with comorbid cardiovascular disease was found to be dependent on depression severity. Specifically, n-3 PUFAs supplementation (2g EPA and 1 g DHA daily) only led to improvement in core depression symptoms among patient with very severe MDD when the treatment was stratified based on depression severity [104].

Table 1. Personalized medicine of omega-3 fatty acids in depression based on two major clinical considerations.

	Population	Study Design	Intervention	Main Findings	References	
Biological specificity	i. Depression associated with Inflammation					
	IFN-induced depression	n=152, HCV patients	Double blind, RCT	2-weeks treatment with EPA (3.5 g/day) (n=50); DHA (1.75 g/day) (n=51); placebo (n=50)	EPA-treated, not DHA-treated significantly decreased the incidence of IFN- α -induced depression in HCV patient (10%, 28% respectively compared to 30% placebo, p=0.037).	[101]
	Cardiovascular disease comorbidity	n=59, CVDs patients comorbid MDD	RCT	2-weeks treatment with n-3 PUFAs (EPA 2.0 g/day & DHA 1.0 g/day) (n=30); placebo (n=29)	No significant differences between groups in HAMD and BDI-II total scores, but n-3 PUFAs significantly reduced HAMD Cognition at week 8 (p<0.05) and HAMD Core subscale in very severe MDD at week 12 (p<0.05).	[104]
		n=108, CHF patients comorbid MDD	Double blind, RCT	2-weeks treatment with n-3 PUFAs (2:1 EPA/DHA 2.0 g/day) (n=36); EPA (2 g/day) (n=36); placebo (n=36)	No significant differences between groups in HAMD and BDI-II total scores. BDI-II cognitive depressive subscales strongly associated for the high EPA group (p<0.05).	[103]
		n=92, CAD patients comorbid MDD	Double blind, RCT	2-weeks treatment with n-3 PUFAs (1.9 g/day) (n=45); placebo (n=47)	Plasma EPA and DHA level increased (p<0.01) but no significant differences between groups in HAMD (p=0.20) and BDI-II (p=0.50) total scores.	[105]
	Pain comorbidity	N=46, Breast cancer survivor	Prospective, RCT	6-weeks diet intervention with high n-3 PUFAs (2040 mg, 12 ounces/week wild-caught Alaskan	High n-3 PUFAs group significantly decrease in pain (p < 0.01), perceived stress (p < 0.05), sleep (p < 0.001), depression (p < 0.001), and fatigue (p < 0.01).	[106]

			salmon) (n=24); low PUFAs (1020 mg, 6 ounces/week) (n=15)		
Obesity and metabolic comorbidity	n=25, Diabetes patients with MDD	Double blind, RCT	12-weeks treatment with EPA (1 g/day) (n=13), placebo (n=12)	No significant impact on BDNF (p = 0.887) and no significant association between changes in BDNF levels and depression severity (p=0.593).	[107]
	n=45, Obese patient with MDD	Double blind, RCT	12-weeks treatment n-3 PUFAs (1.08 g/d EPA & 0.72 g/d DHA) (n=24); placebo (n=21)	Significant reduced depression (p=0.05) in n-3 treatment groups	[108]
	n=61, Obese patient with MDD	Double blind, RCT	12-weeks treatment with EPA (1 g/d, n=15; 2 g/d, n=15; 4 g/day, n=16), placebo (n=15)	EPA 4 g/d produced a sustained effect on IDS-30 scores at both week 8 and week 12. A potential dose-response relationship between EPA dose and change in IDS-C30 scores, but this was not statistically significant.	[27]
ii. Depression associated with Neurodegeneration					
Parkinson's disease comorbidity	n=29, Parkinson's disease with MDD	Double blind, RCT	12-weeks treatment n-3 PUFAs (1200 mg/d) (n=14); placebo (n=15)	Significant decrease in MADRS and CGI-Depression scores but not in BDI in n-3 PUFAs group	[109]
Alzheimer's disease comorbidity	n=26, Patients with MCI or AD	Double blind, RCT	24-weeks treatment n-3 PUFAs (1080 mg/d EPA & 720 mg/d DHA) (n=20); placebo (n=15)	No associations were found between randomization group and ADAS-cog, MMSE or HDRS scores	[110]
	n=204, Patient with AD	Double blind, RCT	6-months treatment n-3 PUFAs (0.6 g/d EPA & 1.7 g/d DHA) (n=103); placebo (n=103)	No overall n-3 PUFAs effect on neuropsychiatric symptoms. Possible positive effects in MADRS in non-APOE ϵ 4 carriers (p=0.005)	[111]
Late-life depression	n=18353, Adults aged 50 years or older without depression	RCT	Median of 5.3 years treatment n-3 PUFAs (65 mg/d EPA & 375 mg/d of DHA) (n=9171), placebo (n=9182)	No significant improvement in n-3 PUFAs group in prevention on depression.	[112]

iii. Physiological deficits						
	Perinatal depression	n=59, Perinatal and postpartum women	Double blind, RCT	8-weeks treatment n-3 PUFAs (1.9 g/d) (n=28), placebo (n=23)	Both groups experienced significant decreases in EPDS and HAM-D scores (p< .0001) from baseline	[113]
		n=36, Perinatal women with MDD	Double blind, RCT	8-weeks treatment n-3 PUFAs (3.4 g/d) (n=18), placebo (n=18)	Significant lower EDPS and BDI observed in n-3 PUFAs group.	[22]
Special populations						
Safety consideration	Children, & adolescents with depression	n=60, Children with DD or MADD	Double blind, RCT	12-weeks treatment n-3 PUFAs (2.4 g/d) (n=30), n-6 PUFAs (n=30)	Significant reductions in CDI scores were observed in the n-3 PUFAs group and in the DD subgroup compared to the n-6 PUFAs and MADD subgroup. No serious side effects were observed, except for increased defecation reported by one participant in the n-3 PUFAs group.	[114]
	High-risk psychosis	n=81, Patients with ultra-high risk of psychotic disorder	Double blind, RCT	12-weeks treatment n-3 PUFAs (1.2 g/d) (n=41), placebo (n=40)	Significant improvement observed in PANSS and GAF score but not in MADRS scores. No significant adverse effects between the treatment groups.	[115]
		n=50, Patients with schizophrenia-spectrum or bipolar disorders with medication	RCT	16-weeks n-3 PUFAs (740 mg/d EPA & 400 mg/d DHA) (n=27), placebo (n=26)	n-3 PUFAs group showed significant improvement in BPRS scores compared to placebo among a subgroup of patients (N=23) who did not receive lorazepam. Lower rates of confusion, anxiety, depression, irritability, and tiredness/fatigue in n-3 PUFAs group as compared to those on placebo	[116]
		n=110, Injured patients with PTSD	Double blind, RCT	12-weeks n-3 PUFAs (1470 mg/d DHA & 147 mg/d EPA) (n=53), placebo (n=57)	Serum BDNF and pro-BDNF changes at week 12 were linked to depression severity, but DHA had no specific effect on these levels. Adverse events, including loose	[117]

					stool and constipation reported, but there were no significant differences between the two groups.	
	Pregnant women with MDD	n=36, Perinatal women with MDD	Double blind, RCT	8-weeks treatment n-3 PUFAs (3.4 g/d) (n=18), placebo (n=18)	Well tolerated and there were no adverse effects on the subjects and newborns.	[22]

Abbreviation: RCT, randomized controlled trial, EPA, Eicosapentaenoic acid, DHA, docosahexaenoic acid, MDD, major depressive disorder, HCV, hepatitis C viral infection, CVD, cardiovascular disease, CAD, coronary artery disease, CHF, chronic heart failure, HAMD, Hamilton Depression Rating Scale, BDI, Beck's Depression Inventory, DD, Depressive disorder, MADD, mixed anxiety and depressive disorder; GAF, Global Assessment of Functioning; MADRS, Montgomery-Åsberg Depression Rating Scale; PANSS, Positive and Negative Syndrome Scale, BPRS, Brief Psychiatric Rating Scale, BPRS, Brief Psychiatric Rating Scale, BDNF, brain-derived neurotrophic factor, CES-D, Center for Epidemiologic Studies Depression Scale, PTSD, post-traumatic stress disorder, EDPS, Edinburgh Postnatal Depression Scale.

Neuropsychiatric symptoms, including depressive symptoms are common in most of neurodegenerative diseases, such as Alzheimer's disease and Parkinson's disease, however there may be only partially or not at all responsive to conventional antidepressant therapies [105,106]. N-3 PUFAs have showed pleiotropic effects on neural structure and function and play a critical role in regulating mood in the brain. Although the exact mechanisms are not yet understood, n-3 PUFAs can potentially improve depressive symptoms and slow cognitive decline in patients with neurodegenerative diseases such as Alzheimer's and Parkinson's [91]. In a study by Lin et al. (2022), n-3 PUFA treatment using 0.8 g EPA and 0.35 g DHA daily or pure 1.6 g EPA daily in Alzheimer's patients resulted in a clinical improvement of inflammatory biomarker, chemokine ligand 4 (CCL4) and a slowdown in cognitive decline, specifically in the spoken ability domain [107]. Similarly, Freund-Levi et al. (2008) found that n-3 PUFAs treatment with 1.7 g DHA and 0.6 g daily supplementation led to significant improvements in neuropsychiatric symptoms, including potentially positive effects on depressive symptoms in non-APOE omega4 carriers and agitation symptoms in APOE omega4 carriers among patients with mild to moderate Alzheimer's disease [108]. Chiu et al. (2008) demonstrated that n-3 PUFAs monotherapy exhibited a higher level of eicosapentaenoic acid on red blood cell membranes and a significant improvement in the cognitive portion of the Alzheimer's Disease Assessment Scale (ADAS-cog) compared to the placebo group in participants with mild cognitive impairment. However, this may not be as effective in those with Alzheimer's disease [109].

Additionally, da Silva et al. (2008) investigated the effect of chronic supplementation with fish oil containing 1.2 g/day of n-3 PUFAs and found that it led to a high rate of remission of depressive symptoms over a 3-month period, regardless of whether the Parkinson's patients were taking antidepressant medication or not [109]. Moreover, a recent study by Borsini et al. (2021) demonstrated the neuroprotective effects of EPA and DHA treatment in preventing neurodegeneration and apoptosis induced by cytokines such as IL1 β , IL-6, and IFN- α in human hippocampal neurogenesis and depression. These effects were mediated through LOX and CYP450-derived EPA/DHA metabolites [118]. Total erythrocyte n-3 PUFA concentrations are positively associated with cognitive function, particularly immediate recall, in older people with previous depression [119]. Similarly, higher levels of EPA and DHA erythrocyte were linked to improved depressive symptoms, especially following six months of high levels of EPA and DHA supplementation, [120]. Recent review study revealed that n-3 PUFAs may represent a promising strategy for managing long COVID, as they can potentially alleviate chronic inflammation and restore tissue homeostasis which can ultimately aid in the recovery from SARS-CoV-2 infection [121]. Likewise, while the primary management of mood disorders like depression in COPD involves the use of antidepressants, their tolerability is limited. However, as n-3 PUFAs are crucial in regulating inflammatory responses, they could be a promising alternative for managing mood disorders in chronic obstructive pulmonary disease (COPD) [122]. However, further clinical trial is necessary to fully comprehend the potential advantages of n-3 PUFAs in managing these comorbidities and its long-term consequences.

It is noteworthy that safety considerations must be carefully evaluated and monitored in the development and implementation of personalized n-3 PUFAs treatment approaches. While numerous findings suggest that n-3 PUFA treatment may be beneficial in improving neuropsychiatric and depressive symptoms in adults, it is crucial to acknowledge that n-3 PUFAs also impact depressive symptoms in vulnerable population including children, adolescents, and pregnant women [114,123,124]. In general, numerous clinical trials have demonstrated that n-3 PUFAs are generally well tolerated in diverse populations. For instance, EPA and DHA are well tolerated in hepatitis C infection patients, no effect of PUFAs treatment on viral load nor excessive bleeding or liver function observed [101]. n-3 PUFAs with a ratio of EPA/DHA at least 1.5 has (≥ 1.5) been effective in treating mild-to-moderate depression in pregnant and postpartum women with minimal side effects. The trials included in the analysis did not show significant difference in incidence of gastrointestinal and neurologic adverse effect between the n-3 PUFAs and placebo groups [124]. In addition to youth with MDD, n-3 PUFAs supplementation also showed its potential effects in the improvement of clinical symptoms in those with high inflammation or a low baseline

n-3 index, particularly youth with attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder (ASD), subthreshold psychotic states, posttraumatic stress disorder (PTSD) [115,117,123]. Overall, n-3 PUFAs supplementation provides no significant adverse effect, a safe and effective therapy to these vulnerable groups [114,115,124]. However, developing personalized n-3 PUFA treatment requires a deep understanding of the molecular and genetic factors that contribute to disease susceptibility and progression. This is particularly important for patients with comorbid MDD and obesity as well as metabolic dysregulation, where tailored n-3 PUFA treatments may be necessary to optimize outcomes and minimize potential adverse effects.

5. Omega-3 Polyunsaturated Fatty Acids (n-3 PUFAs) for Depression Treatment in Obese and Metabolically Dysregulated Patients

Selected key studies of n-3 PUFAs treatment on MDD, obesity and metabolic dysregulation reviewed in this paper are summarized in Table 2.

Table 2. Characteristics key of preliminary studies of n-3 PUFAs treatment on MDD, obesity and metabolic dysregulation.

References	Sample	Study design	Intervention	Outcome scale	Main findings	Notes and limitations
Bot et al. (2011) [107]	n=25, Women with MDD and diabetes with antidepressant	Double blind, RCT	12-weeks treatment with EPA (1 g/day) (n=13), placebo (n=12)	MADRS, Serum BDNF	No significant impact on BDNF (p = 0.887) and no significant association between changes in BDNF levels and depression severity (p=0.593).	1st clinical study to examine the effects of n-3 PUFAs on BDNF. Small sample size. One patient reported allergic reaction and discontinued using EPA, no other severe adverse events reported.
Keshavarz et al. (2018) [108]	n=45, Women with depression comorbid obesity (BMI ≥ 25 kg/m ²), without antidepressant	Double blind, RCT,	12-weeks treatment n-3 PUFAs (EPA 1.08 g/day & DHA 0.72 g/day) (n=24); placebo (n=21)	Body weight, height, BMI, waist and hip circumference, total body fat, muscle percentage, BDI, food craving questionnaire, appetite and food abstinence visual	Reduced depression (p=0.05) and body weight (p=0.049) in n-3 treatment groups	Weight regains after one-month follow-up. Side effects includes nausea, skin rash, hemorragia, and increased appetite reported in both groups.

				Analogue scales		
Mischoulo n et al. (2022) [27]	n=61, Patient with MDD comorbid overweight/obese (BMI ≥ 25 kg/m ²), without antidepressant	Double blind, RCT	12-weeks treatment with EPA (1 g/d, n=15; 2 g/d, n=15; 4 g/day, n=16), placebo (n=15)	IL-6, LPS-stimulated TNF level, plasma hs-CRP level, IDS-C30	EPA 4 g/d produced a sustained effect on IDS-30 scores at both week 8 and week 12. A potential dose-response relationship between EPA dose and change in IDS-C30 scores, but this was not statistically significant.	1st dose-finding trial of EPA in MDD to focus on inflammatory biomarkers as primary outcome among overweight/obese subjects with elevated hs-CRP

Abbreviations: MDD, Major Depression Disorder; BMI, Body Mass Index; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; MADRS, Montgomery-Asberg Depression Rating Scale; BDNF, brain-derived neurotrophic factor; BDI, Beck Depression Inventory; IL-6, interleukin-6; LPS-stimulated TNF level, Lipopolysaccharide-stimulated tumor necrosis factor; hs-CRP, high-sensitivity C-reactive protein; IDS-C30, Inventory of Depressive Symptomatology, Clinical-Rated version.

Individuals with comorbid conditions such as depression, obesity, and metabolic dysregulation pose a challenge in terms of developing effective treatments due to the complex nature of these conditions. Bot et al. (2011) found no significant effect of EPA supplementation on BDNF levels in patients with both depression and diabetes, despite ongoing antidepressant use. However, the study authors noted that the baseline BDNF levels were relatively high and ongoing antidepressant treatment throughout the study may have influenced the results but not depression severity [107].

Apart from diabetes, obesity is a frequently observed risk factor for metabolic syndrome and is often coexisting with depression. n-3 PUFAs at a dose of 1080 mg EPA and 720 mg DHA per day significantly reduced depression and body weight compared to placebo in patients with depression and comorbid obesity, but weight regain occurred in the follow-up period [108]. Nevertheless, several studies have indicated that n-3 PUFAs may have favorable effects on body composition and weight. For instance, a study revealed that the consumption of fish or fish oil led to reduced body weight, fat mass, and waist circumference in the n-3 PUFAs group in comparison to the control group [125]. A reduction in energy intake, carbohydrates, and fat has been observed in overweight and obese females (25.8 – 39.9 kg/m²) with n-3 PUFAs supplementation (2.8 g/day DHA) over a 12-week period, however no significant effect implied on body weight [126]. Obese participants with BMI of 30-40 kg/m² given n-3 PUFA (180 mg EPA, 120 mg DHA) treatment for 4 weeks had reduced caloric intake, increased fullness, and non-significant changes in BMI and serum leptin levels, indicating potential effects on satiety and energy intake [127]. High-dose supplementation (4 g/d) of n-3 PUFAs has been shown to induce significant changes in adipose tissue, circulating fatty acids, and systemic inflammatory markers in individuals with obesity and insulin secretion, indicating the potential therapeutic effects of n-3 PUFAs on body weight [128].

n-3 PUFAs have been acknowledged for their potential therapeutic advantages in individuals with obesity, which linked to the long-term energy imbalance and adipocyte-derived hormones such as leptin and appetite sensations [129]. Depression is also associated with adiposity, and both conditions exacerbate each other. This vicious cycle is fuelled by inflammation [60]. The response to EPA versus DHA may vary depending on baseline inflammatory biomarkers and adiponectin levels for those individuals who had high baseline inflammatory biomarkers [130]. A recent study revealed that high doses of EPA (4 g/d) may be more effective in treating resistant depression with severe inflammation, particularly in those overweight individuals with high inflammation [27]. However, further research is needed to determine ideal dosages for EPA and DHA supplementation, in specific subgroups with comorbidities of depression.

6. Future Perspective

The global health landscape faces significant challenges due to the co-occurrence of depression and obesity, as these conditions worsen each other's effects and negatively impact patients' quality of life and treatment outcomes. N-3 PUFAs supplementation has emerged as a potential therapeutic strategy for addressing both depression and obesity, as it has been shown to have beneficial effects on inflammatory markers, body weight, and depressive symptoms. However, optimal dosing and duration of supplementation for individuals with comorbid depression and obesity or metabolic dysregulation are still unclear. In the future, personalized and precision medicine approaches could play a crucial role in addressing this complex clinical challenge. Traditional anthropometric indices, such as body mass index (BMI), may not fully capture the complexity of obesity-related metabolic complications, and additional clinical parameters may be needed for accurate risk evaluation.

The traditional "one-size-fits-all" approach to treating depression is limited due to the heterogeneity of symptoms and treatment response. Personalized treatment that considers the complexity of comorbidities and individual characteristics may improve outcomes for individuals with coexist MDD and obesity. Therefore, a personalized medicine approach that integrates individualized adipose tissue health and metabolic parameters may offer more effective and tailored interventions. Further research is recommended to better understand how n-3 PUFAs work in obesity and MDD, to establish most favorable dosage and duration of supplementation for people with comorbidities. By implementing personalized and precision medicine approaches in clinical practice could significantly improve treatment outcomes for individuals with comorbid MDD and obesity. Further investigation is warranted to improve the application of N-3 PUFAs supplementation and sharpen up the personalized medicine strategies, ultimately enhancing the efficacy of interventions for this complex patient population.

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