Loss of AATF ameliorates metabolic dysfunction-associated steatohepatitis by suppressing the AKT-mTORC1 signaling pathway

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Abstract

Metabolic dysfunction-associated steatohepatitis (MASH) is a complex and multifaceted condition affecting over 30% of the world's population. It is influenced by a range of molecular factors, making the identification of key disease drivers crucial for the development of targeted therapeutic strategies for MASH. Here, we demonstrate the impact of the loss of apoptosis antagonizing transcription factor (AATF) on MASH, uncovering detailed mechanisms through transcriptome and metabolome analysis. AAV8-mediated specific knockdown of AATF in hepatocytes significantly reduced body weight, liver weight, and insulin resistance in mice fed with western diet (WD). However, no such effects were observed in mice fed with chow diet (CD). Further analyses showed reduced liver injury, steatosis, and steatohepatitis in WDsiAATF mice. Transcriptomic analysis demonstrated that loss of AATF alleviated cellular stress, inflammation, and fibrosis in WD-fed mice. Moreover, AATF silencing led to alterations in lipid metabolism, notably by decreasing hepatic lipogenesis in the WD mice. Interestingly, untargeted metabolomics revealed increased biosynthesis of glycerophospholipids and beta-oxidation of fatty acids in WDsiAATF mice. Our findings reveal the molecular link between AATF and hepatic lipid metabolism, mediated by modulation of the AKT-mTORC1 signaling pathway. Based on these findings, targeting AATF may offer a promising therapeutic avenue for treating MASH.

Keywords

Apoptosis antagonizing transcription factor, metabolic dysfunction-associated steatotic liver disease, fatty acid β-oxidation, therapeutic target, transcriptomics, and metabolomics

Abbreviations

MASLD, metabolic dysfunction-associated steatotic liver disease; NAFLD, nonalcoholic fatty liver disease; MASH, metabolic dysfunction-associated steatohepatitis; NASH, nonalcoholic steatohepatitis; HCC, hepatocellular carcinoma; CVD, cardiovascular disease; CKD, chronic kidney disease; AATF, apoptosis antagonizing transcription factor; DIAMOND, diet-induced animal model of NAFLD; STAT3, signal transducer and activator of transcription 3; MCP-1, Monocyte chemoattractant protein-1; KLF4, Krupple-like factor 4; SP1, Specificity protein 1; PPAR α/γ, peroxisome proliferator-activated receptor alpha/ gamma; CPT-1/2, carnitine palmitoyltransferase 1/2; AMPK, adenosine monophosphate-activated protein kinase; mTOR, mammalian target of rapamycin; NAS Score: NAFLD activity score; GTT, glucose tolerance test; HOMA-IR, homeostatic model assessment of insulin resistance; ITT, insulin tolerance test; AST, aspartate transaminase; ALT, alanine transaminase; TC, total cholesterol; TG, total triglycerides; LDL, low-density lipoprotein; ECL, enhanced chemiluminescence; HRP, horseradish peroxidase; FFPE, formalin-fixed, paraffin-embedded; FBS Fetal bovine serum; LC-MS, liquid chromatography-mass spectrometry; UHPLC, ultrahigh performance liquid chromatography; MeOH, methanol; SIRT1, silent information regulator 1; TIMP3, tissue inhibitor of metalloproteinase 3; TACE, TNF-alpha converting enzyme; MASL, metabolic dysfunction-associated steatotic liver; TBG, thyroxine-binding globulin; AAV8, adeno-associated virus 8; CDNW, chow diet normal water; WDSW, western diet sugar water; PA, Sodium Palmitate; SO, Sodium Oleate; TGF β, transforming growth factor β; Grp78; 78 kDa glucose-regulated protein; CHOP, C/EBP homologous protein; Atf4, activating transcription factor 4; TNF-α, tumor necrosis factor-alpha; IL-6, interleukin-6; IL-1β, interleukin-1β; JNK, c-Jun N-terminal kinases; ERK1/2, extracellular signal-regulated kinase 1/2; PGC-1α, peroxisome proliferator-activated receptor-gamma coactivator; LysoPC, lysophosphatidylcholines; PCA, principal component analysis; VIP, variable importance in the projection.

Introduction

Metabolic dysfunction-associated steatotic liver disease (MASLD), formerly termed non-alcoholic fatty liver disease (NAFLD), stands as the prevailing chronic liver ailment impacting more than 30% of the adult population worldwide (1,2). It notably afflicts individuals with obesity and type 2 diabetes, emerging as a primary contributor to advanced liver disease and hepatocellular carcinoma (HCC) (3,4). MASLD encompasses a spectrum of advancing steatotic liver conditions, spanning from benign metabolic dysfunction-associated steatotic liver (MASL) to steatohepatitis (MASH), presenting with varying degrees of liver fibrosis that could advance to cirrhosis (5). MASLD not only heightens the likelihood of liver-related complications such as cirrhosis, end-stage liver disease, and hepatocellular carcinoma (HCC) but also escalates the risk of multiple extraneous manifestations, including cardiovascular disease (CVD), chronic kidney disease (CKD), and specific forms of extrahepatic cancers (6). As MASLD progresses to the end stage of liver disease, treatment options become increasingly limited, often leading to consideration for liver transplantation (7). Early detection and intervention are, therefore, paramount. While lifestyle modifications remain fundamental to managing the condition, pharmacological treatments can complement these interventions (8,9). Despite numerous clinical studies, the pathogenesis of MASH remains elusive, and the mechanisms underlying its occurrence and progression are not yet fully understood (10). Therefore, elucidating the molecular pathways involved in MASH pathogenesis is crucial for identifying potential therapeutic targets.

MASH manifests with the accumulation of lipids in the liver, stemming from disturbances in both lipid uptake (from circulating sources or de novo synthesis) and lipid disposal (via fatty acid oxidation or secretion of triglyceride-rich lipoproteins) (11). This disruption results in the buildup of lipotoxic compounds, cellular stress, injury, and fibrosis (11,12). The regulation of lipid metabolism is complex and multifaceted, involving various factors like membrane transporters, metabolic enzymes, and transcriptional regulators (13). Glycerophospholipids, a subclass of phospholipids that are the major constituents of cell membranes, play a key role in lipid metabolism, and alterations in the composition of glycerophospholipids have been reported in individuals with MASH (14,15). Phosphatidylcholine (PC), phosphatidylethanolamine (PE), phosphatidylserine (PS), phosphatidylinositol (PI), and cardiolipin (CL) are a diverse array of glycerophospholipids that are well studied for their role in cell signaling and lipid metabolism (15). Interestingly, glycerophospholipids are involved in inflammatory, oxidative stress, and bile acid metabolism pathways, which are key drivers in the disease pathogenesis of MASH (16). Of note, glycerophospholipids are essential for maintaining the integrity of the mitochondrial membrane, which is crucial for various mitochondrial functions, including beta-oxidation of fatty acids (17). It is observed that, in MASH subjects, diminished β-oxidation of fatty acids in the liver fails to adequately mitigate the lipotoxic effects of harmful lipids (18). Disruption of β-oxidation pathways results in lipid buildup in the liver, heightened oxidative stress, and inflammation, all of which further the progression of the disease (19). Thus, glycerophospholipid levels and efficient β-oxidation of fatty acids in the liver contribute to the protection and alleviation of MASLD.

Apoptosis antagonizing transcription factor (AATF) is a multifaceted transcription factor recognized for its pivotal involvement in essential cellular functions (20). It serves as a dynamic regulator of fundamental cellular processes such as transcriptional control, cell cycle and apoptosis regulation, ribosome biogenesis, and response to cellular stress (20). AATF protects cells from oxidative stress, ER stress,

DNA damage, and hypoxia by modulating the cell cycle, autophagy, and apoptosis (21). The widely studied role of AATF is apoptosis regulation exerted by activation of antiapoptotic and inhibition of proapoptotic pathways (22). Pathologically, AATF has been implicated in numerous cancer types, including leukemia, breast cancer, neuroblastoma, lung cancer, and colon cancer (23-25). Our previous investigations have revealed elevated levels of hepatic AATF in HCC, where it plays a significant role in promoting tumor angiogenesis (26). Studies have also demonstrated the inhibitory effects of curcumin on MASH-HCC by downregulating AATF via the KLF4-SP1 pathway (27). We recently explored the involvement of the SIRT1-TIMP3-TACE axis in AATF upregulation, with subsequent TACE inhibition leading to AATF downregulation and attenuation of MASH-associated liver tumorigenesis (28). However, the mechanistic role of AATF in the pathophysiology of MASH remains poorly understood.

In this study, we aimed to investigate the novel role of AATF in experimental MASH. While AATF expression positively correlated with the spectrum of MASLD, liver-specific knockdown of AATF significantly improved MASH by reducing steatosis, inflammation, cellular stress, and fibrosis. Additionally, we investigated the effect of hepatic silencing of AATF on MASH through transcriptomics and an untargeted metabolomics approach. In the current study, we integrated biochemical and molecular parameters with transcriptomic and metabolomic analyses to provide novel insights into the role of AATF in the MASH disease signature. These findings collectively shed light on the unexplored mechanistic role of AATF in regulating lipid metabolism, making it an attractive therapeutic target.

Methods

Animal study

Male C57Bl/6NCrl mice aged 6 weeks procured from Hylasco Biotechnology Pvt. Ltd. (Charles River Laboratories, Hyderabad, Telangana, India) were used for the study. All the mice were accommodated in the central animal housing facility at the Center for Experimental Pharmacology and Toxicology, JSS AHER, following a 12-hour light-dark cycle, consistent with previously established protocols (29). Following one week of acclimatization, study protocols were commenced. All animal-related procedures adhered to the guidelines sanctioned by the Committee for the Purpose of Control and Supervision of Experiments on Animals (CPCSEA), Govt. of India (JSSAHER/CPT/IAEC/118/2022).

<u>Diet-induced MASH model:</u>

After a week of acclimatization, the mice were fed with either a chow diet normal water (CD) or a western diet (21% fat, 41% sucrose, and 1.25% cholesterol by weight, Research Diet, Inc. USA) along with sugar water (WD) containing 18.9 g/L d-glucose and 23.1 g/L d-fructose (HiMedia Laboratories) ad libitum for 24 weeks. Mice were continuously monitored for food intake, water intake, and body weight. After 24 weeks, mice were euthanized, and blood and tissues were collected for further histological, biochemical, and molecular analysis.

AAV expression system

Liver gene expression was modulated using AAV-mediated gene transfer technology as defined previously (30). The siRNA sequences targeting AATF were incorporated into an adeno-associated virus (AAV) vector under the regulation of a liver-specific thyroxine-binding globulin (TBG) promoter. AAV8-TBG-siAATF and AAV8-TBG-siControl constructs were generated by packaging into serotype 8, titrated by Applied Biological Materials Inc. (ABM).

Hepatocyte-specific silencing of AATF in experimental MASH

The mice were fed either a chow diet normal water (CD) or a western diet sugar water (WD). After 12 weeks of dietary intervention, mice were injected via the tail vein with 1×10^{11} genome copies of AAV8 serotype particles and randomized into four groups: (i) CD with AAV8-TBG-siControl, (ii) CD with AAV8-TBG-siAATF, (iii) WD with AAV8-TBG-siControl, and (iv) WD with AAV8-TBG-siAATF. The same dietary regimen was followed until the end of 24 weeks. The technology developed by Applied Biological Materials Inc. (ABM), uses a convergent promoter vector system wherein the siRNA is expressed in both directions, mimicking that of shRNA. Henceforth, the siRNA used in the experiment is stable and provides sustained expression. Throughout the study, mice were continuously monitored for food intake, water intake, and body weight. The glucose tolerance test (GTT) and insulin tolerance test (ITT) were performed during the study period. After 24 weeks, mice were euthanized under fasting conditions, followed by blood and tissue collection for further analysis.

Isolation of primary mouse hepatocytes

Primary hepatocytes were isolated from the livers of mice injected with AAV8-TBG-Null and AAV8-TBG-siAATF following previously established protocols (30). Briefly, mice were anesthetized, and the inferior vena cava was cannulated. Liver perfusion was carried out using pre-warmed perfusion buffer followed by the digestion buffer containing 25 µg/ml Liberase (Sigma Aldrich). The isolated hepatocytes were then filtered through a 70-micron cell strainer (HiMedia) and purified via centrifugation in DMEM low glucose media (HiMedia laboratories) at 50g for 5 minutes at room temperature. Percoll (Sigma Aldrich) gradient separation was employed to isolate hepatocytes from nonparenchymal cells. The isolated cells were suspended in DMEM supplemented with 10% FBS and 100U penicillin-streptomycin. Collagen-coated plates were utilized for cell culture in William's E medium (HiMedia laboratories).

RNA sequencing and transcriptomics analysis

RNA extraction was carried out by All prep DNA/RNA kit (Qiagen). RNA was quantified on a Qubit fluorometer and RIN was obtained using Tapestation 4150 using HS RNA screen tape. The library preparation was carried out using the SMART-Seq Library Prep Kit. The sequencing was performed with the Illumina NovaSeq6000 platform with a read length of 150×2 bp. The reads were mapped to STAR-indexed Mus musculus (GRCm39: GCF_000001635.27) using STAR aligner version 2.7.9a. The alignment file (sorted BAM) from individual samples was quantified using Feature Counts version 2.0.1 based on the filtered GTF file to obtain gene counts. These gene counts of *Mus musculus* were used as inputs to DESeq2 for differential expression estimation.

Differential gene expression analysis

Differential expression analysis was performed with the Bioconductor package DESeq2 (R under the latest version). Genes with read counts less than 10 across the samples were removed before downstream analysis. Raw read counts were normalized by DESeq2. The magnitude (log 2 transformed fold change) and significance (P-value) of differential expression between groups were calculated, and genes with P-values <0.05 were considered significant. We obtained DEGs with the following criteria: P value <0.05 and $|\log 2\text{-fold change}|\geq2$.

PLS-DA analysis was carried out in R using the plsda function in the "mixOmics" package.

Functional Gene Set Enrichment Analysis
Functional gene set enrichment analysis (GSEA) was performed using the R package ClusterProfiler for Gene Ontology Biological Process (GO BP), Molecular Function (GO MF), and Kyoto Encyclopedia of Genes and Genomes (KEGG) pathways. For multiple test corrections, P-values were adjusted by the Benjamini-Hochberg false discovery rate (BH-FDR). Gene sets with a p-value < 0.05 were considered significantly enriched. Gene sets were downloaded from the MSigDB database (https://www.gsea-msigdb.org/gsea/msigdb).

Gene signature heatmaps
Normalized expression of leading genes in the enriched cellular stress, inflammation, and fibrosis pathways of GSEA was used for generating heatmaps using the pheatmap R package. Glycerophospholipid metabolism, lipid metabolism, and fatty acid degradation pathway gene lists were obtained from the KEGG database.

AATF PPI network
The Search Tool for the Retrieval of Interacting Genes (STRING version 12.0) (http://string-db.org) was used to systematically screen the top 100 mouse protein interactors of AATF, set with a high confidence threshold > 0.7. Interactors of AATF were retrieved from the BioGRID database as well. Further, the protein-protein interaction network was created with Cytoscape software, where the color of the node represents the log2foldchange of the gene within the comparison of WDsiAATF vs WDC.
Interactions between AATF and genes involved in the gene ontology biological processes related to lipid metabolism were screened separately within the STRING database.
The gene ontology biological process and molecular functions, as well as KEGG pathways enriched by the interactors of the AATF gene, were analyzed and visualized using the ClueGO app within Cytoscape.

For all the data related to transcriptomics, P<0.05 was considered to indicate a statistically significant difference. All statistical analysis and visualizations were performed in R v.3.2 unless indicated otherwise.

Untargeted metabolomics- Metabolite extraction and LC-MS analysis
Metabolites were extracted following previously established protocols (31). Briefly, liver tissues were lyophilized in a vacuum freeze dryer for 24 hours, and 50 mg of samples were homogenized with 50 mM ammonium bicarbonate (3:1 w/v). Samples were extracted in cold methanol by centrifugation at 18,000× g for 15 minutes at 4°C. Supernatants are dried and reconstituted in MeOH: water (3:1 v/v) for LC/MS analysis. The hepatic metabolome was analyzed using a Vanquish UHPLC system (Thermo Fisher) coupled with an Orbitrap Eclipse Tribrid mass spectrometer (Thermo Fisher). Samples were separated on an RP column, 2.1 x 150 mm, 1.8 um particle size, and 0.3 mL/min flow rate with two eluents for positive and negative polarity modes.

Quantification and statistical analysis
Statistical analyses were performed using GraphPad Prism 6.0 software (GraphPad, Inc., La Jolla, CA, USA). Data were represented as the mean ± standard error of the mean. Statistical significance was analyzed using Student's t-test for two groups or analysis of variance (ANOVA) with post hoc Bonferroni correction for multiple comparisons and p values < 0.05 (*/#) or < 0.001 (**/##) were considered significant.

Results

Silencing of hepatic AATF in experimental MASH

To assess the role of AATF on liver metabolism and MASH, we silenced AATF expression in the hepatocytes of mice using liver-directed adeno-associated virus 8 (AAV8) under the control of the thyroxine-binding globulin (TBG)-mediated gene silencing system. Mice were fed chow diet normal water (CD) or western diet sugar water (WD), and after 12 weeks, mice were administered either AAV8-TBG-siControl or AAV8-TBG-siAATF via tail vein injection and were monitored for an additional 12 weeks. At the end of the 24-week study, serum and tissues from several organs, including the liver, adipose tissue, heart, kidneys, pancreas, and spleen, were collected from the mice. The liver tissue was used for histological, biochemical, and molecular analyses, in addition to transcriptomic and metabolomic studies (**Fig. 1A**). The expression of AATF was assessed in the different tissues obtained from the mice, confirming that AATF expression was silenced exclusively in the livers of AAV8-TBG-siAATF mice when compared to AAV8-TBG-siControl mice (**Fig. 1B** and **Fig. 1C**). Furthermore, we verified that AATF silencing occurred specifically in hepatocytes, with no impact on non-parenchymal cells (**Fig. 1D**).

The rationale for the current study to assess whether hepatic silencing of AATF ameliorates the development of MASH was the confirmation that AATF expression was found to be upregulated in the liver of mouse models of MASH and subjects with MASH compared with healthy normal. Previously, we had shown that AATF is upregulated in a diet-induced mouse model of non-alcoholic fatty liver disease (DIAMOND), which is an isogenic strain derived from a cross of two mouse strains, 129S1/SvImJ and C57BL/6J (32). Here, we carried out comprehensive work in determining the expression of AATF in different experimental models. We initially employed the cellular model of fatty liver disease, which was developed by treating free fatty acids, such as sodium palmitate (PA) or sodium oleate (SO), in the human hepatic cell lines HepG2 and Huh7. Upon confirmation of lipid accumulation as visualized by Oil Red O staining (**Supplementary Fig. 1A**), AATF expression was determined. Our observations revealed a significant upregulation of AATF both at mRNA and protein levels in the *in vitro* model **(Supplementary Fig. 1B - 1D)**. Next, we employed a preclinical model of MASLD that recapitulates human disease progression, developing MASL at 12 weeks and MASH at 24 weeks in western diet sugar water mice compared to chow diet normal water mice (**Supplementary Fig. 1E**). AATF mRNA and protein levels were notably elevated at MAFL and MASH stages compared to the control (**Supplementary Fig. 1F and 1G**). Furthermore, we analyzed AATF expression in human liver biopsies from MASL, MASH, and healthy control subjects (**Supplementary Fig. 1H).** Corroborating with the *in vitro* and *in vivo* data, AATF expression was elevated in human MASL and MASH subjects compared to healthy controls (**Supplementary Fig. 1I and 1J)**. These collective findings underscored the upregulation of AATF during the progressive stages of MASLD, implicating its potential significance in disease progression.

Loss of hepatic AATF ameliorates western diet-induced insulin resistance, liver injury, steatosis, and steatohepatitis

Silencing of hepatic AATF via AAV8-TBG-siATTF significantly reduced body weight, liver weight, liver-body ratio, and body fat mass compared to those administered with AAV8-TBG-siControl in WD mice, but AATF silencing had no effect on CD mice (**Fig. 1E-1H, Supplementary Fig. 2A**). Importantly, AAV8 administration had no adverse effects on the mice. The food intake was monitored throughout the study, and

cumulative calorie intake remained identical for all groups of mice **(Supplementary Fig. 2B and 2C).** AATF silencing also improved glucose tolerance and insulin sensitivity, as demonstrated by the glucose tolerance test (GTT) and the insulin tolerance test (ITT), respectively, in WD mice (**Fig. 1I and 1J**). Notably, WD siAATF mice demonstrated reduced blood glucose levels and fasting insulin levels, as well as a reduced homeostatic model assessment for insulin resistance (HOMA-IR) compared to WD control mice. This indicates amelioration of western diet-induced glucose metabolism impairment and insulin resistance (**Fig. 2A-2C**). Furthermore, we also examined the effect of hepatic AATF silencing on liver injury in MASH mice by measuring the serum levels of liver enzymes, including ALT, AST, total cholesterol, triglycerides, and LDL cholesterol. Consistently, WD siAATF mice showed reduced levels of liver enzymes compared to WD controls (**Fig. 2D-2H**).

Of note, macroscopic examination showed that WD siAATF mice had a healthier liver morphology compared to WD controls (**Fig. 2I**). Histological analysis of liver sections showed decreased steatosis and substantial improvement in steatohepatitis (MASH) upon hepatic AATF silencing compared to controls in WD mice (**Fig. 2J**). Similar results were obtained with Oil Red O staining of liver sections, where there was reduced intracellular lipid droplet accumulation in WD siAATF mice compared to WD controls (**Fig. 2K**). Consistent with these findings, histological scoring for steatosis, lobular inflammation, and hepatocyte ballooning was reduced in hepatic AATF-silenced WD mice, with an improvement in MASLD activity score compared to WD controls (**Fig. 2L**), indicating that hepatic AATF inhibition improves metabolic health by ameliorating liver injury and dysregulated lipid metabolism.

Effect of AATF silencing on hepatic transcriptomic and metabolomic profiles in MASH mice

To explore the liver-specific molecular pathways regulated by AATF in MASH, we performed RNA-sequencing and untargeted metabolomics analysis in the liver tissues of all four groups. Comparisons were made between WDC (western diet-fed mice administered with AAV8-TBG-siControl) and CDC (chow diet-fed mice administered with AAV8-TBG-siControl), WDsiAATF (western diet-fed mice administered with AAV8-TBG-siAATF) and WDC (western diet-fed mice administered with AAV8-TBG-siControl), and CDsiAATF (chow diet-fed mice administered with AAV8-TBG-siAATF) and CDC (chow diet-fed mice administered with AAV8-TBG-siControl). The samples in transcriptomics analysis formed clear clusters between the WDsiAATF, WDC, and CD groups with good intra-group sample correlation (**Fig. 3A and 3B)**. Volcano plots showed a distribution of differentially altered genes in WDsiAATF vs. WDC (**Fig. 3C)**. Differential expression analysis showed 224 up and 144 downregulated genes in the WDsiAATF vs. WDC group (P value <0.05 and log 2-fold change≥2). In WDsiAATF mice, genes related to the anti-inflammatory response, such as neutrophilic granule protein (NGP), lactoferrin (LTF), and major urinary protein 1 (MUP1), which regulates gluconeogenesis and lipogenesis in the liver, were found to be upregulated. In contrast, genes like EPH receptor B2 (EPHB2) and suppression of tumorigenicity 18 (ST18), which play roles in liver fibrosis and inflammation, were downregulated. Additionally, the early growth response gene-2 (EGR2), which is crucial for the differentiation of monocytes into hepatic lipid-associated macrophages, and tubulin beta 2B class IIb (TUBB2B), involved in cholesterol biosynthesis, were also downregulated. GSEA analysis of the KEGG and GO databases showed suppressed extracellular matrix and collagen binding, immune response, activation of primary bile acid synthesis, and nitrogen metabolism (**Fig. 3D)**. Hepatic metabolite profiling was conducted through an untargeted metabolomics analysis. The PLS-DA plot showed the differences between

experimental groups and identified a significant separation of liver metabolites between the WDsiAATF and WDC groups, as well as the WDC and CDC groups (**Fig. 3E).** Univariate analysis identified 487 metabolites altered in the WD siAATF, of which 412 were upregulated in contrast to 197 upregulated metabolites in WDC. Similarly, 867 metabolites were downregulated in WDC mice, whereas only 75 metabolites were downregulated in WDsiAATF mice, clearly showing marked differences in the metabolome profiling upon hepatic AATF silencing **(Fig. 3F).** Consistently, the volcano plots also showed a similar distribution of differentially altered metabolites in WDsiAATF vs. WDC groups **(Fig. 3G).** No significant changes in hepatic transcriptomic and metabolomic profiles were seen in CDsiAATF vs. CDC (**Supplementary Fig. 3)**.

Hepatic AATF loss alleviates cellular stress, inflammation, and fibrosis in experimental MASH

Cellular stress plays a prime role in the pathogenesis of MASH by promoting hepatic inflammation and fibrosis. Several factors contribute to cellular stress, stemming from lipid accumulation in hepatocytes, mitochondrial dysfunction, oxidative stress, and ER stress (33). In our investigation, we explored the impact of hepatic AATF silencing on cellular stress responses. Transcriptomics data showed downregulated ERK1/2 cascade, MAPK pathway, reactive oxygen species, PKA pathways, and apoptotic pathways in the WDsiAATF group (**Fig. 4A and 4B).** We subsequently validated the expression of key ER stress markers using qRT-PCR. Remarkably, in WDsiAATF mice, we found significant downregulation in the mRNA levels of CHOP, Grp78, PERK, and ATF4 compared to WDC (**Fig. 4C).**

Furthermore, to elucidate the intricate crosstalk between cellular stress and inflammation, we hypothesized that hepatocellular stress triggers inflammatory signaling pathways, notably stress kinases, leading to the release of pro-inflammatory cytokines in WDC mice. Owing to that, DEGs in WDsiAATF are attributed to the suppression of TNF-α superfamily cytokine production, macrophage migration, leukocyte proliferation, and differentiation (**Fig. 4D and 4E)**. Silencing of hepatic AATF in WD mice remarkably reduced inflammation, as evidenced by the reduced expression of pro-inflammatory cytokines IL-6, IL-1β, and TNF-α (**Fig. 4F**). Concurrently, phosphorylation of JNK and Erk1/2 was noticeably diminished in WDsiAATF mice compared to WDC (**Fig. 4G and 4H**). The immunostaining for the mouse macrophage marker F4/80 corroborated these findings, showing a marked reduction in response to AATF silencing in WD mice (**Fig. 4I**). These findings signify AATF as an important mediator for cellular stress-induced hepatic inflammation.

More interestingly, transcriptomic analysis of liver tissues from MASH mice revealed key genes associated with fibrosis, as evidenced by negative regulation of extracellular matrix organization, collagen metabolism, the TGF-β receptor signaling pathway, and fibroblast proliferation in WDsiAATF mice (**Fig. 5A and 5B)**. The further validation also confirmed reduced expression of α-SMA, Col1A1, Col3A1, and TGF-β, the key markers for liver fibrosis in the WDsiAATF group (**Fig. 5C**). Additionally, picrosirius red staining and hepatic stellate cell activation marked by desmin were attenuated in WDsiAATF mice, suggesting that AATF silencing reduces fibrogenic activation in WDC (**Fig. 5D and 5E).** Taken together, these results signify the impact of hepatic silencing of AATF on key MASH signatures such as cellular stress, inflammation, and fibrosis.

Hepatic loss of AATF regulates lipid metabolism and ameliorates metabolic dysfunction-associated steatohepatitis

Dysregulated lipid metabolism is the major culprit in MASH pathogenesis, as it contributes to lipid buildup, worsens insulin resistance, and triggers inflammation (34). This lipid accumulation results from excessive lipid influx, reduced fatty acid oxidation, and heightened de novo lipogenesis in the liver, ultimately leading to steatohepatitis (35). We had previously validated the role of AATF as a potential driver of HCC in MASLD (27,28). In this study, we explored the novel role of AATF in lipid metabolism correlating to the MASH progression. Differentially expressed genes (DEG) from RNA sequencing in WDsiAATF were enriched in pathways such as the downregulation of ceramide and sphingolipids, the fatty acyl CoA metabolic process, regulation of lipid localization, and transport (**Fig. 6A and 6B)**. Based on this observation, we further validated the genes involved in fatty acid synthesis, such as FASN, ACC1, ACC2, and SCD1, and found that lipogenic genes were significantly downregulated in WDsiAATF mice compared to WDC (**Fig. 6C)**.

To comprehend the significance of the dysregulated metabolites for specific biological processes, a metabolic pathway analysis was conducted using the online tool MetaboAnalyst 6.0. The KEGG pathway enrichment analysis revealed that 74 pathways were enriched by the differentially expressed metabolites (DEMs) in the WD siAATF vs. WD control groups. Of these, glycerophospholipid metabolism, ether lipid metabolism, nicotinamide metabolism, linoleic acid metabolism, riboflavin metabolism, and pyruvate metabolism were significantly upregulated upon hepatic silencing of AATF in MASH mice. In contrast, branched-chain amino acid biosynthesis, sulfur metabolism, and glycerolipid metabolism were downregulated **(Fig. 6D).** With the focus on only lipid-related pathways, DEMs were further enriched against the lipid superclass within the KEGG database, which unveiled the upregulation of glycerophospholipids (glycerophosphocholines, glycerophosphoserines, and glycerophosphoethanolamines), fatty esters, and eicosanoids in WDsiAATF mice **(Fig. 6E).** Delving deeper into lipid subclass analysis, phosphatidylcholine (PC), phosphatidylserine (PS), phosphatidyl ethanolamine (PE), lysoPC, lysoPE, lysoPS, and vitamin D3 were elevated in WDsiAATF mice **(Fig. 6F).**

Glycerophospholipids are key structural elements of cell membranes and are involved in several cell signaling pathways (16). Importantly, the disruption in the glycerophospholipid metabolism is known to compromise the stability of the membrane and thereby contribute to the development of MASLD (17). Along the same lines, a network analysis of putative interacting proteins of the metabolites significantly altered by hepatic silencing of AATF in WD mice was identified and enriched in the glycerophospholipid metabolism pathway in the KEGG database **(Fig. 7A)**. We further measured the relative abundance of glycerophospholipids and found that the levels of phosphocholine, phosphatidylcholine (PC), lysophophatidylethanolamine (LPE), and lysophosphatidylcholine (LPC) were all significantly increased in WD siAATF mice compared to WD controls (**Fig. 7B**). In support, differential gene expression analysis of the transcriptomics data revealed an increase in genes involved in glycerophospholipid metabolism in WDsiAATF mice (**Fig. 7C**). To gain deeper insights into the biological functions of the differentiated metabolites, a functional relationship network was constructed utilizing MetScape. The resulting network revealed that most of the metabolites were primarily involved in the metabolism of glycerophospholipids, linoleate, and phosphatidyl inositol (**Supplementary Fig. 4**). Furthermore, we investigated the relationships between parameters related to MASH (anthropometry, liver enzymes, lipid profile, blood glucose, and insulin levels) and metabolite signatures using a debiases sparse partial correlation (DSPC) network based on MetaboAnalyst software (**Fig. 7D**). The

correlation networks suggested that the majority of the metabolites belonging to glycerophospholipid metabolism showed strong positive interactions with each other and negative interactions with clinical variables, thus indicating that glycerophospholipid metabolism plays a crucial role in MASH pathogenesis. Collectively, these findings underscore the profound impact of AATF silencing on liver metabolites, particularly in the upregulation of glycerophospholipid biosynthesis.

The process of beta-oxidation of fatty acids plays a crucial role in the development of metabolic-associated steatotic hepatitis (MASH). When beta-oxidation pathways are disrupted, it leads to the accumulation of lipids in the liver, increased oxidative stress, and inflammation, all of which contribute to disease progression (34). In contrast, alpha-linolenic acid (ALA), an essential omega-3 (n-3) polyunsaturated fatty acid (PUFA), offers strong antioxidant benefits along with anti-inflammatory and lipid-lowering effects (36). Along similar lines, our studies revealed the upregulation of metabolites involved in the mitochondrial beta-oxidation pathway and alpha-linolenic acid metabolism alongside the biosynthesis of glycerophospholipids in WDsiAATF through pathway enrichment analysis using the SMPB database (**Fig. 8A**). Consistently, genes involved in fatty acid oxidation were upregulated in WDsiAATF mice (**Fig. 8B)**. Based on this, we proposed that silencing AATF enhances beta-oxidation of fatty acids, thereby improving MASH. Supporting this hypothesis, our results showed a significant upregulation of key genes involved in fatty acid oxidation, including carnitine palmitoyltransferase-1 alpha (CPT1α), acyl-CoA oxidase 1 (ACOX1), peroxisome proliferator-activated receptor gamma coactivator-1 alpha (PGC1α), and acyl-CoA synthetase long-chain family member 1 (ACSL1) in WD siAATF mice compared to the controls (**Fig. 8C**). Furthermore, to understand the possible interacting partners of AATF in regulating MASH progression, we performed an integrative analysis of AATF interacting proteins with the transcriptomic signature of the WDsiAATF group using the STRING and BioGRID databases (**Supplementary Fig. 5)**. The protein-protein interaction network showed that AATF is involved in the positive regulation of fatty acid metabolic processes via CD74 and MAPK9; however, further validation is needed to elucidate the signaling pathway.

Molecular mechanisms underlying hepatic AATF-driven MASH progression

mTORC1 (mammalian target of rapamycin complex 1) is a central regulator of cell growth and metabolism that contributes to the pathogenesis of MASH through its effects on lipid metabolism (37). In MASH, the activation of the AKT (protein kinase B) and mTORC1 signaling pathways is often dysregulated, contributing to the disease progression (38). We hypothesized that AATF silencing inactivates the AKT-mTORC1 signaling pathway to mobilize the hepatic lipid accumulation. Accordingly, we found that phosphorylation of AKT at Thr308 was inhibited in WDsiAATF mice compared to the WDC mice. Following this, activation of mTORC1, represented by the phosphorylation of mTOR and Raptor, was downregulated in WDsiAATF mice (**Fig. 8D)**. Further, SREBP1 levels were downregulated in WDsiAATF mice supporting the mTORC1 mediated lipogenesis (**Fig. 8E**). Previous studies have shown that mTORC1 inhibits lipolysis and β-oxidation of fatty acids (39,40). In our study, we found that inactivation of mTORC1 via AATF activates long-chain acyl-CoA dehydrogenase (LCAD), an enzyme crucial for the initiation of β-oxidation (**Fig. 8F**). Interestingly, PNPLA2 (Patatin-Like Phospholipase Domain-Containing Protein 2), an enzyme involved in lipolysis, particularly breakdown of triglycerides was unregulated in WDsiAATF mice compared to WDC (**Fig. 8G**). PNPLA2 is responsible for the conversion of triglycerides to diacylglycerol and free fatty acids which further undergoes glycerophospholipid synthesis and β-oxidation respectively (41). Collectively, hepatic silencing of AATF ameliorates MASH by enhancing

glycerophospholipid biosynthesis and β-oxidation of fatty acids via inhibition of AKT-mTORC1 signaling pathways (**Fig. 8H**).

Discussion

Metabolic dysfunction-associated steatotic liver disease (MASLD is a multifactorial condition influenced by various molecular drivers (5). Dysregulation of lipid metabolism is a hallmark of MASLD. Increased influx of free fatty acids (FFAs) from adipose tissue and dietary sources, along with impaired fatty acid oxidation and export of triglycerides from the liver, contribute to hepatic steatosis (11). Insulin resistance in hepatocytes leads to impaired suppression of gluconeogenesis and increased lipogenesis, promoting hepatic lipid accumulation (34). Several factors associated with metabolic dysfunction, including lipid accumulation, oxidative stress, and insulin resistance, can trigger ER stress in hepatocytes (33). Inflammatory pathways play a crucial role in the progression of MASLD from simple steatosis to MASH. Activation of inflammatory signaling pathways leads to the production of pro-inflammatory cytokines and chemokines, contributing to hepatocyte injury and fibrosis (42). Thus, identifying and understanding the molecular drivers involved in MASH pathogenesis is essential for developing targeted therapeutic strategies aimed at preventing disease progression and improving clinical outcomes for patients with MASLD. The evolving understanding of the disease underscores the urgent need for new therapeutic targets. The complex pathophysiology of MASH involves multiple metabolic, inflammatory, and fibrotic pathways, making it essential to identify novel targets that can address these different aspects. Advanced molecular profiling techniques, including transcriptomics, proteomics, metabolomics, lipidomics, and epigenomics, can provide valuable insights into the underlying mechanisms driving MASH and guide the development of personalized treatment approaches.

AATF has been implicated in the pathogenesis of several cancers due to its role in the modulation of apoptotic pathways (20). We, for the first time, elucidated how TNF-α upregulates the expression of AATF via SREBP-1 and promotes hepatocarcinogenesis (43). Further studies revealed the role of AATF in impeding HCC angiogenesis by downregulating PEDF (26). Recently, we investigated the role of AATF in MASH-HCC and showed that TACE inhibition by Marimastat prevents AATF-mediated inflammation, fibrosis, and oncogenesis (28). Building on these experimental findings, we sought to understand the role of AATF in MASH. In the current study, we explored for the first time how AATF regulates lipid metabolism and its implications in the development and progression of MASH. We employed a preclinical murine model of MASH comprising C57BL/6 mice that were fed a standard chow diet normal water, or western diet sugar water. This model effectively mimics the features of metabolic syndrome and MASH, including the progression of fibrosis. The mice develop fatty liver within 12 weeks of being fed with western diet sugar water, progressing to MASH and fibrosis by 24 weeks. This spectrum mirrors the dietary pattern, systemic milieu, and metabolic and histological characteristics of MASH, demonstrating the activation of key cellular pathways associated with human disease. This approach overcomes the constraint of the previously employed DIAMOND mouse model, which was an isogenic cross between C57BL/6J and 129S1/SvImJ mouse strains (32). Given that AATF was found to be upregulated in cellular, preclinical, and human MASH, we assessed the impact of liver-specific silencing of AATF on hepatic lipid accumulation in experimental MASH. Of note, while small interfering RNA (siRNA) was chosen for gene silencing, the approach employed in this study closely resembles the characteristics of short hairpin RNA (shRNA), particularly in terms of its stability. The technology developed by Applied Biological Materials Inc. (ABM) utilizes a convergent promoter vector system, which

allows the siRNA to be expressed in both directions, a feature typical of shRNA. Additionally, the AAV8 vector used for gene delivery offers tissue-specific targeting providing stability and sustained gene expression. We examined how this silencing affected the genes, proteins, and metabolites associated with the biological processes involved in the development and progression of MASH. The silencing of hepatic AATF showed a significant reduction in body weight and liver weight in WDSW mice and had no effect on CDNW mice. Insulin resistance was notably improved, and we also observed substantial improvement in both histological and biochemical parameters in WDsiAATF mice compared to WDC. In line with these findings, liver transcriptomics analysis and on-bench validations demonstrated that loss of AATF reduced cellular stress responses, leading to decreased inflammatory cytokines and fibrogenesis in WDSW mice. These results underscore the potential role of AATF in the progression of MASLD and set the groundwork for more detailed molecular investigations.

This is the first study to conduct both hepatic transcriptomic and metabolomic profiling in mice with AATF silenced. Since the precise mechanism(s) by which the loss of AATF alleviates MASH is unclear, we concentrated on detecting changes in liver metabolites in the experimental MASH group with AATF silencing compared to the control group using untargeted metabolomics, which offers a comprehensive overview of the entire metabolome. Based on transcriptomic analysis and our key interest in elucidating the role of AATF in lipid metabolism, we found it intriguing that the leading unregulated pathways among the 74 pathways enriched by differentially expressed metabolites (DEMs) in the WD siAATF compared to the WD control group included glycerophospholipid metabolism, ether lipid metabolism, nicotinamide metabolism, linoleic acid metabolism, riboflavin metabolism, and pyruvate metabolism. Notably, there was a marked increase in glycerophospholipids, particularly phosphatidylcholines (PC), phosphatidylserines (PS), and phosphatidylethanolamines (PE), in the WD siAATF mice. These subclasses of lipids are implicated in MASLD progression, where dysregulation of these glycerophospholipids is linked with insulin resistance, inflammation, and fibrosis, which are the hallmarks of MASLD (44). Additionally, their breakdown products like LysoPC, LysoPS, and LysoPE were also increased. The metabolite-metabolite interaction network highlighted the potential functional relationships of glycerophospholipid with linoleate metabolism. It is noteworthy that alpha-linolenic acid (ALA), an essential omega-3 fatty acid, is largely attributed to its anti-inflammatory, antioxidant, and lipid-lowering properties in MASLD (45). ALA can influence lipid metabolism by modulating the expression of genes involved in fatty acid oxidation and lipid synthesis. It also promotes the activation of peroxisome proliferator-activated receptors (PPARs), which play a crucial role in lipid metabolism (46).

Previous studies have also reported alterations in phospholipid content in the liver biopsies of MASH patients, suggesting that impaired phospholipid synthesis is associated with disease progression (14,15). The low hepatic phosphatidylcholine (PC) levels and the altered hepatic PC to phosphatidylethanolamine (PE) ratio appear to play significant roles in the development of MASLD (47). However, the pathophysiology of these lipid-induced processes remains not fully understood. Moreover, low PC levels have previously been shown to activate sterol regulatory element-binding protein 1 (SREBP1) (48). Essential phospholipids (EPLs) rich in PC are a widely used treatment option for fatty liver disease. There is substantial and consistent clinical evidence indicating that treatment with EPLs leads to the regression of steatosis (49). Studies show that phosphatidylcholine metabolism intersects with various metabolic pathways, and optimizing PC levels could potentially help regulate lipid metabolism and insulin sensitivity, thereby mitigating

MASLD progression (50). In addition, PC may have antioxidant properties, which could counteract oxidative damage in the liver and protect against disease progression (51). In addition to various lipid classes, the liver metabolite profile in WDsiAATF mice showed decreased branched-chain amino acid metabolism and sulfur metabolism involved in the MASH pathogenesis in contrast to increased pyruvate metabolism, NAD and FAD metabolism, as well as one-carbon metabolic pathways. The effect of AATF silencing on non-lipid metabolic pathways reveals new dimensions of AATF's functional significance in MASLD (data not shown; manuscript under preparation).

Another intriguing observation in the current study using pathway enrichment analysis is the upregulation of mitochondrial beta-oxidation of the fatty acid pathway in WDsiAATF mice. Fatty acid oxidation (FAO) helps to efficiently metabolize fatty acids, and thereby enhanced beta-oxidation may alleviate inflammation and oxidative stress in the liver, which are key drivers of MASLD progression (52). Several genes, such as CPT1α, PPARs, and acyl CoA oxidase, encode enzymes involved in FAO, and henceforth, upregulated expression of these genes would enhance fatty acid oxidation capacity, potentially improving metabolic health (53,54). Consistent with this, our study also showed the upregulation of CPT1, PGC1α, ACOX1, and ACSL1 genes in the liver tissue of WDsiAATF compared to WDC. The development of hepatic steatosis is primarily associated with the excessive accumulation of triglycerides in hepatocytes. Our research suggests that loss of hepatic AATF may redirect the liver's metabolism from triglyceride synthesis to the production of diacylglycerol (DAG) and, subsequently, glycerophospholipids, helping to manage or decrease fat accumulation in the liver. Furthermore, increased fatty acid oxidation could mobilize the stored triglycerides, improving metabolic balance, decreasing oxidative stress, and potentially alleviating MASH. An in-depth targeted lipidomics coupled with triglyceride profiling will yield definitive insights, and this is the central focus of our forthcoming research. Interestingly, the protein-protein interaction network of AATF-interacting proteins with the transcriptomic profile of WDsiAATF revealed CD74 as a possible link between AATF and lipid metabolism. Supporting this, studies by Li et al. have shown that CD74 levels were positively correlated with triglyceride levels in human atherosclerotic lesions (55).

Studies by Ishigaki et al. have shown that AATF activates AKT under cellular stress to promote cell survival (56). AKT phosphorylated at Thr308 activates mTORC1, which particularly plays a dominant role in promoting lipogenesis and inhibiting lipid breakdown (57, 58). Thus, we evaluated the effect of the AATF-AKT-mTOR signaling pathway on hepatic lipid metabolism. AATF silencing effectively inactivated mTORC1 activation by AKT, further affecting the lipogenic genes such as SREBP1, FASN, and ACC. Inactivated mTORC1 complex led to the upregulation of LCAD, a key enzyme required to initiate the β-oxidation of fatty acids. Moreover, mTORC1 suppresses PNPLA2, a key lipase involved in the lipolysis of triglyceride to diacylglycerol and free fatty acids (59). The stored fat is mobilized in the form of diacylglycerol, a precursor for glycerophospholipids and free fatty acids, which undergoes β-oxidation for energy production. In our study, AATF silencing increased the PNPLA2 levels which is reflected by the decreased triglyceride levels and upregulated glycerophospholipid synthesis and β-oxidation in WDsiAATF mice.

Despite the extensive studies on MASLD, there is a need to understand the interplay between the molecular drivers involved in lipid metabolism, insulin resistance, oxidative stress, and inflammation that contribute to the pathogenesis of MASLD. This study offers insight for the first time on the involvement of AATF in hepatic lipid metabolism. Further investigations of the lab aim to develop liver-specific AATF knockout mice, allowing for an in-depth exploration of AATF's effects at different

stages of MASLD. Additionally, examining the interactions between the liver, adipose tissue, and skeletal muscles provides a deeper understanding of AATF's role in lipid metabolism. Consequently, this study offers a promising target for intervention and guides future research efforts to address MASH.

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Author Contributions

Conceptualization: A.N.S., D.P.K. Methodology: A.N.S, D.S., M.M., P.A., D.P.K. Investigation: A.N.S., P.K.S., D.S., S.P.S., S.M.M., D.P.K. Formal Analysis: A.N.S, D.S., M.M., G.R., P.K.S., D.P.K. Visualization: A.N.S., D.P.K. Resources: A.N.S,

M.M., G.R., S.P.S., S.M.M., P.K.S., D.P.K. Supervision: A.N.S., D.P.K. Funding Acquisition: D.P.K. Writing- original draft: A.N.S., D.P.K. Writing- Review and Editing: All authors.

Competing interest

The authors declare that there are no conflicts of interest.

Figure Legends

Figure 1. Hepatic silencing of AATF improves metabolic health in experimental MASH

(A) Study design- C57Bl/6 mice were fed chow diet normal water (CD) or western diet sugar water (WD) for 12 weeks. Liver-specific AAV8-TBG-siControl (Control) or AAV8-TBG-siAATF (siAATF) were injected via tail vein into mice and monitored for an additional 12 weeks. (B) Tissue distribution of Control and siAATF in the experimental mice. (C) liver-specific, and (D) hepatocyte-specific AATF silencing as determined by qRT-PCR and western blot. Mean±SEM for n=4 mice per group, **p<0.001 compared to AAV8 control, unpaired t-test. (E) Body weight, (F) liver weight, (G) liver-body weight ratio, and (H) adipose tissue weight was determined. Mean±SEM for 6-8 mice per group, ##p<0.001 compared to CD control; **p<0.001 compared to WD control, unpaired t-test. i Glucose tolerance test and j insulin tolerance test were performed. Mean±SEM for 6-8 mice per group, ##p<0.001 compared to CD control; **p<0.001 compared to WD control, unpaired t-test. AAV; adeno-associated virus, TBG; tyrosine binding globulin, AATF; apoptosis antagonizing transcription factor, CD; chow diet, WD; western diet.

Figure 2. Hepatic loss of AATF improves liver injury and impaired lipid metabolism in MASH mice

Mice were euthanized after 24 weeks and blood was collected. (A) Fasting blood glucose, (B) fasting insulin, and (C) HOMA-IR were determined. (D) Serum levels of ALT, (E) AST, (F) total cholesterol, (G) triglycerides, and (H) LDL-cholesterol were measured. Mean±SEM for 6-8 mice per group, ##p<0.001 compared to CD control; **p<0.001 compared to WD control, unpaired t-test. (I) Representative gross liver images, (J) H&E staining, and (K) Oil Red O staining of the mice liver tissues. n=6 mice per group. Scale bar 50 µm. (L) Histology scores were calculated for mice liver sections. Representative images and scoring of steatosis, lobular inflammation, hepatocyte ballooning, and MASLD activity score. Mean ±SEM for 6-8 mice per group. Scale bar 50 µm, unpaired t-test. **p<0.001 compared to WD control. HOMA-IR; homeostatic model assessment for insulin resistance, ALT, alanine transaminase; AST, aspartate transaminase; LDL; low-density lipoprotein, MASLD; metabolic dysfunction associated steatotic liver disease, CD; chow diet, WD; western diet.

Figure 3: Effect of AATF silencing on hepatic transcriptomic and metabolic profiles in experimental MASH

C57Bl/6 mice were fed chow diet normal water (CD) or western diet sugar water (WD) for 12 weeks. Liver-specific AAV8-TBG-siControl (Control) or AAV8-TBG-siAATF (siAATF) were injected via the tail vein into mice and monitored for an additional 12 weeks. After mice were euthanized, liver tissues were subjected to transcriptomic and untargeted metabolomic analyses. In transcriptomics, (A) PLS-DA plot among the four groups showing a clear group separation between the groups. (B) sample-sample correlation within the four groups. (C) Volcano plot for differentially expressed genes in WDsiAATF vs. WDC groups. The x-axis denotes fold change in expression (log2 scale), y-axis denotes adjusted p-value (negative log10 scale) for the analyzed genes in the data set (each dot represents a single

gene). Red and green dots represent genes significantly upregulated and downregulated, respectively. Blue dots ($p<0.05$) and grey dots represent nonsignificant genes. (DESeq2; cut-offs used: adjusted p-value < 0.05 and log fold change ≥ 2). (D) Top 10 up and downregulated KEGG pathways, GO-BP, and GO-MF in WDsiAATF vs. WDC groups. In metabolomics, (E) PLS-DA plot among the four groups shows a clear group separation between the groups. (F) Venn diagram showing the up and downregulated metabolites between the WDC vs. CDC and WDsiAATF vs. WDC. (G) Volcano plot for differential metabolites in WDsiAATF vs. WDC. Red and green dots represent metabolites significantly upregulated and downregulated, respectively. Blue dots ($p<0.05$) and grey dots represent nonsignificant metabolites. n=3. CD; chow diet, WD; western diet, AAV; adeno-associated virus, TBG; tyrosine binding globulin, AATF; apoptosis antagonizing transcription factor, PLS-DA; partial least squares discriminant analysis, WDC; western diet control, KEGG; Kyoto encyclopedia of genes and genomes, GO; gene ontology, BP; biological processes, MF; molecular function.

Figure 4. Effect of silencing hepatic AATF on cellular stress and inflammation in experimental MASH

Transcriptomic analysis of liver tissues from mice fed with chow diet normal water (CD) or western diet sugar water (WD) administered with AAV8-TBG-siControl or AAV8-TBG-siAATF, n=3 (A) p-value plot of cellular stress-related pathways. (B) heatmap of cellular stress-related genes. (C) hepatic mRNA expression of ER stress markers- CHOP, Grp78, PERK, and ATF4. Mean±SEM, n=4, unpaired t-test. (D) p-value plot of inflammation-related pathways. (E) heatmap of inflammation-related genes. (F) hepatic mRNA expression of inflammatory markers- IL-1β, IL-6, and TNF-α, and serum TNF- α by ELISA. Liver tissue lysates were used for immunoblotting of inflammatory markers- (G) pJNK and (H) pERK1/2. (I) F4/80 staining, Scale bar 50 µm. Mean ±SEM, n=4, unpaired t-test. $^{\#\#}p<0.001$ or $^{\#}p<0.05$ compared to CD control; $^{**}p<0.001$ or $^{*}p<0.05$ compared to WD control. CD; chow diet, WD; western diet, AAV; adeno-associated virus, TBG; tyrosine binding globulin, AATF; apoptosis antagonizing transcription factor, CHOP; C/EBP homologous protein, GRP78; glucose-regulated protein 78, PERK; protein kinase R (PKR)-like endoplasmic reticulum kinase, ATF4; activating transcription factor 4, IL; interleukins, TNF-α; tumor necrosis factor-alpha, ELISA; enzyme-linked immunosorbent assay.

Figure 5. Silencing of hepatic AATF ameliorates liver fibrosis

Transcriptomic analysis of liver tissues (n=3) showing (A) p-value plot of fibrosis-related pathways. (B) Heatmap of fibrosis-related genes. (C) Hepatic mRNA expression of Col1A1, Col3A1, α-SMA, and TGF-β quantified. Mean ±SEM, n=4, unpaired t-test. (D) Representative images of picrosirius red staining with fibrosis scoring. (E) Desmin immunostaining with scoring. Scale bar 50 µm. Mean ±SEM for 6-8 mice, unpaired t-test. $^{\#\#}p<0.001$ or $^{\#}p<0.05$ compared to CD control; $^{**}p<0.001$ compared to WD control. Col; collagen, α-SMA; alpha-smooth muscle actin, TGF- β; transforming growth factor-beta. CD; chow diet, WD; western diet

Figure 6. Effect of silencing hepatic AATF on lipid metabolism in MASH mice

Transcriptomic analysis of liver tissues (n=3) showing (A) p-value plot of lipid metabolism-related pathways. (B) Heatmap of lipid metabolism-related genes. (C) Hepatic mRNA expression of FASN, ACC1, ACC2, and SCD1 were evaluated. Mean ±SEM, n=4, unpaired t-test. Untargeted metabolomics was carried out in mice liver tissues n=3. (D) Bubble plots showing the top 20 KEGG pathways enrichment, (E) lipid superclass, and (F) lipid subclass using the mummichog GSEA algorithm in WDC vs. WDsiAATF. $P<0.05$ were considered significant. CD; chow diet, WD; western diet, AAV; adeno-associated virus, TBG; tyrosine binding globulin, AATF; apoptosis antagonizing transcription factor, FASN; fatty acid synthase, ACC; acetyl-

coa carboxylase, SCD; stearoyl-coa 9-desaturase, KEGG; Kyoto encyclopedia of genes and genomes, GSEA; gene set enrichment analysis.

Figure 7. Metabolic networking of glycerophospholipid metabolism
Transcriptomics and untargeted metabolomics were carried out in mice liver tissues n=3. Metabolites of glycerophospholipid metabolism were analyzed and functional correlation network analysis was carried out. (A) The glycerophospholipid metabolism pathway visualized in the pathview network highlights the dysregulated compounds (up/downregulated) in WDsiAATF vs. WDC. (B) Relative abundance of phosphocholine, PC (phosphatidylcholine), LPE (lysophophatidylethanolamine), and LPC (lysophosphatidylcholine). **p<0.001 or *p<0.05 compared to WDC. (C) Heatmap of genes involved in glycerophospholipid metabolism. (D) Debiased sparse partial correlation network plot visualizing the major relationships of glycerophospholipid metabolic alterations with the clinical variables. Statistical significance was analyzed by a student's t-test. P<0.05 were considered significant. CD; chow diet, WD; western diet, AATF; apoptosis antagonizing transcription factor.

Figure 8. Hepatic loss of AATF alters lipid metabolism via AKT-mTORC1 signaling pathways in MASH mice
Transcriptomics and untargeted metabolomics were carried out in mice liver tissues n=3. Pathway analysis and enrichment analysis of both the data were carried out. An enrichment analysis based on the Small Molecule Pathway Database (SMPDB) was performed on metabolites. (A) upregulated and downregulated pathways. (B) heatmap of genes involved in fatty acid oxidation. (C) hepatic mRNA expression of CPT-1α, ACOX1, PGC-1α, and ACSL1. (D) Liver tissue lysates were used for immunoblotting of pAKT (Thr308), pmTOR, and Raptor. Hepatic mRNA expression of (E) SREBP1, (F) LCAD, and (G) PNPLA2. Mean±SEM, n=4, unpaired t-test, **P < 0.001 or *P < 0.05 compared to WDC. (E) Schematic representation of the effect of hepatic AATF silencing in experimental MASH. ACOX1; Acyl-CoA Oxidase 1, PGC1; Peroxisome proliferator-activated receptor gamma coactivator-1alpha, ACSL1; acyl-CoA synthetase long-chain family member 1, AKT; protein kinase B, mTOR; mammalian target of rapamycin, SREBP1; sterol regulatory element-binding protein 1, LCAD; long-chain acyl-CoA dehydrogenase, PNPLA2; patatin-like phospholipase domain-containing protein 2.

Supplementary Figure legends

Supplementary Figure 1: Expression of AATF in the cellular, preclinical, and clinical samples of MASH
HepG2 and Huh7 cells were treated with 0.5mM of SP, SO, or SP+SO for 24 hours. (A) Lipid accumulation was determined by Oil Red O staining, scale bar 50 µm. (B) mRNA expression of AATF in HepG2. (C) mRNA expression of AATF in Huh7 cells. (D) Protein levels of AATF in HepG2 and Huh7 cells. Mean±SEM, n=3, **p<0.001 or *P < 0.05 compared to control, unpaired t-test. The diet-induced MASH model was developed by feeding the mice with chow diet normal water (CD) or western diet sugar water (WD) for 24 weeks. (E) Representative H&E images and AATF immunohistochemistry of Normal, MASL (12 weeks), and MASH (24 weeks) stages in mice liver tissue, scale bar 50 µm. (F) Hepatic mRNA expression. (G) Protein levels of AATF in normal, MAFL, and MASH liver tissue of mice. Mean±SEM for 6-8 mice per group, **p<0.001 compared to normal, unpaired t-test. (H) Representative H&E images of human normal (n=8), MASL (n=15), and MASH (n=15) liver tissues, scale bar 50 µm. (I) mRNA expression of AATF, and (J) protein expression of AATF in control, MAFL, and MASH human liver biopsy samples. **p<0.001 compared to normal, unpaired t-test. SP; sodium palmitate, SO; sodium oleate. AATF; apoptosis

antagonizing transcription factor, MASL, metabolic dysfunction-associated steatotic liver, MASH, metabolic dysfunction-associated steatohepatitis.

Supplementary Figure 2: (A) Weekly measurement of body weight from week 12 to week 24 followed by the administration of AAV8-TBG-siControl (Control) and AAV8-TBG-siAATF (siAATF) at week 12 to the chow diet normal water (CD) and western diet sugar water (WD) fed mice. (B) Food intake and (C) Calorie intake in mice. Mean±SEM for 6-8 mice per group, one-way ANOVA.

Supplementary Figure 3: (A) Volcano plot presentation of differentially expressed genes between liver samples of mice from WDC and CDC. (B) Volcano plot presentation of differentially expressed genes between liver samples of mice from CDsiAATF and CDC. (C) Volcano plot presentation of differential metabolites from liver samples of mice from WDC and CDC. (D) Volcano plot presentation of differential metabolites from liver samples of mice from CDsiAATF and CDC. x-axis denotes fold change in expression (log2 scale), y-axis denotes adjusted p-value (negative log10 scale) for the analyzed genes or metabolites in the data set (each dot represents a single gene or metabolite). Red and green dots represent genes or metabolites significantly upregulated and downregulated, respectively. Blue dots ($p<0.05$) and grey dots represent nonsignificant genes or metabolites. (DESeq2; cut-offs used: adjusted p-value < 0.05 and log fold change ≥ 2).

Supplementary Figure 4: Metabolite functional interaction network of glycerophospholipid metabolism pathway in WDsiAATF and WDC.

Supplementary Figure 5: Protein-protein interaction of AATF interacting proteins with the lipid metabolism-related proteins was determined using BioGRID and STRING database and visualized in Cytoscape.

Supplementary Table 1: List of primer sequences used in qRT-PCR in the study.

Figure 1

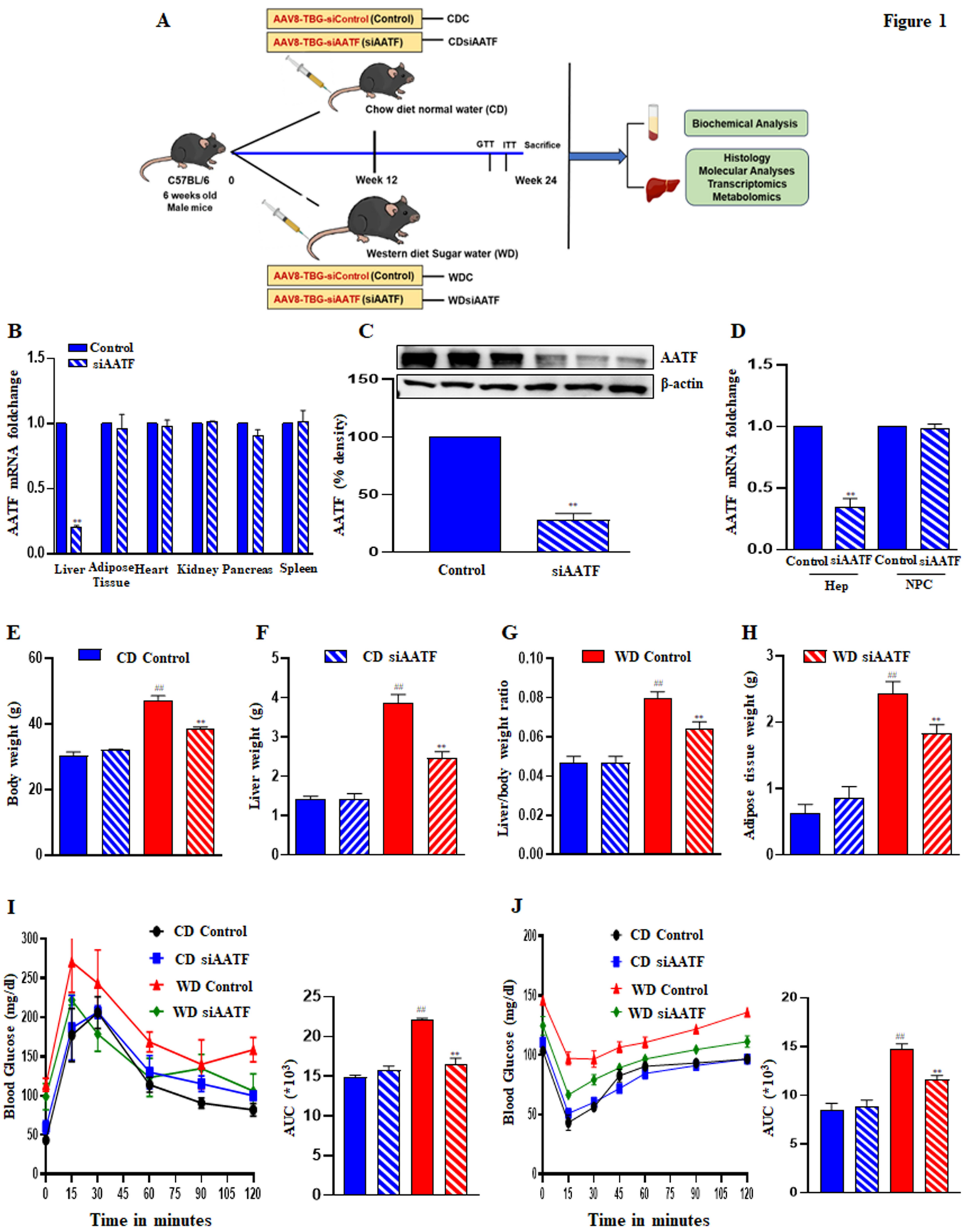

A
AAV8-TBG-siControl (Control)
CDC
AAV8-TBG-siAATF (siAATF)
CDsiAATF
Chow diet normal water (CD)
C57BL/6
6 weeks old
Male mice
0
Week 12
GTT
ITT
Sacrifice
Week 24
Biochemical Analysis
Histology
Molecular Analyses
Transcriptomics
Metabolomics
Western diet Sugar water (WD)
AAV8-TBG-siControl (Control)
WDC
AAV8-TBG-siAATF (siAATF)
WDsiAATF
B
Control
siAATF
AATF mRNA foldchange
Liver
Adipose Tissue
Heart
Kidney
Pancreas
Spleen
C
AATF
β-actin
AATF (% density)
Control
siAATF
D
AATF mRNA foldchange
Control
siAATF
Control
siAATF
Hep
NPC
E
CD Control
Body weight (g)
F
CD siAATF
Liver weight (g)
G
WD Control
Liver/body weight ratio
H
WD siAATF
Adipose tissue weight (g)
I
CD Control
CD siAATF
WD Control
WD siAATF
Blood Glucose (mg/dl)
Time in minutes
AUC (*10³)
J
CD Control
CD siAATF
WD Control
WD siAATF
Blood Glucose (mg/dl)
Time in minutes
AUC (*10³)

Figure 2

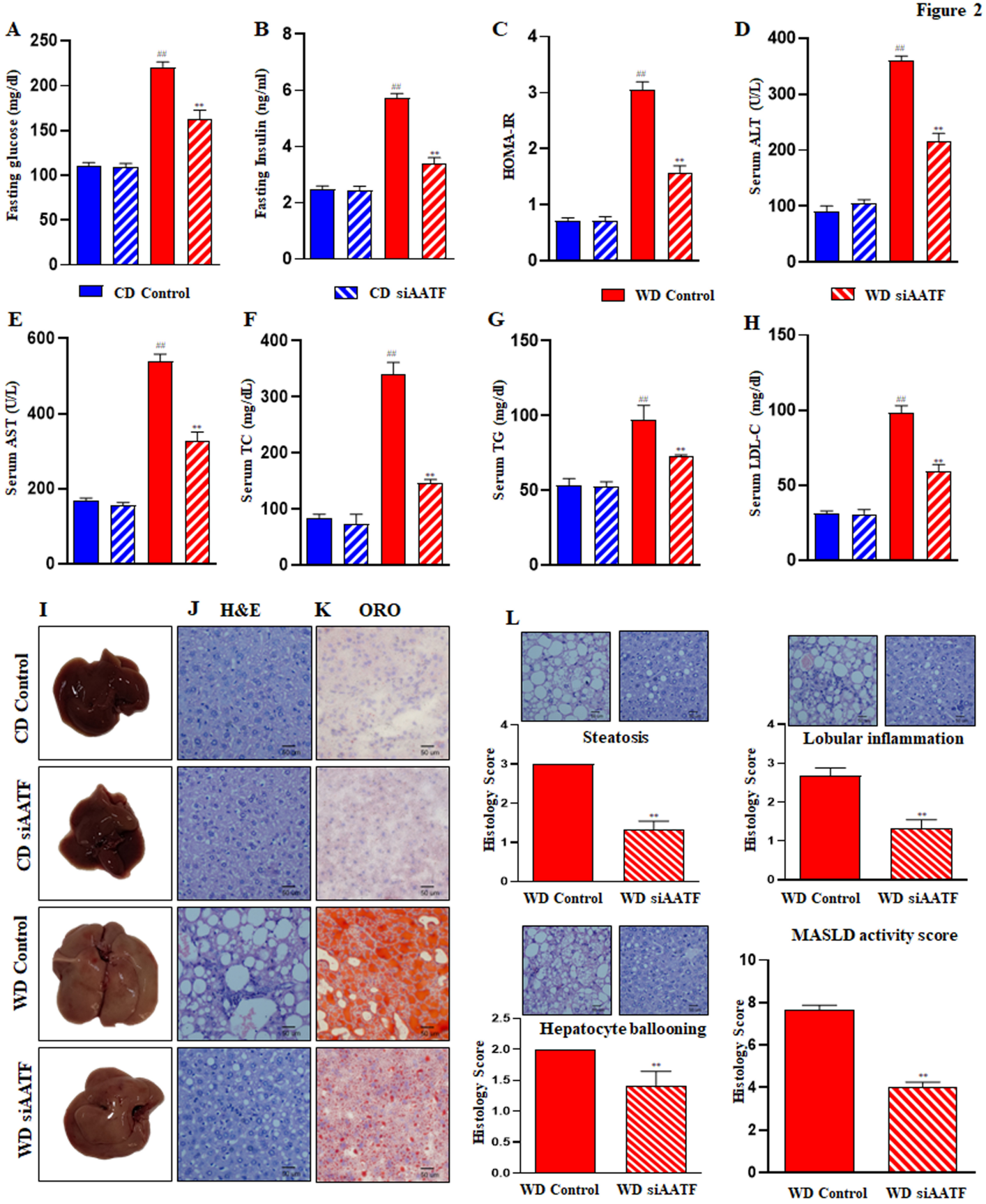

A
Fasting glucose (mg/dl)
B
Fasting Insulin (ng/ml)
C
HOMA-IR
D
Serum ALT (U/L)
CD Control
CD siAATF
WD Control
WD siAATF
E
Serum AST (U/L)
F
Serum TC (mg/dL)
G
Serum TG (mg/dl)
H
Serum LDL-C (mg/dl)
I
J H&E
K ORO
CD Control
CD siAATF
WD Control
WD siAATF
L
Steatosis
Lobular inflammation
Hepatocyte ballooning
MASLD activity score
Histology Score
WD Control
WD siAATF

Figure 3

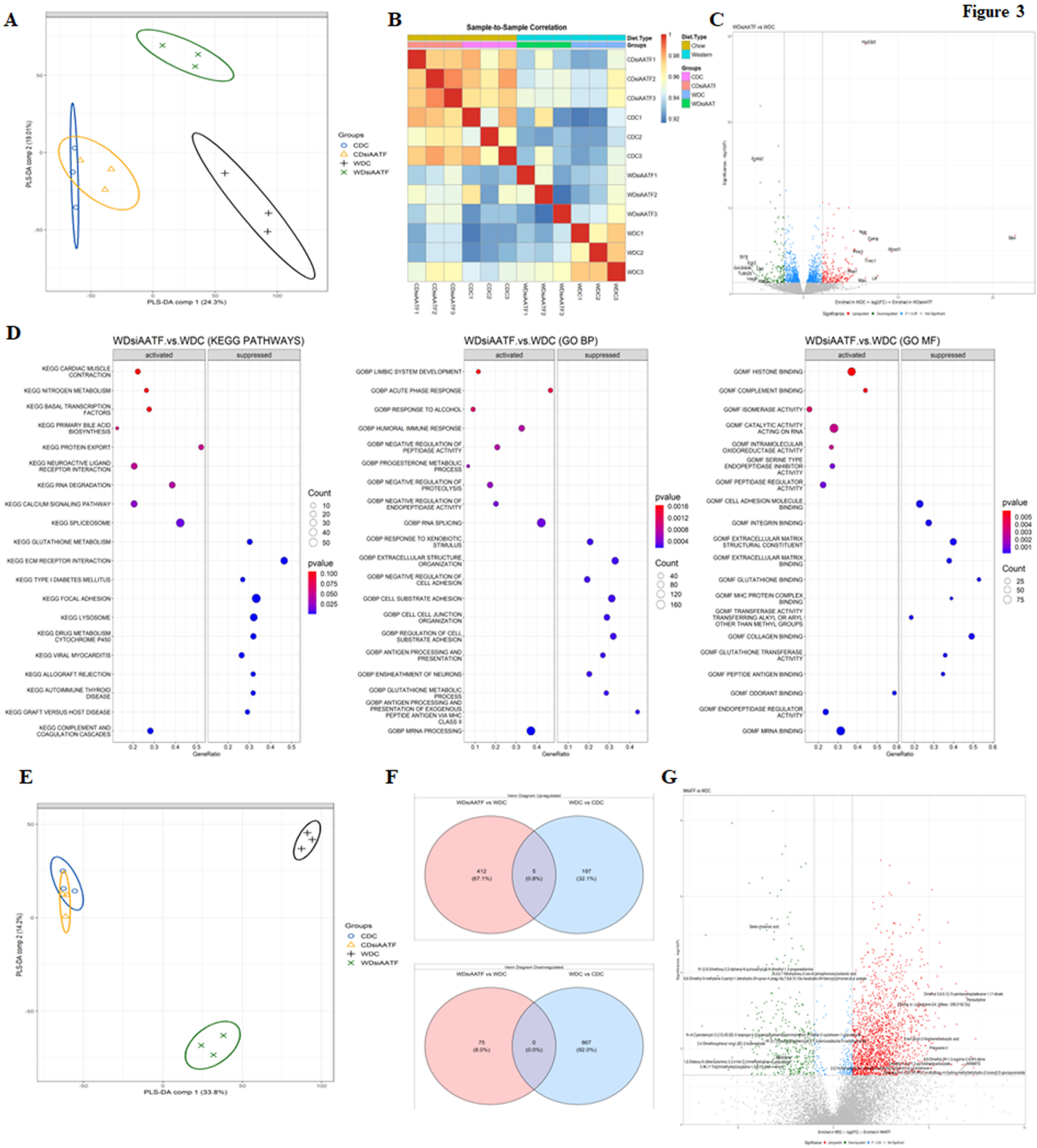

A
PLS-DA comp 1 (24.3%)
PLS-DA comp 2 (19.01%)
Groups
CDC
CDsiAATF
WDC
WDsiAATF
B
Sample-to-Sample Correlation
Diet.Type
Groups
Chow
Western
CDC
CDsiAATF
WDC
WDsiAAT
C
WDsiAATF vs WDC
D
WDsiAATF.vs.WDC (KEGG PATHWAYS)
activated
suppressed
KEGG CARDIAC MUSCLE CONTRACTION
KEGG NITROGEN METABOLISM
KEGG BASAL TRANSCRIPTION FACTORS
KEGG PRIMARY BILE ACID BIOSYNTHESIS
KEGG PROTEIN EXPORT
KEGG NEUROACTIVE LIGAND RECEPTOR INTERACTION
KEGG RNA DEGRADATION
KEGG CALCIUM SIGNALING PATHWAY
KEGG SPLICEOSOME
KEGG GLUTATHIONE METABOLISM
KEGG ECM RECEPTOR INTERACTION
KEGG TYPE I DIABETES MELLITUS
KEGG FOCAL ADHESION
KEGG LYSOSOME
KEGG DRUG METABOLISM CYTOCHROME P450
KEGG VIRAL MYOCARDITIS
KEGG ALLOGRAFT REJECTION
KEGG AUTOIMMUNE THYROID DISEASE
KEGG GRAFT VERSUS HOST DISEASE
KEGG COMPLEMENT AND COAGULATION CASCADES
GeneRatio
Count
pvalue
WDsiAATF.vs.WDC (GO BP)
GOBP LIMBIC SYSTEM DEVELOPMENT
GOBP ACUTE PHASE RESPONSE
GOBP RESPONSE TO ALCOHOL
GOBP HUMORAL IMMUNE RESPONSE
GOBP NEGATIVE REGULATION OF PEPTIDASE ACTIVITY
GOBP PROGESTERONE METABOLIC PROCESS
GOBP NEGATIVE REGULATION OF PROTEOLYSIS
GOBP NEGATIVE REGULATION OF ENDOPEPTIDASE ACTIVITY
GOBP RNA SPLICING
GOBP RESPONSE TO XENOBIOTIC STIMULUS
GOBP EXTRACELLULAR STRUCTURE ORGANIZATION
GOBP NEGATIVE REGULATION OF CELL ADHESION
GOBP CELL SUBSTRATE ADHESION
GOBP CELL CELL JUNCTION ORGANIZATION
GOBP REGULATION OF CELL SUBSTRATE ADHESION
GOBP ANTIGEN PROCESSING AND PRESENTATION
GOBP ENSHEATHMENT OF NEURONS
GOBP GLUTATHIONE METABOLIC PROCESS
GOBP ANTIGEN PROCESSING AND PRESENTATION OF EXOGENOUS PEPTIDE ANTIGEN VIA MHC CLASS II
GOBP MRNA PROCESSING
WDsiAATF.vs.WDC (GO MF)
GOMF HISTONE BINDING
GOMF COMPLEMENT BINDING
GOMF ISOMERASE ACTIVITY
GOMF CATALYTIC ACTIVITY ACTING ON RNA
GOMF INTRAMOLECULAR OXIDOREDUCTASE ACTIVITY
GOMF SERINE TYPE ENDOPEPTIDASE INHIBITOR ACTIVITY
GOMF PEPTIDASE REGULATOR ACTIVITY
GOMF CELL ADHESION MOLECULE BINDING
GOMF INTEGRIN BINDING
GOMF EXTRACELLULAR MATRIX STRUCTURAL CONSTITUENT
GOMF EXTRACELLULAR MATRIX BINDING
GOMF GLUTATHIONE BINDING
GOMF MHC PROTEIN COMPLEX BINDING
GOMF TRANSFERASE ACTIVITY TRANSFERRING ALKYL OR ARYL OTHER THAN METHYL GROUPS
GOMF COLLAGEN BINDING
GOMF GLUTATHIONE TRANSFERASE ACTIVITY
GOMF PEPTIDE ANTIGEN BINDING
GOMF ODORANT BINDING
GOMF ENDOPEPTIDASE REGULATOR ACTIVITY
GOMF MRNA BINDING
E
PLS-DA comp 1 (33.8%)
PLS-DA comp 2 (14.2%)
F
WDsiAATF vs WDC
WDC vs CDC
412 (67.1%)
5 (0.8%)
197 (32.1%)
75 (8.0%)
0 (0.0%)
867 (92.0%)
G
WAATF vs WDC

Figure 4

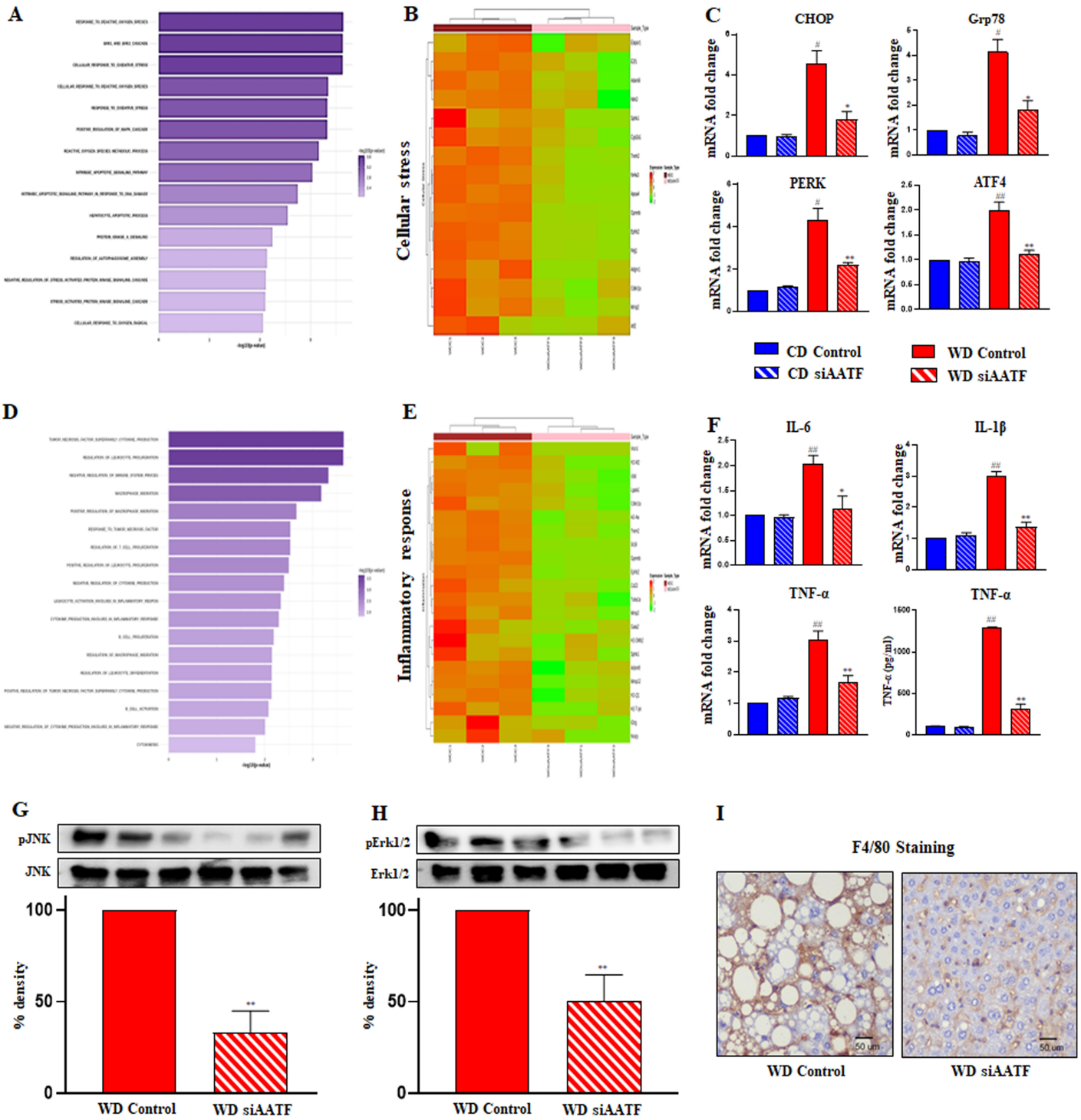

A
B
Cellular stress
C
CHOP
Grp78
PERK
ATF4
mRNA fold change
CD Control
CD siAATF
WD Control
WD siAATF
D
E
Inflammatory response
F
IL-6
IL-1β
TNF-α
TNF-α (pg/ml)
G
pJNK
JNK
% density
WD Control
WD siAATF
H
pErk1/2
Erk1/2
I
F4/80 Staining
50 um

Figure 5

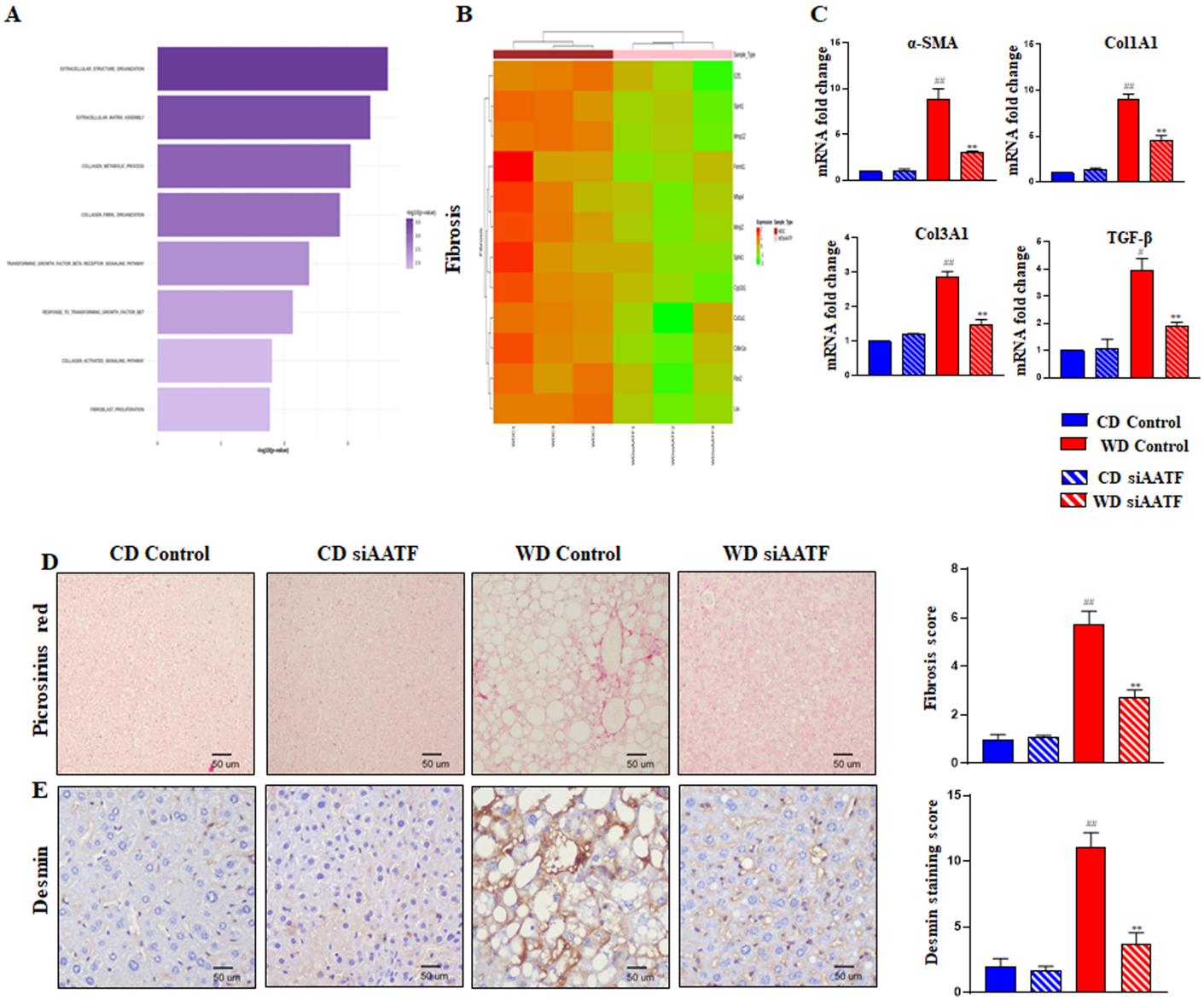

A
B
C
Fibrosis
α-SMA
Col1A1
Col3A1
TGF-β
mRNA fold change
CD Control
WD Control
CD siAATF
WD siAATF
D
E
Picrosirius red
Desmin
50 um
Fibrosis score
Desmin staining score

Figure 6

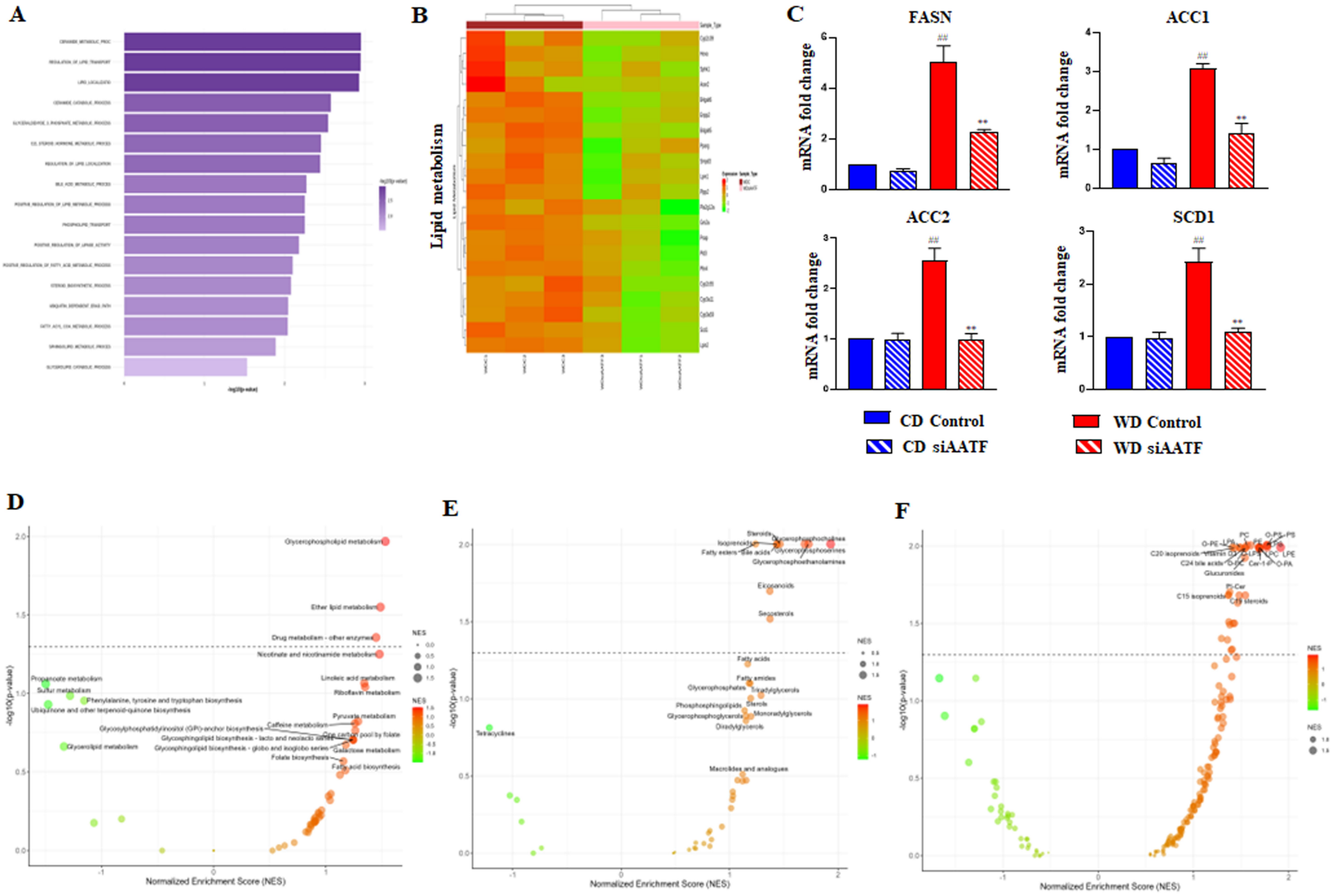

A
B
Lipid metabolism
C
FASN
ACC1
ACC2
SCD1
mRNA fold change
CD Control
CD siAATF
WD Control
WD siAATF
D
E
F
Normalized Enrichment Score (NES)
-log10(p-value)
NES

Figure 7

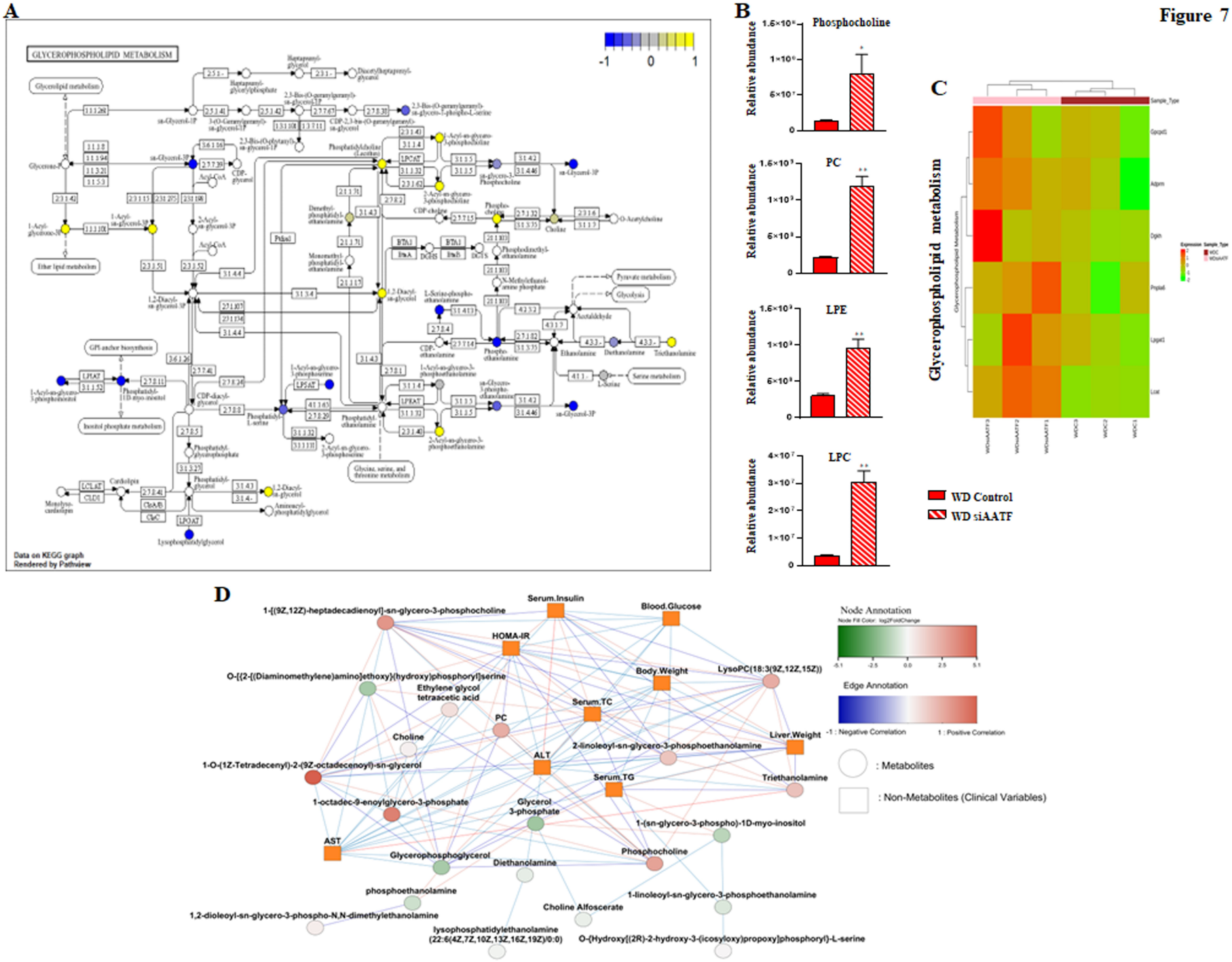
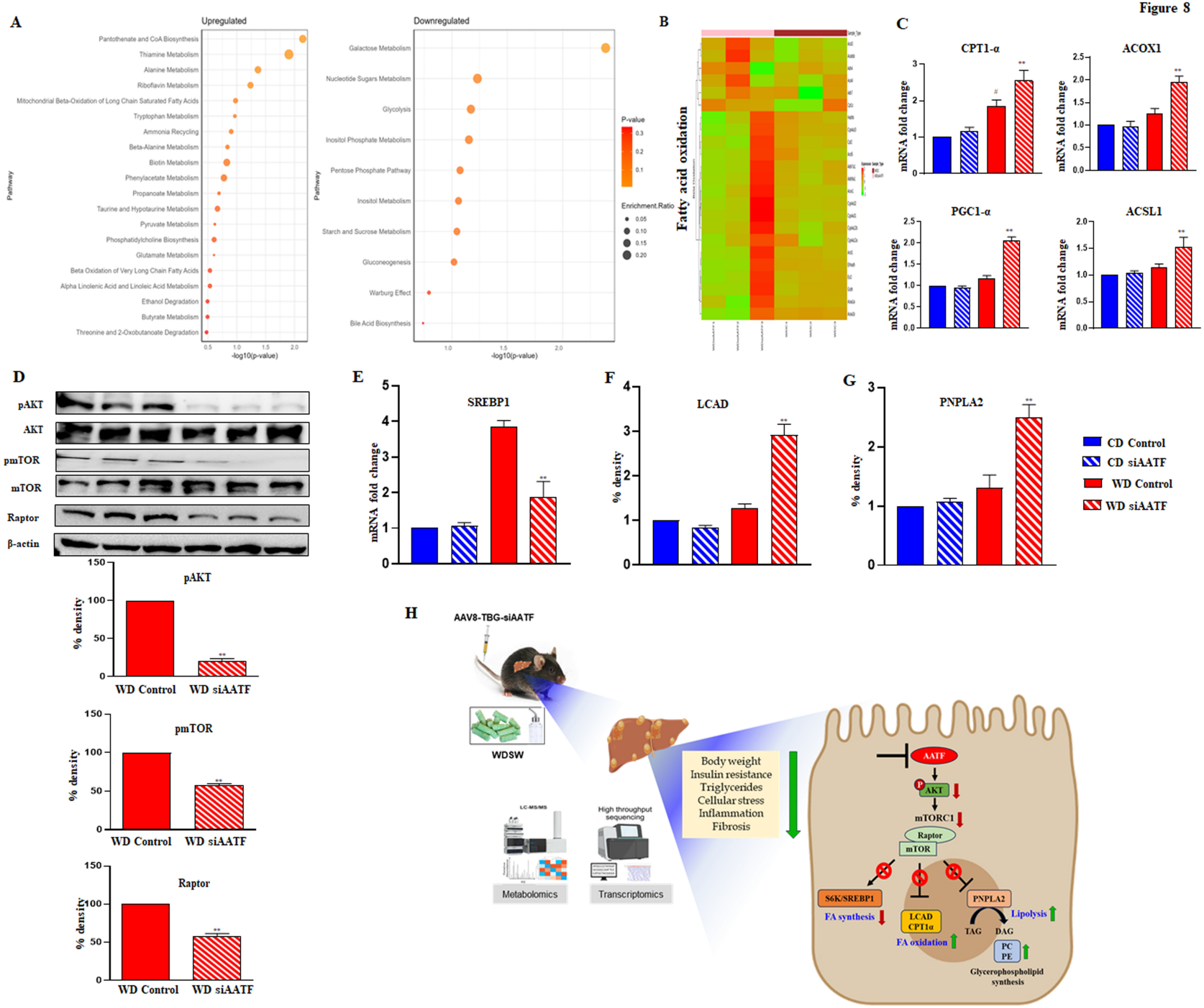
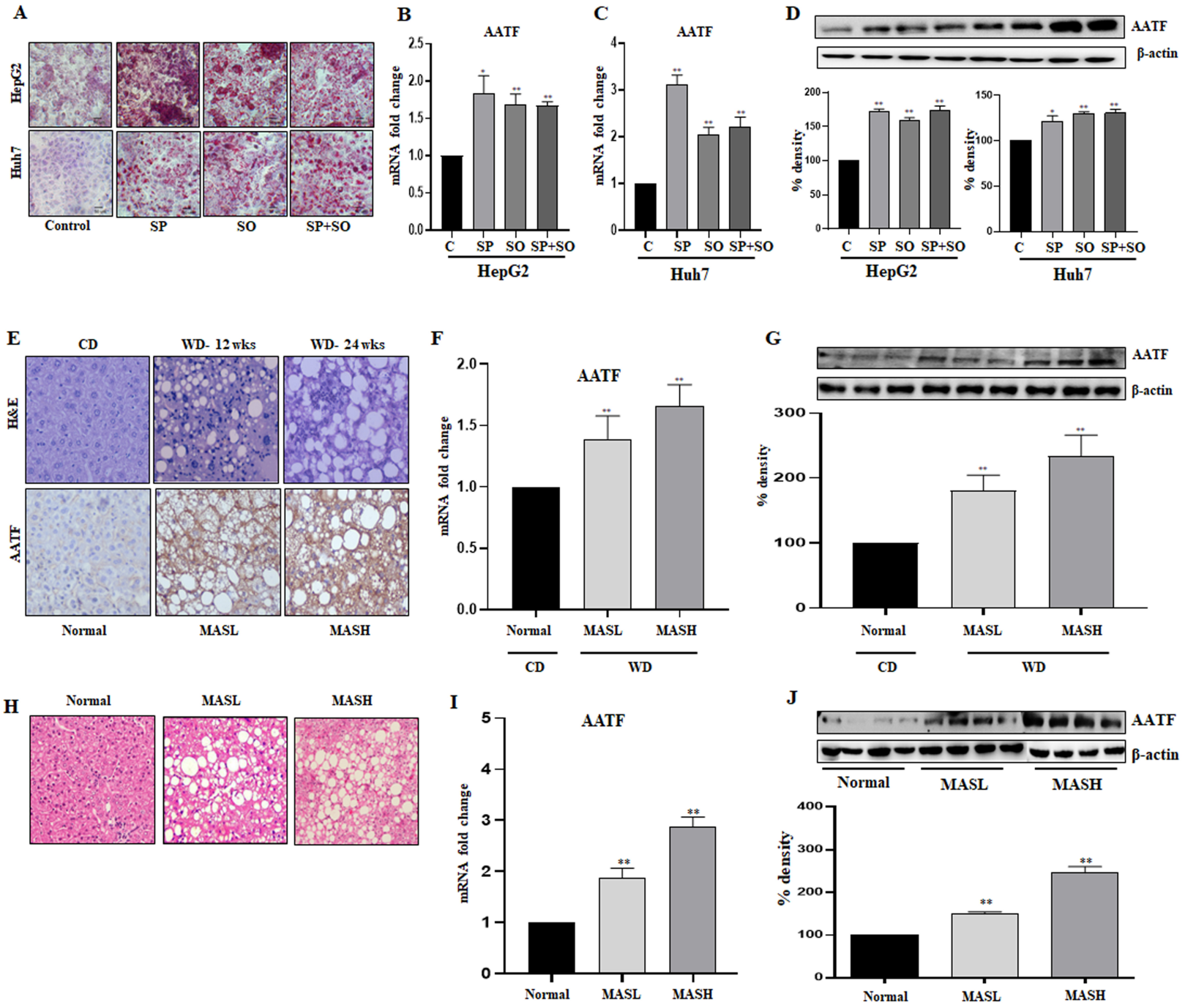

A
GLYCEROPHOSPHOLIPID METABOLISM
-1
0
1
Data on KEGG graph
Rendered by Pathview
B
Phosphocholine
PC
LPE
LPC
Relative abundance
C
Glycerophospholipid metabolism
WD Control
WD siAATF
D
Serum.Insulin
Blood.Glucose
HOMA-IR
Body.Weight
LysoPC(18:3(9Z,12Z,15Z))
Serum.TC
Liver.Weight
ALT
Serum.TG
Triethanolamine
Glycerol 3-phosphate
Phosphocholine
AST
Diethanolamine
Choline Alfoscerate
Node Annotation
Edge Annotation
-1 : Negative Correlation
1 : Positive Correlation
: Metabolites
: Non-Metabolites (Clinical Variables)

Figure 8

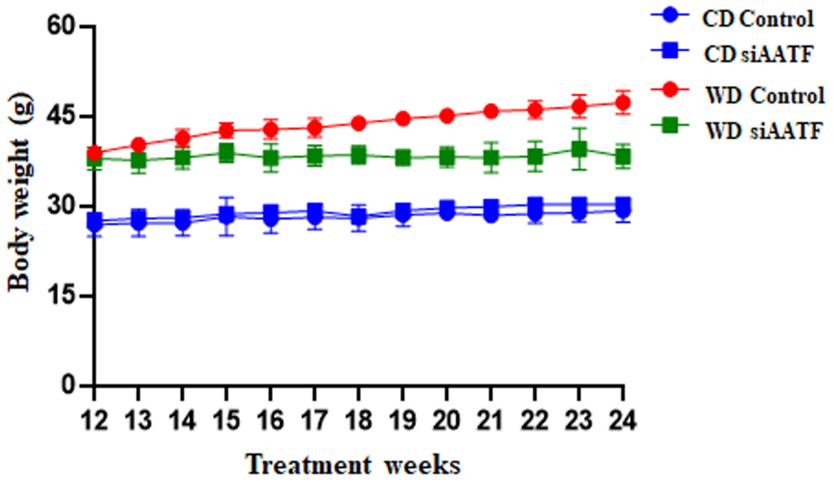

A
Upregulated
Pantothenate and CoA Biosynthesis
Thiamine Metabolism
Alanine Metabolism
Riboflavin Metabolism
Mitochondrial Beta-Oxidation of Long Chain Saturated Fatty Acids
Tryptophan Metabolism
Ammonia Recycling
Beta-Alanine Metabolism
Biotin Metabolism
Phenylacetate Metabolism
Propanoate Metabolism
Taurine and Hypotaurine Metabolism
Pyruvate Metabolism
Phosphatidylcholine Biosynthesis
Glutamate Metabolism
Beta Oxidation of Very Long Chain Fatty Acids
Alpha Linolenic Acid and Linoleic Acid Metabolism
Ethanol Degradation
Butyrate Metabolism
Threonine and 2-Oxobutanoate Degradation
Pathway
-log10(p-value)
Downregulated
Galactose Metabolism
Nucleotide Sugars Metabolism
Glycolysis
Inositol Phosphate Metabolism
Pentose Phosphate Pathway
Inositol Metabolism
Starch and Sucrose Metabolism
Gluconeogenesis
Warburg Effect
Bile Acid Biosynthesis
P-value
Enrichment.Ratio
B
Fatty acid oxidation
C
CPT1-α
ACOX1
PGC1-α
ACSL1
mRNA fold change
D
pAKT
AKT
pmTOR
mTOR
Raptor
β-actin
% density
WD Control
WD siAATF
E
SREBP1
F
LCAD
G
PNPLA2
CD Control
CD siAATF
WD Control
WD siAATF
H
AAV8-TBG-siAATF
WDSW
LC-MS/MS
High throughput sequencing
Metabolomics
Transcriptomics
Body weight
Insulin resistance
Triglycerides
Cellular stress
Inflammation
Fibrosis
AATF
AKT
mTORC1
Raptor
mTOR
S6K/SREBP1
FA synthesis
LCAD
CPT1α
FA oxidation
PNPLA2
Lipolysis
TAG
DAG
PC
PE
Glycerophospholipid synthesis

Supplementary Figure 1

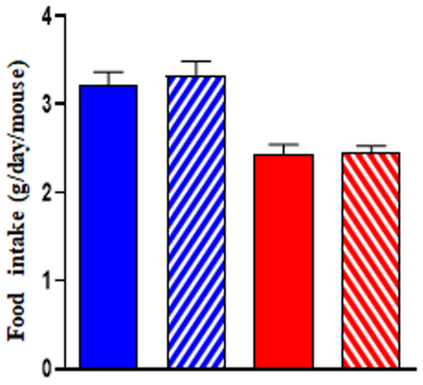


Supplementary Figure 2

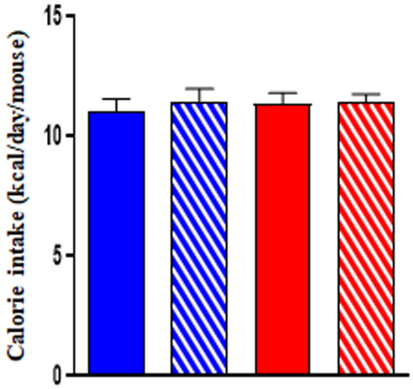
a



b

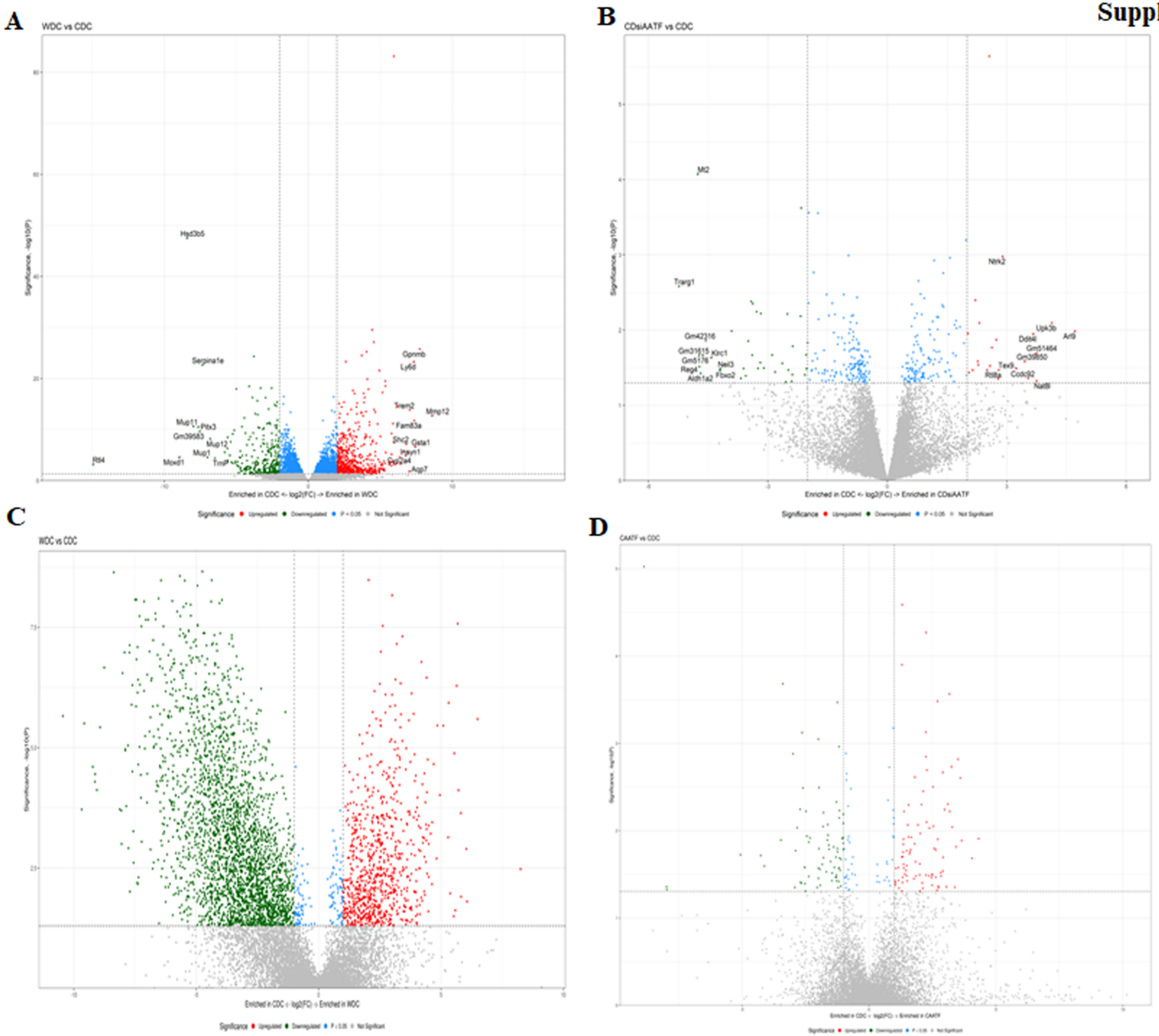


c

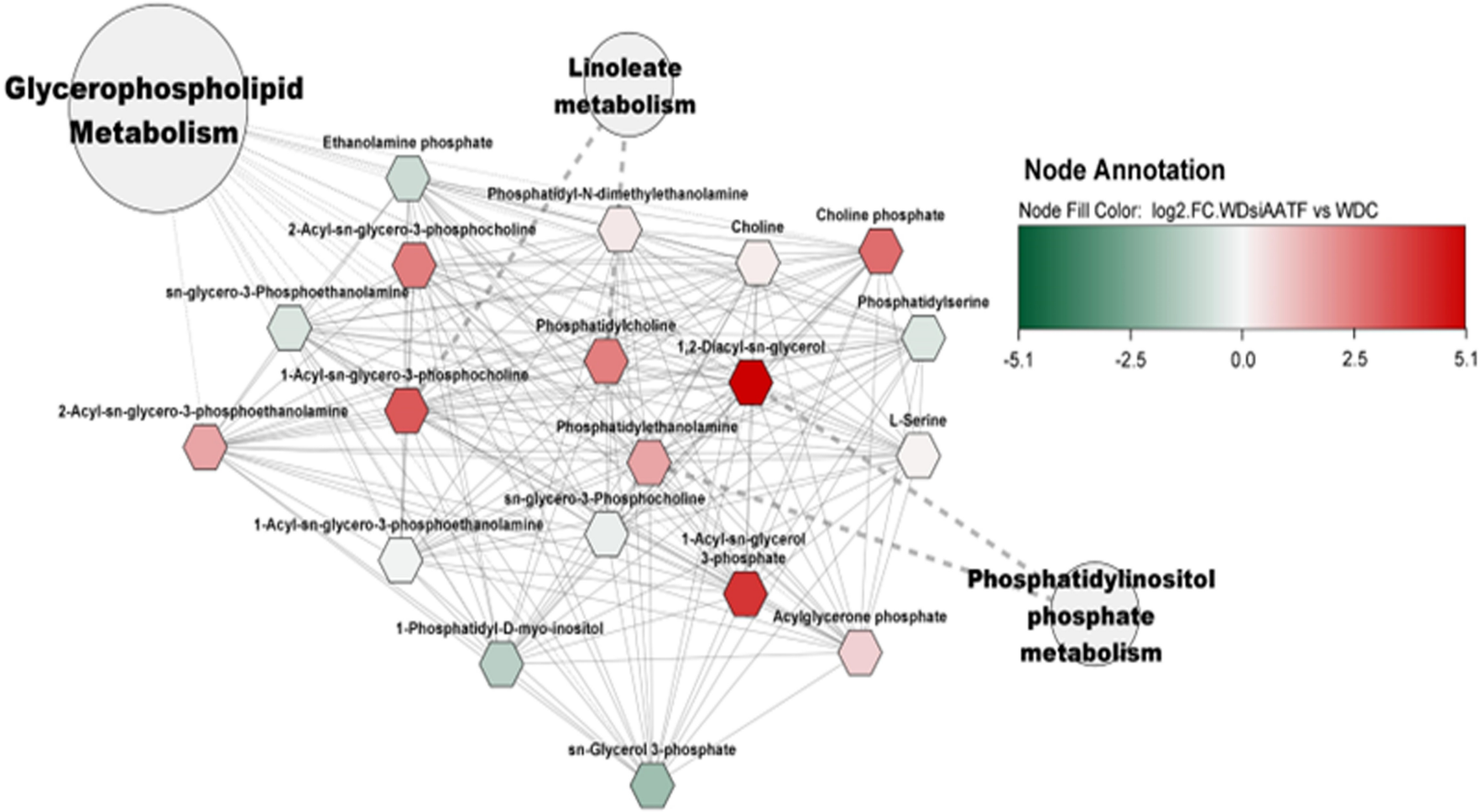


CD Control CD siAATF WD Control WD siAATF

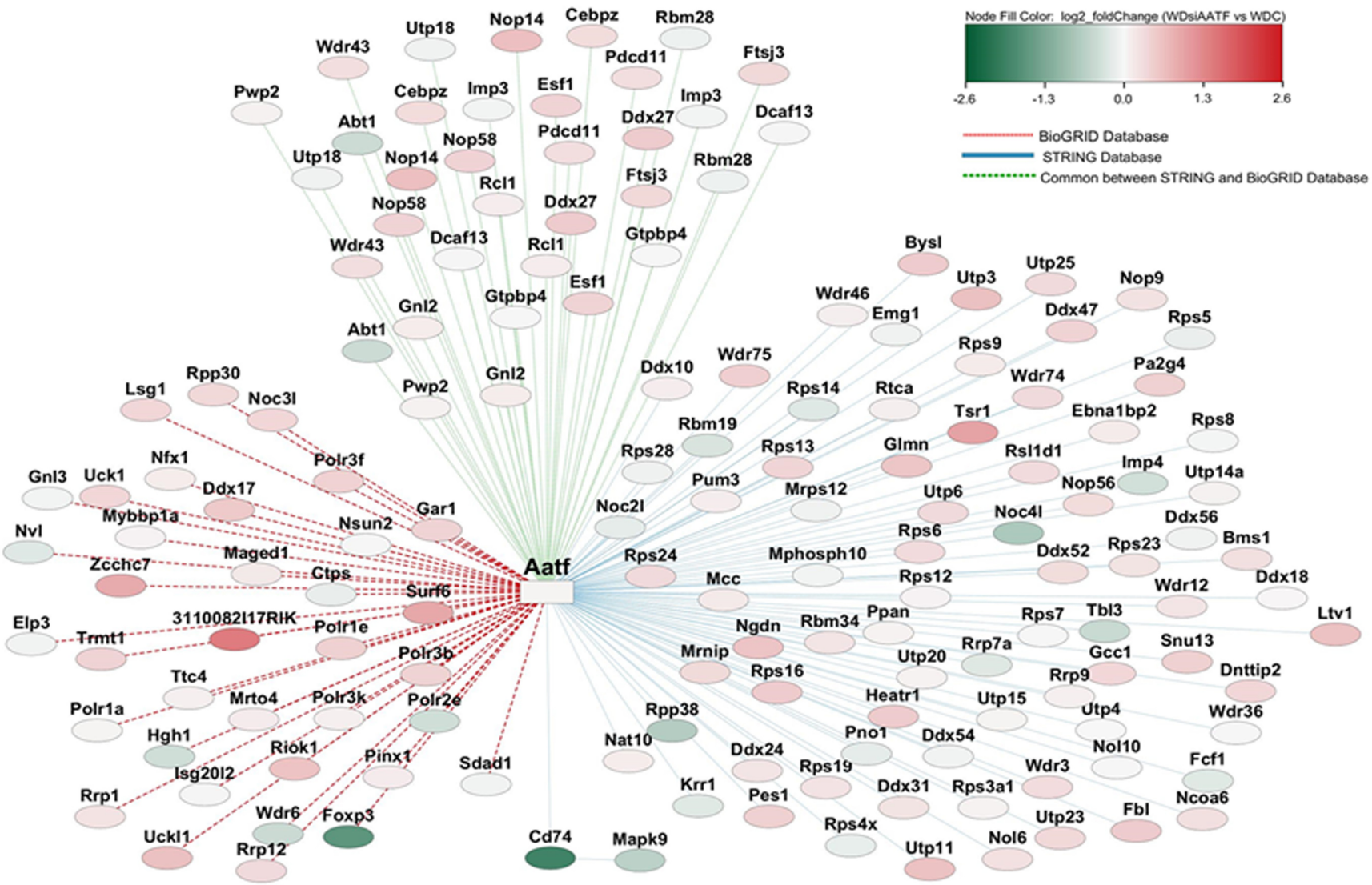
Supplementary Figure 3



Supplementary Figure 4



Supplementary Figure 5



Loss of AATF ameliorates metabolic dysfunction-associated steatohepatitis by suppressing the AKT-mTORC1 signaling pathway

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Supplementary Methods

In vitro model of steatosis

Human hepatic cells, HepG2, and Huh7 cells were a kind donation from Dr. Suresh Giri, Zydus Cadila, Gujrat, India. HepG2 cells were cultured in DMEM containing 1 g/L glucose (HiMedia Laboratories), and Huh7 cells were cultured in DMEM containing 4.5 g/L glucose (HiMedia Laboratories). The culture media were supplemented with 10% fetal bovine serum (Thermo Fisher Scientific), L-glutamine, and 100 U penicillin-streptomycin (Thermo Fisher Scientific) and incubated at 37^0C in 5% CO_2.

To develop an *in vitro* model of steatosis, cells were cultured up to 50% confluency in culture plates, followed by treatment with free fatty acids: 0.5 mM sodium oleate (SO; Sigma-Aldrich), 0.5 mM sodium palmitate (SP); Sigma-Aldrich), or a mixture of both SO and SP (SP+SO) in a 1:1 ratio in 5% fatty acid-free BSA (HiMedia Laboratories) containing culture media. After 24 hours of treatment, the cells were assessed for lipid droplets using Oil Red O staining (Sigma Aldrich). For all the experiments, cells were treated with free fatty acids for 24 hours, and the cell pellets were collected for RNA isolation or protein lysate preparation.

Glucose and Insulin tolerance tests

Mice were fasted overnight, or 5-6 hours for GTT (glucose tolerance test) and ITT (insulin tolerance test), respectively. The basal level of blood glucose was measured using a glucometer (Roche). Further, mice were subjected to oral administration of glucose (1 g/kg body weight) and intraperitoneal injection of insulin (0.75 U/kg body weight). Venous tail blood samples were taken at different intervals between 0 and 120 minutes to measure the blood glucose level.

Biochemical analysis

Blood collected from the fasting mice was centrifuged at 1500 g for 15 min at 4°C. The serum levels of aspartate transaminase (AST), alanine transaminase (ALT), total cholesterol (TC), total triglycerides (TG), and LDL-cholesterol were measured using commercial kits (Monlab tests) according to the manufacturer's protocol.

Histological analysis

Liver tissues were subjected to formalin (Sigma Aldrich) fixation, and paraffin blocks were prepared. 4µm tissue sections were used for hematoxylin and eosin staining to assess the liver morphology. For pathological grading, stained liver sections were scored by pathologists according to the MASLD activity score comprising the sum of steatosis (0-3), lobular inflammation (0-3), and hepatocyte ballooning (0-2). A cumulative activity score of ≥5 was indicative of MASH (1,2).

Oil Red O staining

Oil Red O staining was performed using frozen liver tissues. Cryosections, 12-µm thick, were fixed with 10% formaldehyde (Sigma Aldrich) for 5 minutes and washed with distilled water. Further, the slides were incubated with 60% isopropanol (Sisco Research Laboratories) and Oil Red O solution (Sigma Aldrich) for one hour. After rinsing off excess stain with distilled water, nuclei were counterstained with hematoxylin (HiMedia laboratories). The slides were then mounted, and images were captured using the Leica DM570 microscope (Leica Microsystems). For quantitative analysis, the areas of lipid droplets were quantified using ImageJ software.

Picrosirius red staining
The formalin-fixed paraffin-embedded (FFPE) liver tissue sections were subjected to deparaffinization and rehydration using xylene (HiMedia), followed by decreasing percentages of ethanol. The slides were first stained with hematoxylin for 2 minutes, followed by incubation with the picrosirius red solution (Sigma Aldrich) for 1 hour. Slides were washed in 0.5% acidified water and mounted. The images were captured using the Leica DM570 microscope (Leica Microsystems) and quantified using ImageJ software.

Immunohistochemistry
Immunohistochemistry was carried out according to the standard protocol. Briefly, after deparaffinization and rehydration, FFPE liver tissues were subjected to antigen retrieval with citrate buffer (pH 6) at 94°C for 15 minutes. Following this, the tissue sections were blocked with 3% hydrogen peroxide (PathnSitu Biotechnologies) and normal goat serum (Abcam) for 2 hours. Primary antibodies (AATF-Sigma Aldrich at 1:500, F4/80-Cell signaling technologies at 1:100, and Desmin- Cell signaling technologies at 1:500 dilutions) were used to stain the respective tissue sections overnight at 4°C in a humidified chamber. The detection of signals was accomplished using the Polyexcel HRP/DAB detection system (PathnSitu, Biotechnologies). Images were captured using the Leica DM570 microscope (Leica Microsystems), and quantitative analysis was conducted using ImageJ software.

ELISA
Serum insulin and TNFα levels were quantified using mouse ELISA kits (Krishgen Biosystems) according to the manufacturer's instructions.

Immunoblot analysis
Liver tissues and cell pellets were dissolved in RIPA buffer (Sigma Aldrich) containing protease/phosphatase inhibitor cocktail (Thermo Fischer Scientific). The lysates were obtained by centrifugation at 12000 rpm at 4^0C for 20 minutes. Protein concentration was estimated by Bradford's (Bio-Rad) protein estimation method. Equivalent amounts of protein were resolved in SDS-PAGE, followed by transfer into the nitrocellulose membrane (Bio-Rad). Blots were blocked in 5% nonfat dry milk for 1 hour and probed with primary antibodies of interest (anti-AATF-Sigma Aldrich 1:1000, anti-pAKT, anti-AKT, anti-pmTOR, anti-mTOR, anti-Raptor, and anti-β-actin - Cell signaling technologies 1:1000, anti-pJNK, anti-JNK, anti-pERK1/2, and anti-ERK1/2 – Santa Cruz Biotechnologies 1:100) overnight at 4^0C and secondary antibodies (Cell Signaling Technologies) for 2 hours at room temperature. Blots were visualized using Western Bright ECL HRP substrate (Advansta) in the UVitec Alliance Q9 chemiluminescence imaging system and analyzed for densitometric measurements in ImageJ software. The band intensity was normalized with the respective endogenous control.

RNA isolation, cDNA synthesis and Quantitative real-time PCR
Total RNA was extracted from the frozen live tissues or cell pellets using TRIzol reagent (Sigma Aldrich) according to the manufacturer's instructions. RNA was quantified using the nanodrop spectrophotometer and reverse transcribed using the verso cDNA synthesis kit following the manufacturer's protocol (Thermo Fischer Scientific). Relative gene expressions were assessed using quantitative real-time PCR (q RT-PCR) using the Rotor-Gene Q 5plex HRM system. q RT-PCR was carried out in triplicates per gene using Dynamo Colorflash SYBR green kit (Thermo Fischer Scientific) with 0.5 mM primers (IDT), and 50 ng of cDNA in a 20 µl reaction volume were used to set up the reaction. The mRNA levels of selected genes were

calculated after normalization to β-actin by using the $2^{(-\Delta\Delta C(T))}$ method. Primer sequences are provided in Supplementary Table 1.

Metabolomics data analysis

The data processing was done using the Compound Discoverer 3.3 software (Thermo Fisher Scientific). A pre-existing workflow template titled 'Untargeted Metabolomics with Statistics Detect Unknowns with ID using Online Databases and mzLogic' was used to identify the differences between samples. For identification, the mass tolerance was 5 ppm, and the retention time tolerance was 0.2 min. The minimum peak intensity was 10,000, and the chromatographic S/N threshold was 1.5. The solvent blanks were used to create exclusion lists, mark background components, and filter the background components from the results table. A pooled quality control (QC) sample was used for compound identification only.

To visualize the similarity between the metabolomic profiles of the samples from different groups, principal component analysis (PCA) and heatmap plots were generated. All the analyses were conducted based on the compound's peak areas. Differential metabolite analysis was conducted using a student's t-test, considering p value<0.05 as significant and log2 foldchange ≥ |1| as either an upregulated or downregulated metabolite. The log2 foldchange per metabolite was calculated as the ratio between group areas, transformed to log2 scale, with group area being calculated as the median of compound area per sample within the group. The up- or down-regulated metabolites were visualized using volcano plots. P-values were adjusted for multiple testing using the Benjamini Hochberg correction for false discovery rate.

The GSEA algorithm was applied against the Kyoto Encyclopedia of Genes and Genomes (KEGG) Mus musculus (House Mouse) pathway library, lipid superclass, and subclass. Significant pathways (p<0.05) from the GSEA method were analyzed further. Pathway enrichment against the small molecule pathway database (SMPDB) database was performed separately for upregulated and downregulated metabolites using MetaboAnalyst 6.0. For overlaying the regulation of metabolites involved in the glycerophospholipid metabolism pathway, the compound list and pathway were accessed from the KEGG database and visualized using the Pathview R package. To visualize the metabolic network, MetScape (http://metscape.ncibi.org./) was used and the Cytoscape plugin to identify the interaction between the metabolites involved in the glycerophospholipid metabolism pathway.

References:

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2. Brunt EM, Kleiner DE, Wilson LA, Sanyal AJ, Neuschwander-Tetri BA; Nonalcoholic Steatohepatitis Clinical Research Network. Improvements in Histologic Features and Diagnosis Associated With Improvement in Fibrosis in Nonalcoholic Steatohepatitis: Results From the Nonalcoholic Steatohepatitis Clinical Research Network Treatment Trials. Hepatology. 2019;70(2):522-531. doi:10.1002/hep.30418

Supplementary Table 1: List of primer sequences used in qRT-PCR

Primer	Sequence
Human AATF	**F:** GAGTGATGATGCCAGGACGGA **R:** ACTGTCACTTCCCACGGTCTG
Mouse AATF	**F:** GAGTGATGATGCCAGGACGGA **R:** ACTGTCACTTCCCACGGTCTG
Mouse CHOP	**F:** GAGCCAGAATAACAGCCGGAAC **R:** ACGTGGACCAGGTTCTGCTTTC
Mouse Grp78	**F:** TCTTCTCCACGGCTTCCGATA **R:** GTTAGGGGTCGTTCACCTTCAT
Mouse PERK	**F:** GGAAGAGGACTTTGAGAAAGCA **R:** ACATAGGGCGAGTCTGTCAGTT
Mouse ATF4	**F:** CCCCTACGACAAGAACATTCA **R:** CACTGGCAGAGTAGTCGAAGG
Mouse IL-1β	**F:** TGCCACCTTTTGACAGTGATGA **R:** TGATGTGCTGCTGCGAGATTTG
Mouse IL-6	**F:** GGAGCCCACCAAGAACGATA **R:** AACTGGATGGAAGTCTCTTGC
Mouse TNF-α	**F:** TAGCCCACGTCGTAGCAAACC **R:** CTTTGAGATCCATGCCGTTGGC
Mouse Col1A1	**F:** TGACTGGAAGAGCGGAGAGTA **R:** AGACGGCTGAGTAGGGAACA
Mouse Col3A1	**F:** GACCTAAGGGCGAAGATGGC **R:** GAAGCCACTAGGACCCCTTTC
Mouse α-SMA	**F:** CTACTGCCGAGCGTGAGATTGT **R:** CCCGCTGACTCCATCCCAATGA
Mouse TGF-β	**F:** GCTGCATATCGTCCTGTGG **R:** CTTCCATTTCCACATCCGACT

Mouse FASN	**F:** TGGGTGGGTGTGAGTGGTTC **R:** GGGCAATGCTTGGTCCTTTGA
Mouse ACC1	**F:** GGCAGCTCTGGAGGTGTATGT **R:** TGGGATGTGGGCAGCATGAA
Mouse ACC2	**F:** GTATGGCGTCCCTGGAGGTTTA **R:** CGGTGCTGCAGGCTGTTTAG
Mouse SCD1	**F:** CCCCTACGGCTCTTTCTGAT **R:** TGGTCACGAGCCCATTCATA
Mouse CPT1α	**F:** GGCTTCCATGACTCGGCTCTT **R:** ACCTCTGCTCTGCCGTTGTT
Mouse ACOX1	**F:** TGCAGACGGCCAGGTTCTT **R:** CTGGCTCGGCAGGTCATTCA
Mouse PGC1α	**F:** GGATGGTGCACAGAACCGATA **R:** CCAACCAGAGCAGCACACTAT
Mouse ACSL1	**F:** GAAGGCAGCTCCATCTAATCA **R:** TCTCTATGCAGAATTAGTTCCAA
Mouse SREBP1	**F:** CCAGCAGGTCCCAGTTGTACT **R:** TCACGGTGGCTCCTGCATCT
Mouse LCAD	**F:** CCAGGAACTACGTGAAGCAAAG **R:** TTATGCTGCACCGTCTGTATGT
Mouse PNPLA2	**F:** GAAGCTGCTGTGGTGGAGGA **R:** CCACTCCAACAAGCGGATGG
Human β Actin	**F:** AGAGATGGCCACGGCTGCTT **R:** CAGGACTCCATGCCCAGGAA
Mouse β Actin	**F:** CAGCCTTCCTTCTTGGGTATGG **R:** CCTGCTTGCTGATCCACATCT